Instructor's Manual for

Conceptual Physics,Twelfth Edition

The purpose of this manual is to help you combat the all-too-common notion that a course in physics has to be a course in applied mathematics. Rather than seeing the equations of physics as lifeless recipes for plugging in numerical data, your students can be taught to see physics equations as statements about the connections and relationships in nature. You can teach them to see that terms in equations are like notes on a musical score—they say something. Encountering conceptual physics should be a delightful surprise for your students. When the first experience with physics is delightful, rigor of the next experience will be welcomed!

Instructor's Manual to Conceptual Physics

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Preface

People feel good about themselves when they exceed self-expectations. School is sometimes a place where we fall below expectations—not only self-expectations, but the expectations of teachers, family, and the overall community. Physics courses have been notorious in this regard.

Too often, physics has the reputation of being the “killer course“—the course that diminishes average-ability students, who may drop out or take an incomplete, and spread the word about how unpleasant it is. Or they hear about it and simply avoid it in the first place. But we physics instructors have a secret: We know that the concepts of physics for the most part are much more comprehensible than the public expects. And when that secret is shared with students in a non-intimidating way, one that prompts them to discover they are learning more than they thought they could, they feel wonderful—about us, about physics, but more important, about *themselves*. Because they are not bogged down with time-consuming mathematical exercises of “the most threatening kind—word problems,“ they instead get a deeper and wider overview of physics that can be their most enlightened and positive school experience.

This manual describes a conceptual way of teaching. It helps relate physics to the students’ personal experience in the everyday world, so they learn to see physics not only as a classroom or laboratory activity, but as a part of everyday living. People with a conceptual understanding of physics are more alive to the world, just as a botanist taking a stroll through a wooded park is more alive than most of us to the trees, plants, flora, and the life that teems in them. The richness of life is not only seeing the world with wide-open eyes, but knowing what to look for. This puts you in a very nice role—being one who points out the relationships of things in the world about us. You are in an excellent position to add meaning to your student’s lives.

The appeal of the conceptual approach for nonscience students is obvious. Because conceptual physics has minimum “mathematical road blocks“ and little or no prerequisites, it is a rare chance for the nonscience student to learn solid science in a hard-core science course. I say rare chance, because nonscience students do not have the opportunity to study science as science students have to study the humanities. Any student, science or humanities, can take an intermediate course in literature, poetry, or history at any time and in any order. But in no way can a humanities student take an intermediate physics or chemistry course without first having a foundation in elementary physics and mathematics. Science has a *vertical structure*, as noted by the prerequisites. So it is much easier for a science student to become well rounded in the humanities than for a humanities student to become well rounded in science. Hence the importance of this conceptual course.

Too often a physics course begins with a study of measurement, units of measure, and vector notation. I feel this contributes to the unfortunate impression that physics is a dull subject. If you were being instructed on some computer activity, wouldn’t you object to being shown everything that might appear much later in your development? Don’t we prefer to be shown something when it is needed? The same is true with a physics course. Rather than discuss vectors, wait until you’re dealing with how fast an airplane is blown off course by a crosswind. When the vectors help to learn a topic your class is immersed in, they are valued. Likewise with so much else in physics.

It is important to distinguish between physics concepts and the tools of physics. Why spend valuable time teaching a class of nonscience majors the tools needed for physics majors? By minimizing time spent on graphical analysis, units conversions, measurement techniques, mathematical notation, and problem solving techniques, time is provided to teach a broad survey of physics—from Newton’s laws to E & M to rainbows to nuclear processes. Too often physics courses spend overtime in kinematics because of its appealing tools, with the result that modern physics is given short thrift. Many people who took a physics course can tell you that the acceleration due to gravity is 9.8 m/s^2, but they have no idea that radioactivity contributes to the molten state of Earth’s

interior. They didn't get that far in their course, or if they did, they were rushing through the end of the course. Modern physics gets too little attention.

The rest of my remarks here concern science majors. I maintain that science students who use this book in their first physics course are even greater benefactors than nonscience students. Not because it is an "easy" introduction or even because it gets them excited about physics, but because it *nurtures that gut-level conceptual understanding that is the missing essential for so many science and engineering students*—who like their would-be poet counterparts, have mistaken being able to recite poetry for understanding it.

I feel strongly that the ideas of physics should be understood conceptually before they are used as a base for applied mathematics. We are all acquainted with students who can crank out the answers to many problems by virtue of little-understood formulas and a knack for algebraic manipulation—students who even in graduate school are able to do well in written exams (which are most always exercises in problem solving), but who do poorly in oral exams (which are most always conceptual). Is this a surprising outcome for students who have never had a good exposure to the concepts and ideas of physics that weren't at the same time paired with the techniques of mathematical problem solving? To many of these people, physics *is* applied mathematics—so much so, that a physics course without mathematical problem solving seems a contradiction! Conceptual understanding in every physics course they ever encountered took a back seat to problem-solving techniques. The name of the game in every physics course has been PROBLEM SOLVING. Students are solving problems involving the manipulation of twigs and branches when they lack a conceptual understanding of the trunk and base of the tree from which the branches stem.

We all know that the beauty of physics is its elegant mathematical structure. If you want to teach mathematics to your students, a physics course is the way to go. This is because the mathematics is applied to actual things and events. But if you want to teach *physics* to your students, put the niceties of mathematical problem solving in the back seat for a semester and teach physics conceptually. You'll provide your students, especially your mathematical whizzes, a look at physics they may otherwise miss. First having an understanding of concepts on a conceptual level is an essential foundation for any serious further study of physics. Provide your students with a good look at the overall forest before they make measurements of any single tree—place comprehension comfortably *before* calculation.

For an algebra-trig based course that goes beyond the conceptual course, problem solving is central. A blend of conceptual and problem solving is now an option, for Phil Wolf and I have written a supplementary student problems book that we think will be greeted as being as novel as Conceptual Physics was nearly 40 years ago. The book, now in its third edition, is described on the pages that follow. With this supplement, *Conceptual Physics* can be the textbook for courses with a light algebra-trig component.

The challenge is yours. Let's get to work!

Teaching Tips

• ATTITUDE toward students and about science are of utmost importance. Consider yourself not the master in your classroom, but the main resource person, the pacesetter, the guide, the bridge between your student's ignorance and information you've acquired in your study. Guide their study—steer them away from the dead ends you encountered, and keep them on essentials and away from time-draining peripherals. You are there to help them. If they see you so, they'll appreciate your efforts. This is a matter of self-interest. An appreciated teacher has an altogether richer teaching experience than an under-appreciated teacher.

• ENGAGE your students. Recall your own student days with teachers whose engagement was with the subject matter, but seldom with you or your fellow students. Engagement, eye contact for starters, is crucial to your success as a teacher. Be *with* your students.

• Make your course ENJOYABLE. We all enjoy the discovery of learning more than we expected of ourselves. Guide that discovery. When a student's first encounter with physics is delightful, the rigor that comes later will be welcomed.

• Don't be a "know-it-all." When you don't know your material, don't pretend you do. You'll lose more respect faking knowledge, than not knowing it. If you're new to teaching, students will understand you're still pulling it together, and will respect you nonetheless. But if you fake it, and they CAN tell, whatever respect you've earned plummets.

• Be firm, and expect good work of your students. Be fair and get papers graded and returned quickly. Be sure the bell curve of grades reflects a reasonable average. If you have excellent students, some should score 100% or near 100% on exams. This way you to avoid the practice of fudging grades at the end of the term to compensate for off-the-mark low exam scores. The least respected professor in my memory was one who made exams so difficult that the class average was near the noise level, where the highest marks were some 50%.

• Be sure that what knowledge you want from your students is reflected by your test items. The student question, "Will that be on the test?" is a good question. What is important—by definition—is what's on the test. If you consider a topic important, provide an opportunity for students to demonstrate their understanding of that topic. An excellent student should be able to predict what will be on your test. Remember your own frustration in your student days of preparing for a topic only to find it not part of the test. Don't let your students experience the same. Using short questions that fairly span course content is the way to go.

• Consider having students repeat work that you judge to be poor—before it gets a final grade. A note on a paper saying you'd rather not grade it until they've given it another try is the mark of a concerned and caring teacher.

• Do less professing and more questioning. Valuable information should to be the answer to a question. Having frequent "check-your-neighbor" intervals should be an important feature of your class. Beware of the pitfall of too quickly answering your own questions. Use "wait-time," where you allow ample time before giving the next hint.

• Show RESPECT for your students. Although all your students are more ignorant of physics than you are, some are likely more intelligent than you are. Underestimating their intelligence is likely overestimating your own. Respect is a two-way street. Students who know you care, respect you in return.

On Class Lectures

Profess less and question more! Engage your students in lecture by frequently posing questions. Instead of answering your own question, direct your students to come up with an answer, and check their thinking with their neighbor—right then and there. This technique has enlivened my classes for more than 25 years. I call it CHECK YOUR NEIGHBOR. The procedure goes something like this; before moving on to new material, you want to summarize what you've already discussed. So you pose the challenge, "If you understand this—if you really do—then you can answer the following question." Then pose your question slowly and clearly, perhaps in multiple-choice form or one requiring a short answer. Direct your class to make a response—usually written. Tell them to "CHECK YOUR NEIGHBOR"; look at their neighbors' papers, and briefly discuss the answer with them. At the beginning of the course you can add that if their neighbors aren't helpful, to sit somewhere else next time! The check-your-neighbor practice changes *teaching by telling* to *teaching by questioning*—perhaps first admonished by Socrates. Questioning brings your students into an active role, no matter how large the class. It also clears misconceptions before they are carried along into new material. In the suggested lectures of this manual, I call such questions, CHECK QUESTIONS. The check-question procedure may also be used to *introduce* ideas. A discussion of the question, the answer, and some of the misconceptions associated with it, will get more attention than the same idea presented as a statement of fact. And one of the very nice features of asking for neighbor participation is that it gives you pause to reflect on your delivery.

Harvard's Eric Mazur, profiled at the outset of Chapter 9, pioneers the conceptual approach to physics with science and engineering majors. Eric is a strong advocate of what he calls CONVINCE YOUR NEIGHBOR, much akin to Next-Time Questions. Students answer questions with clickers, an extension of whiteboards. This feature is also a central component of the Modeling Workshops that are gaining in popularity. I regret that I didn't employ whiteboards in my classes before I retired in 2000. And electronic clickers are now popular, giving the instructor immediate feedback on questions posed. By whatever method, have your students check their neighbors!

On homework, a note of caution: Please, please, do not overwhelm your students with excessive written homework! (Remember those courses you took as a student where you were so busy with the chapter-end material that you didn't get into the chapter material itself?) The chapter-end exercises are significantly more numerous in this edition only to provide you a wide selection to consider. Depending on your style of teaching, you may find that posing and answering exercises in class is an effective way to develop physics concepts. A successful course may place either very much or very little emphasis on the exercises. Likewise with the problems, which are meant to be assigned after concepts are treated and tested. Please don't let your course end up as a watered-down physics major's problem solving course!

I strongly recommend lecture notes. In all of my teaching years I brought a note or two to every lecture. A list of topics gives you a checklist to glance at when students are going through a check-your-neighbor routine. Such notes insure you don't forget main points, and a mark or two will let you know in your next lecture what you may have missed or where you stopped.

You may find that your students are an excellent source of new analogies and examples to supplement those in the text. A productive class assignment is:

> Choose one (or more) of the concepts presented in the reading assignment and cite any illustrative analogies or examples that *you* can think of.

This exercise not only prompts your students to relate physics to their own experiences, but adds to your future teaching material. I've relied on this procedure to provide me with credible wrong answers for devising multiple-choice exams!

Equations are important in a conceptual course—not as a recipe for plugging in numerical values, but more important, as a guide to thinking. The equation tells the student what variables to consider in treating an idea. How much an object accelerates, for example, depends not only on the net force, but on mass as well. The equation $a = F/m$ reminds one to consider both quantities. Does gravitation depend on an object's speed? Consideration of $F \sim mM/d^2$ shows that it doesn't, and so forth. The problem sets, Think and Solves, at the ends of most chapters involve computations that help to illustrate concepts rather than challenge your students' mathematical abilities. They are relatively few in number to avoid overload. Again, for those who make problem solving a greater part of the course, see the student supplement *Problem Solving in Conceptual Physics* that complements this 12*th Edition*.

Getting students to come to class prepared is a perennial problem. An ineffective way to address this is to preach about the importance of reading assigned material before coming to class. When you do that, you might as well be whistling Dixie. What does work is rewarding the reading directly. What a great idea: If we want students to behave a certain way, we reward them when they do! Start your class with a short quiz on the reading assignment. Suk R. Hwang of the University of Hawaii at Hilo begins each class by handing out a half sheet of paper with one or two questions that highlight the reading assignment. Before lecturing on gravity, for example, the students will take one or two minutes to respond to "State Newton's law of gravity in both words and equation form." Suk collects the sheets and then begins his lecture. The whole process takes less than five minutes. He assigns a grade to the sheets, with brief comments, and returns them. But the grades do not count at all when tallying the final course grade. He is out front with his class when he tells them that the only purpose of the quizzes is to increase the probability of coming to class having first read the assigned reading material. Suk finds that because students abhor returning blank sheets, or dislike not being able to correctly answer the simple questions, they DO the reading assignment. Evidently a well-answered paper, even though it doesn't count to the final grade, is sufficient reward for the student.

More and more instructors are finding that giving daily short quizzes or assigning summary reports gets students to class prepared. Importantly, the instructor needn't be submerged in paperwork. Spot grading or even no grading is sufficient. With a prepared class, instead of presenting material, you can refine and polish, with students that can fully benefit by the questions you pose. Less professing—more questioning!

Make use of the NEXT-TIME QUESTIONS located on your Instructor Resource DVD, which poses intriguing questions accompanied by my cartoons, with and accompanying answer page. These can be photocopied and posted on display boards to capture attention and create discussion. They are also available on the Arbor Scientific website: www.arborsci.com. What I passionately ask is that you heed this advice: Employ "wait time" before displaying the answers. If you put them in printed form, you can display them in a designated space, perhaps a glass case near your office. My policy was to display four or six of them weekly—answers to the ones posted the previous week, with new ones. These can also be projected in your classroom, perhaps via PowerPoint. They will certainly prompt out-of-class discussion. When impatient students want to check their answers with me before posting time I advise them to consult with their friends. When they tell me they have done so and that their friends are also perplexed, I suggest they seek new friends! So post them in a hallway for all to ponder or conclude your lessons with them in class as ties to the next class meeting—hence their name, *Next-Time Questions*. Most all of these first appeared as *Figuring Physics* in *The Physics Teacher*, the must-read magazine of the American Association of Physics Teachers (AAPT).

New with this edition are my Hewitt-Drew-it! PHYSICS screencasts, which are QR coded throughout the textbook. These are quickie tutorials that complement the textbook, often with visual explanations of concepts. Creating these has been my passion for the past two years.

The student ancillary PRACTICING PHYSICS BOOK can serve as a tutor on the side. At CCSF it is carried in the student bookstore as "recommended but not required" and used by about one-third of the students taking the course. Answered practice pages are in the back of the book, reduced in

size. I consider the Practicing Physics Book my best pedagogical creation, along with my new screencasts.

The Conceptual Physics package of text and ancillaries lend themselves to teaching by way of the 3-stage LEARNING CYCLE, developed by Robert Karplus some 40 years ago.

EXPLORATION—giving all students a common set of experiences that provide opportunities for student discussion. Activities are both in the *Laboratory Manual* and the chapter-end Think-and-Do's in the textbook.

CONCEPT DEVELOPMENT—lectures, textbook reading, doing practice pages from *Practicing Physics*, viewing *Hewitt-Drew-it! screencasts*, and class discussions.

APPLICATION—doing end-of-chapter exercises and problems, *Next-Time Questions*, experiments from the *Laboratory Manual*, and for your math-savvy students, *Problem Solving in Conceptual Physics*.

The first step of the learning cycle increases the effectiveness of instruction by insuring students have first-hand experience with much of the phenomena to be discussed. For example, before hearing a lecture on torques, have your students pass around a meterstick with a weight dangling from a string (as nicely shown by Mary Beth Monroe in the third chapter-opening photo for Chapter 8 on page 132). Holding the meterstick horizontally with the weight near the end, students feel the greater effort needed to rotate the stick. When the weight is positioned closer to their hand, rotational effort is much less. Aha, now you're ready to discuss the concept of torque, and to distinguish it from weight.

Many of the suggested lectures in this manual will require more than one class period, depending on your pace of instruction and what you choose to add or omit. The lectures of each instructor, of course, must be developed to fit his or her style of teaching. My suggested lectures may or may not be useful to you. If you're new to teaching conceptual physics and your lecture tendency is to lean on chalkboard derivations, you may find them quite useful, and a means of jumping off and developing your own non-computational way of teaching.

DVDs of my classroom lectures are described on page xv.

Please bring to my attention any errors you find in this manual, in the text, in the test bank, or in any of the ancillaries. I welcome correspondence suggesting improvements. E-mail, Pghewitt@aol.com. Good luck in your course!

ANCILLARY PACKAGE FOR THE 12th EDITION

For Instructors

INSTRUCTOR RESOURCE DVD (IR-DVD):
Contains a wealth of goodies, including all textbook illustrations, tables from the text, interactive presentation applets and animations, parts of Hewitt's videoed lectures and demos, in-class clicker questions for use with PRS and HiTT Classroom Response Systems, most of which can be edited and customized for classroom presentations. The main ancillaries are:

> **NEXT-TIME QUESTIONS**:
> These are insightful questions, with answers, to central ideas in physics. Each was formerly published as *Figuring Physics* in the American Association of Physics Teachers (AAPT) magazine, *The Physics Teacher*. Aside from projecting these via PowerPoint or otherwise, consider printing copies and posting for student display. Allow a sufficient 'wait time' before posting solutions. There are Next-Time-Questions for every chapter.
>
> **TEST BANK**:
> Contains more than 2000 multiple-choice questions, categorized by level of difficulty and skill type. The friendly graphical interface enables you to easily view, edit, and add questions, transfer questions to tests, and print tests in a variety of fonts and forms. Search and sort features let you quickly locate questions and arrange them in a preferred order. A built-in question editor gives you power to create graphs, import graphics, insert mathematical symbols and templates, and insert variable numbers or text.

VIDEOS *Conceptual Physics Alive!*:
Features my classroom lectures while teaching Conceptual Physics at the University of Hawaii in 1989-1990. These are available in DVD or rental of individual lessons streamed from Arbor Scientific, (www.arborsci.com) P.O. Box 2750, Ann Arbor, MI 48106-2750.
Additionally, the 12-lecture set of videos taken at CCSF in 1982 have been resurrected by Marshall Ellenstein, and with other "goodies," comprise a 3-disc DVD set "*Conceptual Physics Alive*! *The San Francisco Years.*" The goodies include the 60-minute ***Teaching Conceptual Physics***, which documents how I teach physics conceptually, and the 55-minute ***Lecture Demonstrations in Conceptual Physics***, which is more classroom footage with emphasis on demonstrations (most of which are in the "Suggested Lectures" in this manual). Another goodie is a 45-minute general-interest opening lecture, ***The Fusion Torch and Ripe Tomatoes***. At one-quarter the price of the Hawaii tapes, they are available from Media Solutions, 1128 Irving St., San Francisco, CA 94122 (www.mediasolutions-sf.com/hewitt/sfyorders.pdf).

For Students

PRACTICING PHYSICS BOOK:
This booklet of more than 100 practice pages helps students to learn concepts. This is very different from traditional workbooks that are seen as drudgery by students. These are insightful and interesting activities that prompt your students to engage their minds and DO physics. They play the role of a tutor when you post solutions at appropriate times (like the posting of Next-Time Questions). Practice Book solutions, reduced to one-half size, are included at the end of the book. ***Practicing Physics*** is

low priced and can be offered as a suggested supplement to the textbook in your student bookstore. ISBN: 0805391983.

PROBLEM SOLVING BOOK:
Now in its Third Edition, this is my latest effort to boost the teaching of physics, with co-author Phil Wolf. It is meant for those who wish a stronger problem-solving component in their teaching, and particularly for those wishing to extend *Conceptual Physics* to an algebra-trig course. I feel the novelty of the problems and the simple method employed for solving them will be as important to the way physics is taught as was *Conceptual Physics* when it was introduced some 40 years ago. No longer does the instructor have to plead with students to complete the problem before plugging in numerical values. Instructors no longer have to plead with students to show their work. Why? Because the phrasing of the problems makes these concerns mandatory. Variables are given in letters, not numbers (mass is *m*, velocity is *v*, and so forth). Not until a second part of a problem are numerical values given and a numerical solution asked for. Each chapter set of problems is followed by a second set of *Show-That Problems*, which give the numerical answer and ask the student to show how it comes about. I've been using this method for decades when teaching the algebra-trig and calculus based physics courses. Now it is available to users of *Conceptual Physics*. Solutions to the problems are given on the website in the Instructor's Resource area. At your discretion you can post solutions for your students. ISBN: 0805393773.

LABORATORY MANUAL:
This manual, written by myself and mostly by Dean Baird, is rich with simple activities to precede the coverage of course material, as well as experiments that are a follow through to course material. It also employs the computer in tech labs. New to this 12th edition, the instructor manual for the laboratory manual is separate from this manual.

Flexibility of Material for Various Course Designs

You'll teach more physics in your course if you spend less time on topics that are more math than physics. Topics I suggest you remove from your front seat include units conversions, graphical analysis, measurement techniques, error analysis, overtime on significant figures, and the wonderful and seductive time-consuming toys for kinematics instruction.

Very few one-semester and virtually no one-quarter courses will include all the material presented in the text. The wide variety of chapters provides a selection of course topics to suit the tastes of individual instructors. Most begin their course with mechanics, and treat other topics in the order presented in the text. Some will go immediately from mechanics to relativity. Many will begin with a study of light and treat mechanics later. Others will begin with the atom and properties of matter before treating mechanics, while others will begin with sound, then go to light, and then to electricity and magnetism. Others who wish to emphasize modern physics will skim through Chapters 11, 19, 30 and 31, to then get into Parts 7 and 8. Some will cover many chapters thereby giving students the widest possible exposure of physics, while others will set the plow deeper and treat fewer chapters.

The following breakdown of parts and chapters is intended to assist you in selecting a chapter sequence and course design most suited to your objectives and teaching style. You should find that the chapters of Conceptual Physics are well suited to stand on their own.

PART 1: MECHANICS After the first chapter, About Science, Mechanics begins with forces, rather than kinematics as in earlier editions. Newton's first law kicks off by featuring the concept of mechanical equilibrium. Force vectors are introduced. After this chapter, kinematics is treated, which I urge you to go through quickly. The important concepts of velocity and acceleration are developed in further chapters, which makes prolonged time in Chapter 3 a poor policy. Certainly avoid kinematics problems that are more math than physics, and that many students encounter in their math courses anyway. Chapter 4 goes to Newton's second law, followed by a separate chapter for the third law. There is more treatment of vectors in this 12-th Edition. They use no trig beyond the Pythagorean Theorem. There are no sines, cosines, or tangents, for the parallelogram method is used. (Trig is introduced in the *Problem Solving Book*, however.) Chapters, 2-5, are central to any treatment of mechanics. Only Chapters 2, 4, and 9 have a historical flavor. Note in the text order that momentum conservation follows Newton's 3rd law, and that projectile motion and satellite motion are combined in Chapter 10. My recommendation is that all the chapters of Part I be treated in the order presented. To amplify the treatment of vectors, consider the Practice Book and Appendix D. For an extended treatment of mechanics consider concluding your treatment with Appendix E, *Exponential Growth and Doubling Time*.

PART 2: PROPERTIES OF MATTER The very briefest treatment of matter should be of Chapter 11, atoms, which is background for nearly all the chapters to follow in the text. Much of the historical development of our understanding of atoms is extended in Chapter 32, which could well be coupled to Chapter 11. Chapters 12, 13 and 14 are not prerequisites to chapters that follow. Part 2, with the exception of the brief treatment of kinetic and potential energies in the Bernoulli's principle section of Chapter 14 may be taught before, or without, Part 1. With the exception noted, Part 1 is not prerequisite to Part 2.

PART 3: HEAT Except for the idea of kinetic energy, potential energy, and energy conservation from Part 1, the material in these chapters is not prerequisite to the chapters that follow, nor are Parts 1 and 2 prerequisites to Part 3.

PART 4: SOUND Material from these chapters (forced vibrations, resonance, transverse and standing waves, interference) serves as a useful background for Chapters 26, 29 and 31. Parts 1-3 are not prerequisites to Part 4.

PART 5: ELECTRICITY AND MAGNETISM Part 1 is prerequisite to Part 5. Also helpful are Chapters 11, 14, and 19. The chapters of Part 5 build from electrostatics and magnetism to electromagnetic induction—which serve as a background for the nature of light.

PART 6: LIGHT Parts 4 and 5 provide useful background to Part 6. If you begin your course with light, then be sure to discuss simple waves and demonstrate resonance (which are treated in Part 4). If you haven't covered Part 5, then be sure to discuss and demonstrate electromagnetic induction if you plan to treat the nature of light. The very briefest treatment of light can cover Chapters 26-28. A very brief treatment of lenses is in Chapter 28. A modern treatment of light should include Chapters 30 and 31.

PART 7: ATOMIC AND NUCLEAR PHYSICS Chapter 11 provides a good background for Part 7. Chapter 33 is prerequisite to Chapter 34. Otherwise, Part 7 can stand on its own.

PART 8: RELATIVITY This part can stand on its own and will nicely follow immediately from Part 1, if the ideas of the Doppler effect and wave frequency are treated in lecture. A thorough treatment of only Parts 1 and 8 should make a good quarter-length course.

1 About Science

Much of this introductory chapter, like most introductions, can be regarded as a personal essay by the author. While many physics instructors may discuss somewhat different topics in a somewhat different way, the comments made here may prove to be useful as a background for further comments of your own.

The chapter opens with a pair of photos of my wife beneath a tree in front of our residence in San Francisco. They replace the rendered photos of a partial eclipse of the previous edition. This pair of photos is real, and others taken by Dean Baird and Paul Doherty are in Chapter 26. The pair of photos lead to the profile of Eratosthenes, and his early measurements of the Earth. Such merits further explanation and a good way to kick off your course. Follow this up with the early measurement of the Moon and Sun by Aristarchus. More on these early measurements is found in the excellent book *Physics for the Inquiring Mind*, by Eric Rogers, originally published in 1960 by Princeton University Press.

You may consider elaborating on the idea about the possible ***wrongness*** **versus rightness** of ideas; an idea that characterizes science. This is generally misunderstood, for it is not generally a criterion in other disciplines. State that it is the prerogative of science, in contrast to the speculative procedures of philosophy and meta-physics, to embrace only ideas that can be tested and to disregard the rest. Ideas that can't be tested are not necessarily wrong—they are simply useless insofar as advancement in scientific knowledge is concerned. Ideas must be verifiable by other scientists. In this way science tends to be self-correcting.

Expand on the idea that **honesty in science** is not only a matter of public interest, but is a matter of self-interest. Any scientist who misrepresents or fudges data, or is caught lying about scientific information, is ostracized by the scientific community. There are no second chances. The high standards for acceptable performance in science, unfortunately, do not extend to other fields that are as important to the human condition. For example, consider the standards of performance required of politicians.

Distinguish between *hypothesis*, *theory*, *fact*, and *concept*. Point out that theory and hypothesis are not the same. A **theory** applies to a synthesis of a large body of information. The criterion of a theory is not whether it is true or untrue, but rather whether it is useful or nonuseful. A theory is useful even though the ultimate causes of the phenomena it encompasses are unknown. For example, we accept the theory of gravitation as a useful synthesis of available knowledge that relates to the mutual attraction of bodies. The theory can be refined, or with new information it can take on a new direction. It is important to acknowledge the common misunderstanding of what a scientific theory is, as revealed by those who say, "But it is not a fact; it is only a theory." Many people have the mistaken notion that a theory is tentative or speculative, while a fact is absolute.

Impress upon your class that a **fact** is not immutable and absolute, but is generally a close agreement by competent observers of a series of observations of the same phenomena. The observations must be testable. Since the activity of science is the determination of the most probable, there are no absolutes. Facts that were held to be absolute in the past are seen altogether differently in the light of present-day knowledge.

By **concept**, we mean the intellectual framework that is part of a theory. We speak of the concept of time, the concept of energy, or the concept of a force field. Time is related to motion in space and is the substance of the Theory of Special Relativity. We find that energy exists in tiny grains, or quanta, which is a central concept in the Quantum Theory. An important concept in Newton's Theory of Universal Gravitation is the idea of a force field that surrounds a material body. A concept envelops the overriding idea that underlies various phenomena. Thus, when we think "conceptually" we envelop a generalized way of looking at things.

Prediction in science is different than prediction in other areas. In the everyday sense, one speaks of predicting what has not yet occurred, like whether or not it will rain next weekend. In science, however, prediction is not so much about what *will* happen, but about what *is* happening and is not yet noticed, like what the properties of a hypothetical particle are and are not. A scientist predicts what can and cannot happen, rather than what will or will not happen.

In biology, for example, you explain events once you see them. In a sense you're looking at the historical behavior and then you explain patterns. In physics you're more likely to predict patterns before they're seen.

Max Born, Nobel-prize recipient and one of the most outstanding physicists of the twentieth century, is quoted in the insight box of page 12. It was to a letter to Max by his close friend Albert Einstein in 1926 that Einstein made his famous remark regarding quantum mechanics, often paraphrased as "God does not play dice with the universe." Max Born died in 1970, and was the maternal grandfather of the popular singer Olivia Newton-John.

Science and Technology

In discussions of science and technology and their side effects, a useful statement is: *You can never do just one thing*. This is similar to "there is never just one force" in discussions of Newton's third law.

With regard to risk, you can prove something to be unsafe, but you can never prove something to be completely safe.

Engineering is the practical application of science to commerce or industry. The tripartite arrangement of science, technology, and engineering has always been the combination for successful advancement.

> "Any sufficiently advanced society is indistinguishable from magic." Arthur C. Clark

One can quip that a first stage of scientific discovery is to deny that it's true, the second is to deny that it's important, and the third is to credit the wrong person.

The medieval philosopher, William of Occam, wisely stated that when deciding between two competing theories, choose the simpler explanation—don't make more assumptions than are necessary when describing phenomena.

Physicists have a deep-seated need to know "Why?" and "What if?". Mathematics is foremost in the toolkits they develop to tackle these questions. Galileo stated that the book of nature is written in mathematics. (Tidbit: Galileo and Shakespeare were born in the same year, 1564.)

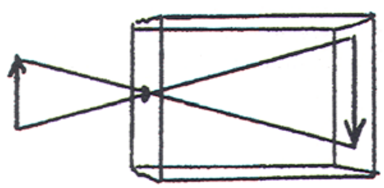
Science is never a closed book, for its conclusions are based on evidence, and new evidence can contradict old conclusions and lead to a better understanding of nature. Anytime anybody tells you that they are "absolutely certain" of some general idea, you can be assured that their conclusion is not scientific, because science never produces absolute certainty. - Art Hobson

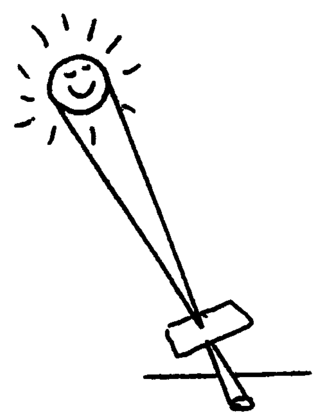
Science and Religion
Do the two contradict each other—must one choose between them? These questions are foremost among many students, yet physics texts usually sidestep such questions, for religion is very personal for so many people. I hope the very brief treatment in the text presents a satisfactory answer to these questions. Your feedback on this matter will be appreciated.

With regard to science courses and liberal arts courses, there is a central factor that makes it difficult for liberal arts students to delve into science courses the way that science students can delve into liberal arts courses—and that's the **vertical nature of science courses**. They build upon each other, as noted by their prerequisites. A science student can take an intermediate course in literature, poetry, or history at any time, and in any order. But in no way can a humanities student take an intermediate physics or chemistry course without first having a foundation in elementary physics and mathematics. Hence the importance of this conceptual course.

Except of the measurements by early Greek scientists, I do not lecture about Chapter 1 material and instead assign it as reading. It can be omitted without interfering with the following chapters.

Measuring Solar Diameter: One of my very favorite class assignments is the task of measuring the diameter of the Sun with a ruler or tape measure. This makes sense by first explaining the physics of a pinhole camera. The pinhole image technique is described on **Practice Page** 2. Hold a meterstick up and state to the class that with such a measuring device, a strip of measuring tape or a simple ruler, they can measure the diameter of the Sun. Call attention to Figure 1.6, then sketch a simple pinhole camera on the board thusly.





Tell of how a small hole poked in a piece of cardboard will show the image of the Sun when the card is placed in sunlight. You can explain this without referring to Figure 1.6 in the text because the figure gives the ratio you wish them to determine. I find this first assignment very successful, in that simple measurements yield a most impressive value—a confidence builder. For those who don't succeed, or succeed partially, I urge them to try again for full credit.

Practicing Physics Book:
• Making Hypotheses
• Pinhole Formation

Next-Time Questions (in the Instructor Resource DVD):
• Scientific Claims
• Pinhole Image of the Sun
• Solar Image
• Cone, Ball, and a Cup

Laboratory Manual:
There are no labs for Chapter 1

Answers for Chapter 1

Reading Check Questions

1. *Science* is the product of human curiosity about how the world works—an organized body of knowledge that describes order and causes within nature and an ongoing human activity dedicated to gathering and organizing knowledge about the world.
2. The general reaction has been to forbid new ideas.
3. Alexandria was farther north, at a higher latitude.
4. The shadow tapers because of the large size of the Sun, certainly not a point source of light.
5. Like the Sun, the Moon's diameter is 1/110 the distance between Earth and the Moon.
6. The Sun's diameter is 1/110 the distance between Earth and the Sun.
7. At the time of a half moon he knew the angle between a line joining the Moon and Earth was at 90° to the line joining the Moon and the Sun.
8. The circular spots are pinhole images of the Sun.
9. The equations are guides to thinking that show the connections between concepts in nature.
10. First, observe; 2. Question; 3. Predict; 4. Test predictions; 5. Draw a conclusion.
11. The answer is as stated in the Summary of Terms.
12. Competent scientists must be experts at changing their minds.
13. A scientific hypothesis must be testable.
14. Whereas mistakes or misrepresentations are given second chances in daily life, second chances are not given to scientists by the scientific community.
15. See if you can state the position of an antagonist to the antagonist's satisfaction, and compare it to how well the antagonist can state your position. If you can, and your antagonist can't, the likelihood is that you are correct in your position.
16. To know more than what's in your bag of beliefs and attitudes is to expand your education.
17. No. Science and religion can work well together, and even complement each other. (Religious extremists, however, may assert that the two are incompatible).
18. One benefit is an open and exploring mind.
19. Science is gathering knowledge and organizing it; technology puts scientific knowledge to practical use and provides the instruments scientists need to conduct their investigations.
20. The other sciences build upon physics, and not the other way around.

Think and Do

21. The triangle coin image-coin distance is similar to the larger triangle Sun diameter-Sun distance, so the numbers of coins and Suns are the same. The number of Suns that would fit between Earth's surface and the Sun is 110.

22. Open ended, as lists will vary.

Think and Explain

23.The penalty for fraud is professional excommunication.

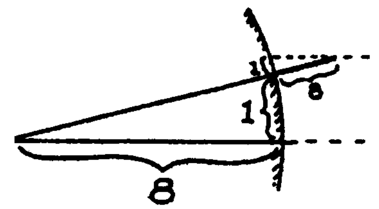
24. (a) This is a scientific hypothesis, for there is a test for wrongness. For example, you can extract chlorophyll from grass and note its color.
(b) This statement is without a means of proving it wrong and is not a scientific hypothesis. It is speculation.
(c) This is a scientific hypothesis. It could be proved wrong, for example, by showing tides that do not correspond to the position of the Moon.

25. Aristotle's hypotheses was partially correct. Plant material comes partly from the soil, but mainly from the air and water. An experiment would be to weigh a pot of soil with a small seedling, then weigh the potted plant later after it has grown. The fact that the grown plant will weigh more is evidence that the plant is composed of more material than the soil offers. Keep a record of the weight of water used to water the plant, and cover the soil with plastic wrap to minimize evaporation losses. Then the weight of the grown plant can be compared with the weight of water it absorbs. How can the weight of air taken in by the plant be estimated?

26. The Sun's radius is approximately 7×10^8 m. The distance between the Earth and Moon is about 4×10^8 m. So the Sun's radius is much larger, nearly twice the distance between the Earth and Moon. The Earth and Moon at their present distance from each other would easily fit inside the Sun. The Sun is *really* big—surprisingly big!

27. What is likely being misunderstood is the distinction between theory and hypothesis. In common usage, “theory” may mean a guess or hypothesis, something that is tentative or speculative. But in science a theory is a synthesis of a large body of validated information (e.g., cell theory or quantum theory). The value of a theory is its usefulness (not its “truth”).

28. Yes, there is a geometric connection between the two ratios. As the sketch shows, they are approximately equal.



$$\frac{\text{Pole shadow}}{\text{Pole height}} = \frac{\text{Alexandria - Syene distance}}{\text{Earth radius}}$$

From this pair of ratios, given the distance between Alexandria and Syene, the radius of the Earth can be calculated!

29. The shadow would be longer because on the smaller planet the angle of the pole would be greater relative to the sunlight. The ratio of the shadow to pole height would be greater than 1 to 8 as in the previous answer.

Think and Discuss

30. To publicly change your mind about your ideas is a sign of strength rather than a sign of weakness. It takes more courage to change your ideas when confronted with counter evidence than to hold fast to your ideas. If a person’s ideas and view of the world are no different after a lifetime of varied experience, then that person was either miraculously blessed with unusual wisdom at an early age, or learned nothing. The latter is more likely. Education is learning that which you don’t yet know about. It would be arrogant to think you know it all in the later stages of your education, and stupid to think so at the beginning of your education.

31. The examples are endless. Knowledge of electricity, for example, has proven to be extremely useful. The number of people who have been harmed by electricity who understood it is far fewer than the number of people who are harmed by it who don’t understand it. A fear of electricity is much more harmful than useful to one’s general health and attitude.

32. Your advice will depend on your own views about questioning authority. Would you suggest that your young congregate with a smaller number of friends who have reasonable doubts than ones who are absolutely certain about everything? If the concern is for the largest numbers of potential friends, groups in the United States that feature non-questioning of authority have enormously large memberships.

2 Newton's First Law of Motion—Inertia

The little girl with the Newton's Cradle apparatus in the Part One opener is Charlotte Ackerman, of San Francisco. She appears later as a chapter opener in Chapter 20. Photo openers begin with a recent inertia demonstration of me on my back with a blacksmith's anvil resting on my body, and friend Will Maynez who swings the sledge hammer. The photo of the balanced rock is by my friend Howie Brand, who retired to Thailand. Sweden friends Cedric and Anne Linder, profiled on the next page, pose with the vector demonstration. Karl Westerberg of CCSF shows one of my favorite demos with the suspended ball and strings.

Galileo was introduced in Chapter 1 and is also featured in this chapter. On August 25 in 1609 (405 years before 2014) he demonstrated his newly constructed telescope to the merchants of Venice, and shortly thereafter, aimed it on the skies. And as we know, his findings had much to do with the advent of science in those intellectual scary times.

Whereas the study of mechanics in earlier editions began with kinematics, we begin our study with a much easier concept for your students—forces. We postpone what I call the black hole of physics instruction—overemphasis on kinematics. You should find that starting a course off with forces first will lessen the initial roadblock that kinematics poses. Of particular interest to me is the Personal Essay in the chapter, which relates to events that inspired me to pursue a life in physics—my meeting with Burl Grey on the sign-painting stages of Miami, Florida. Relative tensions in supporting cables are what first caught my interest in physics, and I hope to instill the same interest with your students with this opening chapter. This story is featured on the first of the Hewitt-Drew-It screencasts, *Equilibrium Rule*, which nicely introduces vectors.

Force vectors are easier to grasp than velocity vectors treated in the following chapter. (More on vectors in Appendix A.)

Note that in introducing force I first use pounds—most familiar to your students. A quick transition, without fanfare, introduces the newton. I don't make units a big deal and don't get into the laborious task of unit conversions, which is more appropriate for physics majors.

The distinction between mass and weight will await the following chapter, when it's needed in Newton's second law. I see the key to good instruction as treating somewhat difficult topics only when they are used. For example, I see as pedagogical folly spending the first week on unit conversions, vector notation, graphical analysis, and scientific notation. How much better if the first week is a hook to promote class interest, with these things introduced later when needed.

Practicing Physics Book:

• Static Equilibrium
• The Equilibrium Rule: $\Sigma\mathbf{F} = 0$
• Vectors and Equilibrium

Laboratory Manual:
• Walking the Plank *Equilibrium Rule* (Experiment)

Next-Time Questions (in the Instructor Resource DVD):
• Ball Swing
• Pellet in the Spiral
• Falling Elephant and Feather

Hewitt-Drew-It! Screencasts:
• *Equilibrium Rule*
•*Net Force and Vectors*
•*Nellie's Ropes*
•*Force Vectors on an Incline*
• *Equilibrium Problems*
•*Nellie's Rope Tensions*
•*Force Vector Diagrams*

SUGGESTED LECTURE PRESENTATION

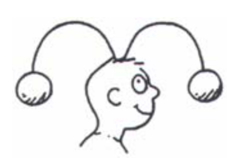
Newton's 1st Law

Begin by pointing to an object in the room and stating that if it started moving, one would reasonably look for a cause for its motion. We would say that a force of some kind was responsible, and that would seem reasonable. Tie this idea to the notion of force maintaining motion as Aristotle saw it. State that a cannonball remains at rest in the cannon until a force is applied, and that the force of expanding gases drives the ball out of the barrel when it is fired. (I have a 10-cm diameter solid steel sphere, actually a huge ball bearing, that I use in this lecture. Use one, or a bowling ball, if available.) But what keeps the cannonball moving when the gases no longer act on it? This leads you into a discussion of inertia. In the everyday sense, inertia refers to a habit or a rut. In physics it's another word for laziness, or the resistance to change as far as the state of motion of an object is concerned. I roll the ball along the lecture table to show its tendency to keep rolling. Inertia was first introduced not by Newton, but by Galileo as a result of his inclined-plane experiments.

> DEMONSTRATION: Show that inertia refers also to objects at rest with the classic ***tablecloth-and-dishes demonstration***. [Be sure to pull the tablecloth slightly downward so there is no upward component of force on the dishes!] I precede this demo with a simpler version, a simple block of wood on a piece of cloth—but with a twist. I ask what the block will do when I suddenly whip the cloth toward me. After a neighbor check, I surprise the class when they see that the block has been stapled to the cloth! This illustrates Newton's zeroth law—be skeptical. Then I follow up with the classic tablecloth demo. Don't think the classic demo is too corny, for your students will really love it.

Of course when we show a demonstration to illustrate a particular concept, there is almost always more than one concept involved. The tablecloth demo is no exception, which also illustrates impulse and momentum (Chapter 6 material). The plates experience two impulses; one that first involves the friction between the cloth and dishes, which moves them slightly toward you. It is brief and very little momentum builds up. Once the dishes are no longer on the cloth, a second impulse occurs due to friction between the sliding dishes and table, which acts in a direction away from you and prevents continued sliding toward you, bringing the dishes to rest. Done quickly, the brief displacement of the dishes is hardly noticed. Is inertia really at work here? Yes, for if there were no friction, the dishes would strictly remain at rest.

> DEMONSTRATION: Continuing with inertia, do as Jim Szeszol does and fashion a wire coat hanger into an m shape as shown. Two globs of clay are stuck to each end. Balance it on your head, with one glob in front of your face. State you wish to view the other glob and ask how you can do

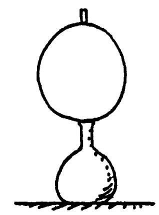


so without touching the apparatus. Then simply turn around and look at it. It's like the bowl of soup you turn only to find the soup stays put. Inertia in action! (Of course, like the tablecloth demo, there is more physics here than inertia; this demo can also be used to illustrate rotational inertia and the conservation of angular momentum.)

A useful way to impart the idea of mass and inertia is to place two objects, say a pencil and a piece of chalk, in the hands of a student and ask for a judgment of which is heavier. The student will likely respond by shaking them, one in each hand. Point out that in so doing the student is really comparing their inertias, and is making use of the intuitive knowledge that weight and inertia are directly proportional to each other. In Chapter 4 you'll focus more on the distinction between mass and weight, and between mass and volume.

CHECK QUESTION: How does the law of inertia account for removing snow from your shoes by stamping on the floor, or removing dust from a coat or rug by shaking it?

DEMONSTRATION: Do as Marshall Ellenstein does and place a metal hoop atop a narrow jar. On top of the hoop balance a piece of chalk. Then whisk the hoop away and the chalk falls neatly into the narrow opening. The key here is grabbing the hoop on the inside, on the side farthest from your sweep. This elongates the hoop horizontally and the part that supports the chalk drops from beneath the chalk. (If you grab the hoop on the near side, the elongation will be vertical and pop the chalk up into the air!)



Units of Force—Newtons:
I suggest not making a big deal about the unfamiliar unit of force—the newton. I simply state it is the unit of force used by physicists, and if students find themselves uncomfortable with it, simply think of "pounds" in its place. Relative magnitudes, rather than actual magnitudes, are the emphasis of conceptual physics anyway. Do as my influential pal Burl Grey does in Figure 2.13 and suspend a familiar mass from a spring scale. If the mass is a kilogram and the scale is calibrated in newtons, it will read 10 N (more precisely, 9.8 N). If the scale is calibrated in pounds it will read 2.2 pounds. State that you're not going to waste good time in conversions between units (students can do enough of that in one of those dull physics courses they've heard about).

CHECK QUESTION: Which has more mass, a 1-kg stone or a 1-lb stone? [A 1-kg stone has more mass, for it weighs 2.2 lb. But we're not going to make a big deal about such conversions. If the units newtons bugs you, think of it as a unit of force or weight in a foreign language for now!]

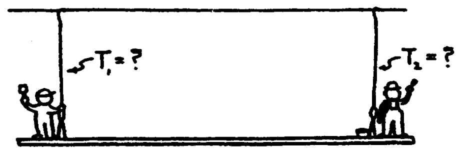
Net Force
Discuss the idea of more than one force acting on something, and the resulting net force. Figure 2.10 or Figure 2.12 captures the essence.

Support Force (Normal Force)
Ask what forces act on a book at rest on your lecture table. Then discuss Figure 2.15, explaining that the atoms in the table behave like tiny springs. This upward support force is equal and opposite to the weight of the book, as evidenced by the book's state of rest. The support force is a very real force. Without it, the book would be in a state of free fall.

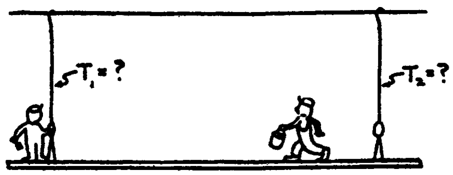
Statics and the Equilibrium Rule: Cite other *static* examples, where the net force is zero as evidenced by no changes in motion. Hold the 1-kg mass at rest in your hand and ask how much net force acts on it. Be sure they distinguish between the 10-N gravitational force on the object and the zero net force on it—as evidenced by its state of rest. (The concept of acceleration is introduced in the next chapter.) When suspended by the spring scale, point out that the scale is pulling up on the object, with just as much force as the Earth pulls down on it. Pretend to step on a bathroom scale. Ask how much gravity is pulling on you. This is evident by the scale reading. Then ask what the net force is that acts on you. This is evident by your absence of motion change. Consider two scales, one foot on each, and ask how each scale would read. Then ask how the scales would read if you shifted your weight more on one than the other. Ask if there is a rule

to guide the answers to these questions. There is; $\Sigma F = 0$. For any object in equilibrium, the net force on it must be zero. Before answering, consider the skit in my Personal Essay.

Sign painter Skit: Draw on the board the sketch below, which shows two painters on a painting rig suspended by two ropes.



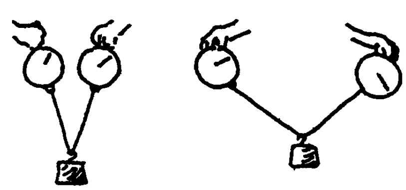
Step 1: If both painters have the same weight and each stands next to a rope, the supporting force of the ropes will be equal. If spring scales were used, one on each rope, the forces in the ropes would be evident. Ask what the scale reading for each rope would be in this case. [The answer is each rope will support the weight of one man + half the weight of the rig—both scales will show equal readings.]



Step 2: Suppose one painter walks toward the other as shown in the second sketch above, which you draw on the chalkboard (or show via overhead projector). Will the tension in the left rope increase? Will the tension in the right rope decrease? Grand question: Will the tension in the left rope increase *exactly* as much as the decrease in tension of the right rope? You might quip that is so, how does either rope "know" about the change in the other rope? After neighbor discussion, be sure to emphasize that the answers to these questions lie in the framework of the equilibrium rule: $\Sigma F = 0$. Since there is no change in motion, the net force must be zero, which means the upward support forces supplied by the ropes must add up to the downward force of gravity on the two men and the rig. So a decrease in one rope must necessarily be met with a corresponding increase in the other. (This example is dear to my heart. Burl and I didn't know the answer way back then because neither he nor I had a model for analyzing the problem. We didn't know about Newton's first law and the Equilibrium Rule. How different one's thinking is when one has or does not have a model to guide it. If Burl and I had been mystical in our thinking, we might have been more concerned with how each rope "knows" about the condition of the other—an approach that intrigues many people with a nonscientific view of the world.)

Inertia and the Moving Earth:
Stand facing a wall and jump up. Then ask why the wall does not smash into you as the Earth rotates under you while you're airborne. Relate this to the idea of a helicopter ascending over San Francisco, waiting motionless for 3 hours and waiting until Washington, D.C. appears below, then descending. Hooray, this would be a neat way to fly cross-country! Except, of course, for the fact that the "stationary" helicopter remains in motion with the ground below. "Stationary" relative to the stars means it would have to fly as fast as the Earth turns (what jets attempt to do).

Forces at an Angle:
This chapter introduces vectors as they relate to tensions in ropes at an angle. Other cases are developed in the Practicing Physics Book. As a demonstration, support a heavy weight with a pair of scales as shown. Show that as the angles are wider, the tensions increase. This explains why one can safely hang from a couple of strands of vertical clothesline, but can't when the clothesline is horizontally strung. Interesting stuff.



Answers and Solutions for Chapter 2

Reading Check Questions

1. Aristotle classified the motion of the Moon as natural.
2. Aristotle classified the motion of the Earth as natural.
3. Copernicus stated that Earth circles the Sun, and not the other way around.
4. Galileo discovered that objects in fall pick up equal speeds whatever their weights.
5. Galileo discovered that a moving object will continue in motion without the need of a force.
6. Inertia is the *name* given to the property of matter that resists a change in motion.
7. Newton's law is a restatement of Galileo's concept of inertia.
8. In the absence of force, a moving body follows a straight-line path.
9. The net force is 70 pounds to the right.
10. A description of force involves magnitude and direction, and is therefore a vector quantity.
11. The diagonal of a parallelogram represents the resultant of the vector pair.
12. The resultant is $\sqrt{2}$ pounds.
13. The tension in each rope would be half Nellie's weight.
14. Yes, although science texts favor the newton.
15. The net force is zero.
16. The net force is zero.
17. All the forces on something in mechanical equilibrium add vectorally to zero.
18. $\Sigma F = 0$.
19. The support force is 15 N. The net force on the book is zero.
20. Weight and support force have equal magnitudes.
21. Yes. The ball moving at constant speed in a straight-line path is in dynamic equilibrium.
22. An object in either static or dynamic equilibrium has a zero net force on it.
23. The force of friction is 100 N.
24. They had no understanding of the concept of inertia.
25. The bird still moves at 30 km/s relative to the Sun.
26. Yes, like the bird of Figure 2.18, you maintain a speed of 30 km/s relative to the Sun, in accord with the concept of inertia.

Think and Solve

27. Since each scale reads 350 N, Lucy's total weight is 700 N.

28. 800 N on one scale, 400 N on the other. ($2x + x = 1200$ N; $3x = 1200$ N; $x = 400$ N)

29. From the equilibrium rule, $\Sigma F = 0$, the upward forces are 800 N, and the downward forces are 500 N + the weight of the scaffold. So the scaffold must weigh 300 N.

30. From the equilibrium rule, $\Sigma F = 0$, the upward forces are 800 N + tension in the right scale. This sum must equal the downward forces 500 N + 400 N + 400 N. Arithmetic shows the reading on the right scale is 500 N.

Think and Rank

31. C, B, A
32. C, A, B, D
33. a. B, A, C, D
    b. B, A, C, D
34. a. A=B=C (no force)
    b. C, B, A
35. B, A, C
36. (a)

Think and Explain

37. Aristotle favored philosophical logic while Galileo favored experimentation.

38. The tendency of a rolling ball is to continue rolling—in the absence of a force. The fact that it slows down is likely due to the force of friction.

39. Copernicus and others of his day thought an enormous force would have to continuously push the Earth to keep it in motion. He was unfamiliar with the concept of inertia, and didn't realize that once a body is in motion, no force is needed to keep it moving (assuming no friction).

40. Galileo discredited Aristotle's idea that the rate at which bodies fall is proportional to their weight.

41. Galileo demolished the notion that a moving body requires a force to keep it moving. He showed that a force is needed to *change* motion, not to keep a body moving, so long as friction was negligible.

42. Galileo proposed the concept of inertia before Newton was born.

43. Nothing keeps asteroids moving. The Sun's force deflects their paths but is not needed to keep them moving.

44. Nothing keeps the probe moving. In the absence of a propelling or deflecting force it would continue moving in a straight line.

45. If you pull the cloth upward, even slightly, it will tend to lift the dishes, which will disrupt the demonstration to show the dishes remaining at rest. The cloth is best pulled horizontally for the dishes to remain at rest.

46. The inertia of a whole roll resists the large acceleration of a sharp jerk and only a single piece tears. If a towel is pulled slowly, a small acceleration is demanded of the roll and it unwinds. This is similar to the hanging ball and string shown in Figure 2.5.

47. Your body tends to remain at rest, in accord with Newton's first law. The back of the seat pushes you forward. Without support at the back of your head, your head is not pushed forward with your body, which likely injures your neck. Hence, headrests are recommended.

48. In a bus at rest your head tends to stay at rest. When the bus is rear-ended, the car lurches forward and you and your head also move forward. Without headrest your body tends to leave your head behind. Hence a neck injury.

49. The law of inertia applies in both cases. When the bus slows, you tend to keep moving at the previous speed and lurch forward. When the bus picks up speed, you tend to keep moving at the previous (lower) speed and you lurch backward.

50. The maximum resultant occurs when the forces are parallel in the same direction—32 N. The minimum occurs when they oppose each other—8 N.

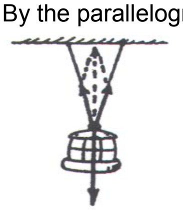
51. The vector sum of the forces equals zero. That means the net force must be zero.

52. Vector quantities are force and acceleration. Age and temperature are scalars.

53. You can correctly say the vectors are equal in magnitude and opposite in direction.
54. A hammock stretched tightly has more tension in the supporting ropes than one that sags. The tightly stretched ropes are more likely to break.

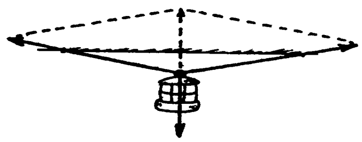
55. The tension will be greater for a small sag. That's because large vectors in each side of the rope supporting the bird are needed for a resultant that is equal and opposite to the bird's weight.

56. By the parallelogram rule, the tension is less than 50 N.



57. The upward force is the tension in the vine. The downward force is that due to gravity. Both are equal when the monkey hangs in equilibrium.

58. By the parallelogram rule, the tension is greater than 50 N.



59.No. If only a single nonzero force acts on an object, its motion will change and it will not be in mechanical equilibrium. There would have to be other forces to result in a zero net force for equilibrium.

60.At the top of its path (and everywhere else along its path) the force of gravity acts to change the ball's motion. Even though it momentarily stops at the top, the net force on the ball is not zero and it therefore is not in equilibrium.

61.Yes. If the puck moves in a straight line with unchanging speed, the forces of friction are negligible. Then the net force is practically zero, and the puck can be considered to be in dynamic equilibrium.

62.You can say that no net force acts on your friend at rest, but there may be any number of forces that act—that produce a zero net force. When the net force is zero, your friend is in static equilibrium.

63. The scale will read half her weight. In this way, the net force (upward pull of left rope + upward pull of right rope − weight) = 0.

64.In the left figure, Harry is supported by two strands of rope that share his weight (like the little girl in the previous exercise). So each strand supports only 250 N, below the breaking point. Total force up supplied by ropes equals weight acting downward, giving a net force of zero and no acceleration. In the right figure, Harry is now supported by one strand, which for Harry's well-being requires that the tension be 500 N. Since this is above the breaking point of the rope, it breaks. The net force on Harry is then only his weight, giving him a downward acceleration of *g*. The sudden return to zero velocity changes his vacation plans.

65.The upper limit he can lift is a load equal to his weight. Beyond that he leaves the ground!

66.800 N; The pulley simply changes the direction of the applied force.

67. The force that prevents downward acceleration is the support (normal) force—the table pushing up on the book.

68.Two significant forces act on the book: the force due to gravity and the support force (normal force) of the table.

69.If the upward force were the only force acting, the book indeed would rise. But another force, that due to gravity, results in the net force being zero.

70.When standing on a floor, the floor pushes upward against your feet with a force equal to that of gravity, your weight. This upward force (normal force) and your weight are oppositely directed, and since they both act on the same body, you, they cancel to produce a net force on you of zero—hence, you are not accelerated.

71.Only when you are in equilibrium will the support force on you correctly show your weight. Then it is equal to the force of gravity on you.

72.Without water, the support force is ***W***. With water, the support force is ***W*** + ***w***.

73.The friction on the crate has to be 200 N, opposite to your 200-N pull.

74.The friction force is 600 N for constant speed. Only then will $\Sigma F = 0$.

75.The support force on the crate decreases as the load against the floor decreases. When the crate is entirely lifted from the floor, the support force by the floor is zero. The support force on the workmen's feet correspondingly increases as the load transfers from the floor to them. When the crate is off the floor and at rest, its weight is transferred to the men, whose normal force is then increased.

76. The net force on the rope is zero. The force exerted by the rope on each person is 300 N (in opposite directions).

77. Two forces must be equal and opposite so that the net force = 0. Then the parachutist is in dynamical equilibrium.

78. We aren't swept off because we are traveling just as fast as the Earth, just as in a fast-moving vehicle you move along with the vehicle. Also, there is no atmosphere through which the Earth moves, which would do more than blow our hats off!

Think and Discuss

79. Your friend should learn that inertia is not some kind of force that keeps things like the Earth moving, but is the name given to the property of things to keep on doing what they are doing in the absence of a force. So your friend should say that *nothing* is necessary to keep the Earth moving. Interestingly, the Sun keeps it from following the straight-line path it would take if no forces acted, but it doesn't keep it moving. Nothing does. That's the concept of inertia.

80. You should disagree with your friend. In the absence of external forces, a body at rest tends to remain at rest; if moving, it tends to remain moving. Inertia is a *property* of matter to behave this way, not some kind of force.

81. The tendency of the ball is to remain at rest. From a point of view outside the wagon, the ball stays in place as the back of the wagon moves toward it. (Because of friction, the ball may roll along the cart surface—without friction the surface would slide beneath the ball.)

82. The car has *no* tendency to resume to its original twice-as-fast speed. Instead, in accord with Newton's first law, it tends to continue at half speed, decreasing in speed over time due to air resistance and road friction.

83. No. If there were no friction acting on the cart, it would continue in motion when you stop pushing. But friction does act, and the cart slows. This doesn't violate the law of inertia because an external force indeed acts.

84. An object in motion tends to stay in motion, hence the discs tend to compress upon each other just as the hammer head is compressed onto the handle in Figure 2.5. This compression results in people being slightly shorter at the end of the day than in the morning. The discs tend to separate while sleeping in a prone position, so you regain your full height by morning. This is easily noticed if you find a point you can almost reach up to in the evening, and then find it is easily reached in the morning. Try it and see!

85. No. If there were no force acting on the ball, it would continue in motion without slowing. But air drag does act, along with slight friction with the lane, and the ball slows. This doesn't violate the law of inertia because external forces indeed act.

86. Normal force is greatest when the table surface is horizontal, and progressively decreases as the angle of tilt increases. As the angle of tilt approaches 90°, the normal force approaches zero. When the table surface is vertical, it no longer presses on the book, then freely falls.

87. No. The normal force would be the same whether the book was on slippery ice or sandpaper. Friction plays no role unless the book slides or tends to slide along the table surface.

88. A stone will fall vertically if released from rest. If the stone is dropped from the top of the mast of a moving ship, the horizontal motion is not changed when the stone is dropped—providing air resistance on the stone is negligible and the ship's motion is steady and straight. From the frame of reference of the moving ship, the stone falls in a vertical straight-line path, landing at the base of the mast.

89. A body in motion tends to remain in motion, so you move with the moving Earth whether or not your feet are in contact with it. When you jump, your horizontal motion matches that of the Earth and you travel with it. Hence the wall does not slam into you.

90. The coin is moving along with you when you toss it. While in the air it maintains this forward motion, so the coin lands in your hand. If the train slows while the coin is in the air, it will land in front of you.

91. If the train rounds a corner while the coin is in the air, it will land off to the side of you. The coin continues in its horizontal motion, in accord with the law of inertia.

92. This is similar to Question 88. If the ball is shot while the train is moving at constant velocity (constant speed in a straight line), its horizontal motion before, during, and after being fired is the same as that of the train; so the ball falls back into the smokestack as it would have if the train were at rest. If the train increases its speed, the ball will hit the train behind the smokestack because the ball's horizontal speed continues unchanged after it is fired, but the speeding-up train pulls ahead of the ball. Similarly, on a circular track the ball will also miss the smokestack because the ball will move along a tangent to the track while the train turns away from this tangent. So the ball returns to the smokestack in the first case, and misses in the second and third cases because of the *change* in motion.

3 Linear Motion

The photo openers begin with my niece, Joan Lucas, riding her horse Ghost. The second photo is of my cherished friend from school days, Sue Johnson (wife of Dan Johnson) who with her racing-shell team won national honors in rowing. Shown also is Norwegian friend Carl Angell who rolls a ball through a photo timer. Also shown is friend and colleague from City College of San Francisco, Chelcie Liu, showing the tracks he made while teaching his daughter Cindy some physics. The tracks have been and are well used.

This chapter opens with a profile on Galileo.

TAKE CARE NOT TO SPEND OVERTIME ON THIS CHAPTER!! Doing so is the greatest pacing mistake in teaching physics! Time spent on kinematics is time not spent on why satellites continually fall without touching Earth, why high temperatures and high voltages (for the same reason) can be safe to touch, why rainbows are round, why the sky is blue, and how nuclear reactions keep the Earth's interior molten. Too much time on this chapter is folly. I strongly suggest making the distinction between speed, velocity, and acceleration, and move quickly to Chapter 4. (I typically spend only *one* class lecture on this chapter.) **By all means, avoid the temptation to do the classic motion problems that involve 90% math and 10% physics!** Too much treatment of motion analysis can be counterproductive to maintaining the interest in physics starting with the previous chapter. I suggest you tell your class that you're skimming the chapter so you'll have more time for more interesting topics in your course—let them know they shouldn't expect to master this material, and that mastery will be expected in later material (that doesn't have the stumbling blocks of kinematics). It's okay not to fully understand this early part of your course. Just as wisdom is knowing what to overlook, good teaching is knowing what to omit.

Perchance you are getting into more problem solving than is customary in a conceptual course, be sure to look at the student ancillary, *Problem Solving Book, 3rd Edition*. It has ample problems for a lightweight algebra-trigonometry physics course.

The box on *Hang Time* on page 50 may be especially intriguing to your students if they're unaware of the short time involved. Even basketball legend Michael Jordan's hang time was less than 0.9 s. Height jumped is less than 1.25 m (4 feet—those who insist a hang time of 2 s are way off, for 1 s up is 16 feet—clearly, no way!). A neat rule of thumb is that height jumped in feet, where g = 32 ft/s^2, is equal to four times hang time squared [$d = g/2(\mathrm{T}/2)^2 = g/2(\mathrm{T}^2/4) = 32/8(\mathrm{T}^2) = 4\mathrm{T}^2$].

I feel compelled to interject here (as I mean to stress all through this manual) the importance of the "check with your neighbor" technique of teaching. Please do not spend your lecture talking to yourself in front of your class! The procedure of "check with your neighbor" is a routine that keeps you and your class engaged. I can't stress enough its importance!

The distinction between velocity and acceleration is prerequisite to the following chapters on mechanics.

The **Practicing Physics Book** of worksheets treats the distinction between velocity acquired and distance fallen for free fall via a freely-falling speedometer-odometer. Students *do* learn from these, in class or out of class, so whether you have your students buy their own from your bookstore or you photocopy select pages for class distribution, get these to your students. There are four Practice Pages for this chapter:

- Free Fall Speed
- Acceleration of Free Fall
- Hang Time
- Non-Accelerated Motion

Problem Solving Book: Chapter 3 has abundant and insightful kinematics problems requiring straight-forward algebra, some with solutions.

Laboratory Manual:

- Go! Go! Go! *The Fundamentals of Graphing Motion* (Experiment)
- Sonic Ranger *Graphing Motion in Real Time* (Tech Lab)
- Motivating the Moving Man *Motion Graphing Simulation* (Tech Lab)

  The textbook does not treat motion graphically, but leaves that to the laboratory manual. Labs are enhanced with the sonic ranger device, which is conceptual graphing at its best. If not done as lab experiments, demonstrate the sonic ranger as part of your lecture.

Next-Time Questions (in the Instructor Resource DVD):

- Relative Speeds
- Bikes and Bee

Hewitt-Drew-It! Screencasts: (All accessed via QR code in the text)

- *Free Fall*
- *Ball Toss*
- *Velocity Vectors*
- *Sideways Drop*
- *Bikes and Bee*

SUGGESTED LECTURE PRESENTATION

Your first question: What means of motion has done more to change the way cities are built than any other? [Answer: The elevator!]

Explain the importance of simplifying. Motion is best understood if you first neglect the effects of air resistance, the effects of buoyancy, spin, and the shape of moving objects—that beneath these are simple relationships that might otherwise be masked by “covering all bases,” and that these *relationships* are what Chapter 3 and your lecture are about. State that by completely neglecting the effects of air resistance not only exposes the simple relationships, but is a reasonable assumption for heavy and compact (dense) objects traveling at moderate speeds; e.g., one would notice no difference between the rates of fall of a heavy rock dropped from the classroom ceiling to the floor below, when falling through either air or a complete vacuum. For a feather and heavy objects moving at high speeds, air resistance does become important, and will be treated in Chapter 4.

Mention that there are few pure examples in physics, for most real situations involve a combination of effects. There is usually a “first order” effect that is basic to the situation, but then there are 2nd, 3rd, and even 4th or more order effects that interact also. If we begin our study of some concept by considering all effects together before we have studied their contributions separately, understanding is likely to be difficult. To have a better understanding of what is going on, we strip a situation of all but the first order effect, and then examine that. When that is well understood, then we proceed to investigate the other effects for a fuller understanding.

DEMONSTRATION: Drop a sheet of paper and note how slowly it falls because of air resistance. Crumple the paper and note it falls faster. Air resistance has been reduced. Then drop a sheet of paper

and a book, side by side. Of course the book falls faster, due to its greater weight compared to air resistance. (Interestingly, the air drag is greater for the faster-falling book—an idea you'll return to in the next chapter.) Now place the paper against the lower surface of the raised horizontally-held book and when you drop them, nobody is surprised to see they fall together. The book has pushed the paper with it. Now repeat with the paper on *top* of the book and ask for predictions and neighbor discussion. Then surprise your class by refusing to show it! Tell them to try it out of class! (Good teaching isn't giving answers, but raising good questions—good enough to prompt wondering. Let students discover that the book will "plow through the air" leaving an air-resistance free path for the paper to follow!)

Air resistance will be treated in later chapters, but not this one. Again, simplifying brings out the concepts better. You can briefly acknowledge the important effects of air drag: In a bicycle race, for example, the lead cyclist carries along a flow of air that creates a "sweet spot" of low air pressure for the cyclist riding close behind. Air resistance on spinning balls changes their course, and so on. In keeping with the adage "Wisdom is knowing what to overlook," we neglect the effects of air in this chapter to more clearly reveal the connections between distance, time, speed, velocity, and acceleration. Let your students know that the effects of air drag are treated in future chapters.

Speed and Velocity
Define speed by writing its equation in longhand form on the board while giving examples—automobile speedometers, etc. Similarly define velocity, citing how a race car driver is interested in his *speed*, whereas an airplane pilot is interested in her *velocity*—speed and direction. Cite the difference between a scalar and a vector quantity and identify speed as a scalar and velocity as a vector. Tell your class that you're not going to make a big deal about distinguishing between speed and velocity, but you *are* going to make a big deal of distinguishing between velocity and another concept—*acceleration*.

Acceleration
Define acceleration by identifying it as a vector quantity, and cite the importance of CHANGE. That's change in speed, or change in direction. Hence both are acknowledged by defining acceleration as a rate of change in velocity rather than speed. Ask your students to identify the three controls in an automobile that make the auto *change* its state of motion—that produce *acceleration*. Ask for them (accelerator, brakes, and steering wheel). State how one lurches in a vehicle that is undergoing acceleration, especially for circular motion, and state why the definition of velocity includes direction to make the definition of acceleration all-encompassing. Talk of how without lurching one cannot sense motion, giving examples of coin flipping in a high-speed aircraft versus doing the same when the same aircraft is at rest.

Units for Acceleration: Give numerical examples of acceleration in units of kilometers/hour per second to establish the idea of acceleration. Be sure that your students are working on the examples with you. For example, ask them to find the acceleration of a car that goes from rest to 100 km/h in 10 seconds. It is important that you not use examples involving seconds twice until they taste success with the easier kilometers/hour per second examples. Have them check their work with their neighbors as you go along. Only after they get the hang of it, introduce meters/second/second in your examples to develop a sense for the units m/s^2. This is treated in the screencasts, *Unit Conversion* and *Acceleration Units*.

Falling Objects: If you round 9.8 m/s^2 to 10 m/s^2 in your lecture, you'll more easily establish the relationships between velocity and distance. In lab you can use the more precise 9.8 m/s^2.

CHECK QUESTION: If an object is dropped from an initial position of rest from the top of a cliff, how *fast* will it be traveling at the end of one second? (You might add, "Write the answer on your notepaper." And then, "Look at your neighbor's paper—if your neighbor doesn't have the right answer, reach over and help him or her—talk about it." And then possibly, "If your neighbor isn't very cooperative, sit somewhere else next time!")

After explaining the answer when class discussion dies down, repeat the process asking for the speed at the end of 2 seconds, and then for 10 seconds. This leads you into stating the relationship $v = gt$, which by now you can express in shorthand notation. After any questions, discussion, and

examples, state that you are going to pose a different question—not asking of how *fast*, but for how *far*. Ask how far the object falls in one second. Ask for a written response and then ask if the students could explain to their neighbors *why* the distance is only 5 m rather than 10 m. After they've discussed this for almost a minute or so, ask "If you maintain a speed of 60 km/h for one hour, how far do you go?"—then, "If you maintain a speed of 10 m/s for one second, how far do you go?" Important point: You'll appreciably improve your instruction if you allow some thinking time after you ask a question. Not doing so is the folly of too many instructors. Then continue, "Then why is the answer to the first question not 10 meters?" After a suitable time, stress the idea of *average* velocity and the relation $d = v_{ave}t$.

Show the general case by deriving on the board $d = {}^1\!/_2gt^2$. (We tell our students that the derivation is a sidelight to the course—something that will be the crux of a follow-up physics course. In any event, the derivation is not something that we expect of them, but to show that $d = {}^1\!/_2gt^2$ is a reasoned statement that doesn't just pop up from nowhere.)

CHECK QUESTIONS: How far will a freely falling object that is released from rest, fall in 2 s? In 10 s? (When your class is comfortable with this, then ask how far in ${}^1\!/_2$ second.)

To avoid information overload, we restrict all numerical examples of free fall to cases that begin at rest. Why? Because it's simpler that way. (We prefer our students to understand simple physics than to be confused about not-so-simple physics!) We do go this far with them.

CHECK QUESTION: Consider a rifle fired straight downward from a high-altitude balloon. If the muzzle velocity is 100 m/s and air resistance can be neglected, what is the *acceleration* of the bullet after one second? (If most of your class say that it's *g*, you're on!)

I suggest *not* asking for the time of fall for a freely-falling object, given the distance. Why? Unless the distance given is the familiar 5 meters, algebraic manipulation is called for. If one of our teaching objectives were to teach algebra, this would be a nice place to do it. But we don't have time to present this stumbling block and then teach how to overcome it. We'd rather put our energy *and theirs* into straight physics!

Kinematics can be rich with puzzles, graphical analysis, ticker timers, photogates, and algebraic problems. My strong suggestion is to resist these and move quickly into the rest of mechanics, and then into other interesting areas of physics. Getting bogged down with kinematics, with so much physics ahead, is a widespread practice. Please do your class a favor and hurry on to the next chapters. If at the end of your course you have time (ha-ha), *then* bring out the kinematics toys and have a go at them.

The Two-Track Demo

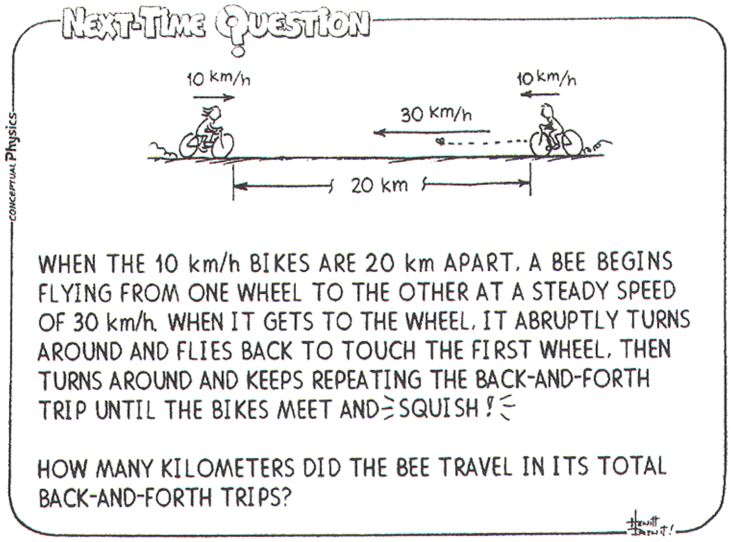
Be sure to fashion a pair of tracks like those shown by Chelcie Liu in the chapter opener photo. Chelcie simply bent a pair of angle iron used as bookcase supports. The tracks are of equal length and can be bent easily with a vice. Think and Discuss 95 and 96 refer to this demo. Be prepared for the majority of your class to say they reach the end of the track at the same time. Aha, they figure they have the same speed at the end, which throws them off base. Same *speed* does not mean same *time*. I like to quip "Which will win the race, the fast ball or the slower ball?" You can return to this demo when you discuss energy in Chapter 7.

Hang Time

As strange as it first may seem, the longest time a jumper can remain in air is less than a second. It is a common illusion that jumping times are more. Even Michael Jordan's best *hang time* (the time the feet are off the ground) was 0.9 second. Then $d = {}^1\!/_2gt^2$ predicts how high a jumper can go vertically. For a hang time of a full second, that's ${}^1\!/_2$ s up and ${}^1\!/_2$ s down. Substituting, $d = 5(0.5)^2 = 1.25$ m (which is about 4 feet!). So the great athletes and ballet dancers jump vertically no more than 4 feet high! Of course one can clear a higher fence or bar; but one's *center of gravity* cannot be raised more than 4 feet in free jumping. In

fact very few people can jump 2 feet high! To test this, stand against a wall with arms upstretched. Mark the wall at the highest point. Then jump, and at the top, again mark the wall. For a human being, the distance between marks is at most 4 feet! We'll return to hang time for running jumps when we discuss projectile motion in Chapter 10.

NEXT-TIME QUESTION: For OHT or posting. Note the sample reduced pages from the *Next-Time Questions* book, full 8-$^{1}/_{2}$ × 11, just right for OHTs. Next-Time Questions for each chapter are on your Resource DVD, each with its answer. Consider displaying printed NTQs at some general area outside the classroom—perhaps in a glass case. This display generates general student interest, as students in your class and those not in your class are stimulated to think physics. After a few days of posting then turn the sheets over to reveal the answers. That's when new NTQs can be displayed. How better to adorn your corridors! Because of space limitations, those for other chapters are not shown in this manual. [I'm not showing the answer here, but it makes the point to solving this problem is consideration of time *t*. Whether or not one thinks about time should not be a matter of cleverness or good insight, but a matter of letting the equation for distance guide thinking. The *v* is given, but the time *t* is not. The equation instructs you to consider time. Equations are important in guiding our thinking about physics.]



Velocity Vectors

Consider Figure 3.12 of the airplane flying in a cross wind. The resulting speed can only be found with vectors. The only vector tools the student needs is the *parallelogram rule*, and perhaps the *Pythagorean Theorem*. Avoid sines and cosines unless your students are studying to be scientists or engineers. Here we distinguish between physics and the *tools* of physics. Tools for pre-engineers and scientists only. Physics for everybody!

This is a good time for the Hewitt-Drew-It Screencast *Velocity Vectors*, which treats an airplane flying at different directions relative to the wind.

Answers and Solutions for Chapter 3

Reading Check Questions

1. Relative to the chair your speed is zero. Relative to the Sun it's 30 km/s.
2. The two necessary units are distance traveled and time of travel.
3. A speedometer registers instantaneous speed.
4. Average speed is 30 km/min.
5. The horse travels 25 km/h x 0.5 h = 12.5 km.
6. Speed is a scalar and velocity is speed and direction, a vector.
7. Yes. A car moving at constant velocity moves at constant speed.
8. The car maintains a constant speed but not a constant velocity because it changes direction as it rounds the corner.
9. The acceleration is 10 km/h/s.
10. Acceleration is zero, because velocity doesn't change.
11. You are aware of changes in your speed, but not steady motion. Therefore you are aware of acceleration, but not constant velocity.
12. When motion is in one direction along a straight line, either may be used.
13. Galileo found that the ball gained the same amount of speed each second, which says the acceleration is constant.
14. Galileo discovered that the greater the angle of incline, the greater the acceleration. When the incline is vertical, the acceleration is that of free fall.
15. A freely-falling object is one on which the only force acting is the force of gravity. This means falling with no air resistance.
16. Gain in speed is 10 m/s each second.
17. The speed acquired in 5 seconds is 50 m/s; in 6 seconds, 60 m/s.
18. The unit 'seconds' occurs in velocity, and again in the time velocity is divided by to compute acceleration. Hence the square of seconds in acceleration.
19. The moving object loses 10 m/s for each second moving upward.
20. Galileo found distance traveled is directly proportional to the square of the time of travel ($d = \frac{1}{2} gt^2$).
21. The distance of fall in 1 second is 5 m. For a 4-s drop, falling distance is 80 m.
22. Air resistance reduces falling acceleration.
23. 10 m/s is speed, 10 m is distance, and 10 m/s^2 is acceleration.
24. The resultant is 141 km/h at an angle of 45° to the airplane's intended direction of travel.

Think and Do

25. Tell Grandma that, in effect, velocity is how fast you're traveling and acceleration is how quickly how-fast changes. Please don't tell Grandma that velocity is speed!

26. This can be a social activity, with good physics.

27. This is a follow-up to the previous activity, a good one!

28. Hang times will vary, but won't exceed 1 second!

Plug and Chug

29. Average speed $= \dfrac{\text{distance traveled}}{\text{time}} = \dfrac{\Delta d}{\Delta t} = \dfrac{30 \text{ m}}{2 \text{ s}} = 15 \text{ m/s}$.

30. Average speed $= \dfrac{\Delta d}{\Delta t} = \dfrac{1.0 \text{ m}}{0.5 \text{ s}} = 2 \text{ m/s}$

31. Acceleration $= \dfrac{\text{change in velocity}}{\text{time}} = \dfrac{\Delta v}{\Delta t} = \dfrac{100 \text{ km/h}}{10 \text{ s}} = 10 \text{ km/h} \cdot \text{s}$

32. Acceleration $= \dfrac{\text{change in velocity}}{\text{time}} = \dfrac{\Delta v}{\Delta t} = \dfrac{10 \text{ m/s}}{2 \text{ s}} = 5 \text{ m/s}^2$.

33. Starting from rest, distance = $\frac{1}{2} at^2 = \frac{1}{2}(5 \text{ m/s}^2)(3 \text{ s})^2 = 22.5$ m.

34. Distance of fall = $\frac{1}{2} gt^2 = \frac{1}{2}(10 \text{ m/s}^2)(3 \text{ s})^2 = 45$ m.

Think and Solve

35. Since it starts going up at 30 m/s and loses 10 m/s each second, its time going up is 3 seconds. Its time returning is also 3 seconds, so it's in the air for a total of 6 seconds. Distance up (or down) is $\frac{1}{2} gt^2 = 5 \times 3^2 = 45$ m. Or from $d = vt$, where average velocity is (30 + 0)/2 = 15 m/s, and time is 3 seconds, we also get d = 15 m/s × 3 s = 45 m.

36. (a) The velocity of the ball at the top of its vertical trajectory is instantaneously zero.
(b) Once second before reaching its top, its velocity is **10 m/s**.
(c) The amount of change in velocity is **10 m/s** during this 1-second interval (or any other 1-second interval).
(d) One second after reaching its top, its velocity is **-10 m/s**—equal in magnitude but oppositely directed to its value 1 second before reaching the top.
(e) The amount of change in velocity during this (or any) 1-second interval is 10 m/s.
(f) In 2 seconds, the amount of change in velocity, from 10 m/s up to 10 m/s down, is **20 m/s** (not zero!).
(g) The acceleration of the ball is **10 m/s²** before reaching the top, when reaching the top, and after reaching the top. In all cases acceleration is downward, toward the Earth.

37. Using $g = 10$ m/ s², we see that $v = gt$ = (10 m/s²)(10 s) = 100 m/s;

$$v_{av} = \frac{(v_{\text{beginning}} + v_{\text{final}})}{2} = \frac{(0 + 100)}{2} = \mathbf{50\ m/s}\text{, downward.}$$

We can get "how far" from either $d = v_{av}t$ = (50 m/s)(10 s) = **500 m**, or equivalently,
$d = \frac{1}{2} gt^2 = 5(10)^2 = 500$ m. (How nice we get the same distance using either formula!)

38. $a = \frac{\Delta v}{\Delta t} = \frac{25 \text{ m/s} - 0}{10 \text{ m/s}} = 2.5 \text{ m/s}^2.$

39. From $d = \frac{1}{2} gt^2 = 5t^2$, $t = \sqrt{d/5} = \sqrt{0.6/5} = 0.35$ s. Doubling for a hang time of **0.7 s**.

40. a. $t = ?$ From $\bar{v} = \frac{d}{t} \Rightarrow t = \frac{d}{\bar{v}} = \frac{L}{(v_f + v_0)/2} = \frac{2L}{v}.$

b. $t = \frac{2L}{v} = \frac{2(1.4 \text{ m})}{15.0 \text{ m/s}} = 0.19\text{s}.$

Think and Rank

41. D, C, A, B
42. C, B=D, A
43. a. B, A=C
    b. A, B, C
    c. C, B, A
44. a. C, B, A
    b. A=B=C (10 m/s²)
45. B, A, C
46. a. B, A, C
    b. C, B, A

Think and Explain

47. The shorter the better, so Mo has the more favorable reaction time and can respond quicker to situations than Jo can.

48. Jo travels 1.2 m during the time between seeing the emergency and applying the brakes.
$d = vt$ = 6 m/s x 0.20 s = 1.2 m.

49. The impact speed will be the relative speed, 2 km/h (100 km/h – 98 km/h = 2 km/h).

50. She'll be unsuccessful. Her velocity relative to the shore is zero (8 km/h – 8 km/h = 0).

51. Your fine for speeding is based on your instantaneous speed; the speed registered on a speedometer or a radar gun.

52. The speeds of both are exactly the same, but the velocities are not. Velocity includes direction, and since the directions of the airplanes are opposite, their velocities are opposite. The velocities would be equal only if both speed and direction were the same.

53. Constant velocity means no acceleration, so the acceleration of light is zero.

54. The car approaches you at twice the speed limit.

55. (a) Yes, because of the change of direction. (b) Yes, because velocity changes.

56. Emily is correct. Jacob is describing speed. Acceleration is the time rate of change in speed—"how fast you get fast," as Emily asserts.

57. No. You cannot say which car underwent the greater acceleration unless you know the times involved.

58. The acceleration is zero, for no change in velocity occurs. Whenever the change in velocity is zero, the acceleration is zero. If the velocity is "steady," "constant," or "uniform," the change in velocity is zero. Remember the definition of acceleration!

59. The greater change in speeds occurs for (30 km/h − 25 km/h = 5 km/h), which is greater than (100 km/h − 96 km/h = 4 km/h). So for the same time, the slower one has the greater acceleration.

60. At 0° the acceleration is zero. At 90° the acceleration is that of free fall, *g*. So the range of accelerations is 0 to *g*, or 0 to 10 m/s^2.

61. Its speed readings would increase by 10 m/s each second.

62. Distance readings would indicate greater distances fallen in successive seconds. During each successive second the object falls faster and covers greater distance.

63. The acceleration of free fall at the end of the 5th, 10th, or any number of seconds is *g*. Its *velocity* has different values at different times, but since it is free from the effects of air resistance, its *acceleration* remains a constant *g*.

64. In the absence of air resistance, the acceleration will be *g* no matter how the ball is released. The acceleration of a ball and its speed are entirely different.

65. Whether up or down, the rate of change of speed with respect to time is 10 m/s^2, so each second while going up the speed decreases by 10 m/s. Coming down, the speed increases by 10 m/s each second. So with no air resistance, the time rising equals the time falling.

66. With no air resistance, both will strike the ground below at the same speed. Note that the ball thrown upward will pass its starting point on the way down with the same speed it had when starting up. So its trip on downward, below the starting point, is the same as for a ball thrown down with that speed.

67. When air resistance affects motion, the ball thrown upward returns to its starting level with less speed than its initial speed; and also less speed than the ball tossed downward. So the downward thrown ball hits the ground below with a greater speed.

68. Counting to twenty means twice the time. In twice the time the ball will roll 4 times as far (distance moved is proportional to the square of the time).

69. The acceleration due to gravity remains a constant *g* at all points along its path as long as no other forces like air drag act on the projectile.

70.

Time (in seconds)	Velocity (in meters/second)	Distance (in meters)
0	0	0
1	10	5
2	20	20
3	30	45
4	40	80
5	50	125

6	60	180
7	70	245
8	80	320
9	90	405
10	100	500

71. If it were not for the slowing effect of the air, raindrops would strike the ground with the speed of high-speed bullets!

72. No, free-fall acceleration is constant, which accounts for the constant increase of falling speed.

73. Air drag decreases speed. So a tossed ball will return with less speed than it possessed initially.

74. On the Moon the acceleration due to gravity is considerably less, so hang time would be considerably more (six times more for the same takeoff speed!).

75. As water falls it picks up speed. Since the same amount of water issues from the faucet each second, it stretches out as distance increases. It becomes thinner just as taffy that is stretched gets thinner the more it is stretched. When the water is stretched too far, it breaks up into droplets.

76. The speed of falling rain and the speed of the automobile are the same.

77. Open ended.

78. Open ended.

Think and Discuss

79. Yes. Velocity and acceleration need not be in the same direction. A car moving north that slows down, for example, accelerates toward the south.

80. Yes, again, velocity and acceleration need not be in the same direction. A ball tossed upward, for example, reverses its direction of travel at its highest point while its acceleration *g*, directed downward, remains constant (this idea will be explained further in Chapter 4). Note that if a ball had zero acceleration at a point where its speed is zero, its speed would *remain* zero. It would sit still at the top of its trajectory!

81. Acceleration occurs when the speedometer reading changes. No change, no acceleration.

82. "The dragster rounded the curve at a constant speed of 100 km/h." Constant velocity means not only constant speed but constant direction. A car rounding a curve changes its direction of motion.

83. Any object moving in a circle or along a curve is changing its velocity (accelerating) even if its speed is constant, because direction is changing. Something with constant velocity has both constant direction *and* constant speed, so there is no example of motion with constant velocity and varying speed.

84. A vertically-thrown ball has zero speed at the top of its trajectory, but acceleration there is *g*.

85. An object moving in a circular path at constant speed is a simple example of acceleration at constant speed because its velocity is changing direction. No example can be given for the second case, because constant velocity means zero acceleration. You can't have a nonzero acceleration while having a constant velocity. There are no examples of things that accelerate while not accelerating.

86. (a) Yes. For example, an object sliding or rolling horizontally on a frictionless plane. (b) Yes. For example, a vertically thrown ball at the top of its trajectory.

87. The acceleration of an object is in a direction opposite to its velocity when velocity is decreasing—for example, a ball rising or a car braking to a stop.

88. Only on the middle hill does speed along the path decrease with time, for the hill becomes less steep as motion progresses. When the hill levels off, acceleration will be zero. On the left hill, acceleration is constant. On the right hill, acceleration increases as the hill becomes steeper. In all three cases, speed increases.

89. The one in the middle. The ball gains speed more quickly at the beginning where the slope is steeper, so its average speed is greater even though it has less acceleration in the last part of its trip.

90. Free fall is defined as falling only under the influence of gravity, with *no* air resistance or other non-gravitational forces. So your friend should omit "free" and say something like, "Air resistance is more effective in slowing a falling feather than a falling coin."

91. If air resistance is not a factor, an object's acceleration is the same 10 m/s^2 regardless of its initial velocity. If it is thrown downward, its velocity will be greater, but not its acceleration.
92. Its acceleration would actually be less if the air resistance it encounters at high speed retards its motion. (We will treat this concept in detail in Chapter 4.)

93. When acceleration of the car is in a direction opposite to its velocity, the car is "decelerating," slowing down.

94. In the absence of air resistance both accelerations are *g*, the same. Their velocities may be in opposite directions, but *g* is the same for both.

95. The ball on B finishes first, for its average speed along the lower part as well as the down and up slopes is greater than the average speed of the ball along track A.

96. (a) Average speed is greater for the ball on track B.
(b) The instantaneous speed at the ends of the tracks is the same because the speed gained on the down-ramp for B is equal to the speed lost on the up-ramp side. (Many people get the wrong answer for the previous question because they assume that because the balls end up with the same speed that they roll for the same time. Not so.)

97. The resultant speed is indeed 5 m/s. The resultant of any pair of 3-unit and 4-unit vectors at right angles to each other is 5 units. This is confirmed by the Pythagorean theorem;
$a^2 + b^2 = c^2$ gives $3^2 + 4^2 = 5^2$. (Or, $\sqrt{[3^2 + 4^2]} = 5$.)

98. Again, from the Pythagorean theorem; $a^2 + b^2 = c^2$ gives $3^2 + 4^2 = 5^2$. (Or, $\sqrt{[3^2 + 4^2]} = 5$.) So the boat has a speed of 5 m/s.

99. Again, from the Pythagorean theorem; $a^2 + b^2 = c^2$ gives $120^2 + 90^2 = 150^2$.
(Or, $\sqrt{[120^2 + 90^2]} = 150$.) So the groundspeed is 150 km/h.

100. How you respond may or may not agree with the author's response: There are few pure examples in physics, for most real situations involve a combination of effects. There is usually a "first order" effect that is basic to the situation, but then there are 2nd, 3rd, and even 4th or more order effects that interact also. If we begin our study of some concept by considering all effects together before we have studied their contributions separately, understanding is likely to be difficult. To have a better understanding of what is going on, we strip a situation of all but the first order effect, and then examine that. When we have a good understanding of that, then we proceed to investigate the other effects for a fuller understanding. Consider Kepler, for example, who made the stunning discovery that planets move in elliptical paths. Now we know that they don't quite move in perfect ellipses because each planet affects the motion of every other one. But if Kepler had been stopped by these second-order effects, he would not have made his groundbreaking discovery. Similarly, if Galileo hadn't been able to free his thinking from real-world friction he may not have made his great discoveries in mechanics.

4 Newton's Second Law of Motion

Jill Johnsen of CCSF demonstrates ball drops in the opening photo of this chapter. Efrain Lopez, formerly from CCSF and now at California State University at Hayward, demonstrates equilibrium. Regarding the wingsuit skydiver in the center opening photo, I'm puzzled at the late date of this version of human flight. First we went to the Moon, then we discovered hang gliding, then bungee jumping, then maneuverable parachuting, and now, lastly, humans are doing what flying squirrels have been doing for eons! The order simply doesn't make sense! The bottom photo is my granddaughter Emily at soccer practice.

The personal profile features Isaac Newton.

Inertia, acceleration, and falling objects as introduced in Chapters 2 and 3, and are further developed in this chapter. Here we distinguish between mass and weight without making a big deal about their units of measurement (because I think time is better spent on physics concepts). A brief treatment of units and systems of measurement is provided in Appendix A.

Practicing Physics Book:
- Mass and Weight
- Converting Mass to Weight
- A Day at the Races with $a = F/m$
- Dropping Masses and Accelerating
- Cart
- Force and Acceleration
- Friction
- Falling and Air Resistance
- Force-Vector Diagrams

Problem Solving Book:
More than 100 problems complement this chapter!

Laboratory Manual:
- The Weight *Mass and Weight* (Activity)
- Putting the Force Before the Cart *Force, Mass, and Acceleration* (Activity)
- Reaction Time *Free Fall* (Activity)
- The Newtonian Shot *Force and Motion Puzzle* (Activity)

Next-Time Questions (in the Instructor Resource DVD):
- Skidding Truck
- Spool Pull
- Falling Balls
- Skydiver
- Truck and Car Collision
- Block Pull
- Direction of Friction
- Book Push Against the Wall
- Acceleration at the Top
- Net Force Half-Way Up
- Acceleration on the Way Up
- Balanced Scale
- Galileo

Hewitt-Drew-It! Screencasts:
- *Mass/Weight*
- *Newton's Second Law*
- *Acceleration Units*
- *Skydiver Problem*

SUGGESTED LECTURE PRESENTATION

In Chapter 2 the concept of inertia was introduced—the notion that once an object is in motion, it will continue in motion if no forces are exerted on it. Moving things tend to remain moving at constant velocity. In the previous chapter we learned about acceleration—the change in velocity that objects experience when a force *is* exerted. In this chapter we'll treat the relationship between force and acceleration.

Friction

Drag a block at constant velocity across your lecture table. Acknowledge the force of friction, and how it must exactly counter your pulling force. Show that pulling force with a spring balance. Now since the block moves without accelerating, ask for the magnitude of the friction force. It must be equal and opposite to your scale reading. Then the net force is zero. While sliding the block is in dynamic equilibrium. That is, $\Sigma F = 0$.

> CHECK QUESTIONS: (similar to one in the text.) Suppose in a high-flying airplane the captain announces over the cabin public address system that the plane is flying at a constant 900 km/h and the thrust of the engines is a constant 80,000 newtons. What is the acceleration of the airplane? [Answer: Zero, because velocity is constant.] What is the combined force of air resistance that acts all over the plane's outside surface? [Answer: 80,000 N. If it were less, the plane would speed up; if it were more, the plane would slow down.]

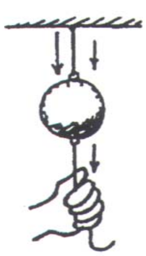
Continue your activity of pulling the block across the table with a spring balance. Show what happens when you pull harder. Your students see that when the pulling force is greater than the friction force, there is a net force greater than zero, as evidenced by the observed acceleration. Show different constant speeds across the table with the same applied force, which shows that friction is not dependent on speed. Distinguish between static and sliding friction, and show how a greater force is needed to get the block moving from a rest position. Show all this as you discuss these ideas. Cite the example in the book about skidding with locked brakes in a car [where the distance of skid for sliding friction is greater than static friction, where lower braking application results in nonsliding tires and shorter sliding distance]. Discuss the new automatic braking systems (ABS) of cars.

Friction in the **Practicing Physics Book** nicely treats details of friction.

After you have adequately discussed friction and net force, pose the following (Be careful that your class may not be ready for this, in which case you may confuse rather than enlighten.):

Mass and Weight

To distinguish between mass and weight compare the efforts of pushing horizontally on a block of slippery ice on a frozen pond versus lifting it. Or consider the weightlessness of a massive anvil in outer space and how it would be difficult to shake, weight or no weight. And if moving toward you, it would be harmful to be in its way because of its great tendency to remain in motion. The following demo (often used to illustrate impulse and momentum) makes the distinction nicely:



> DEMONSTRATION: Hang a massive ball by a string and show that the top string breaks when the bottom is pulled with gradually more force, but the bottom string breaks when the string is jerked. Ask which of these cases illustrates weight. [Interestingly enough, it's the weight of the ball that makes for the greater tension in the top string.] Then ask which of these cases illustrates inertia. [When jerked, the tendency of the ball to resist the sudden downward acceleration, its inertia, is responsible for the lower string breaking.] This is the best demo I know of for showing the different effects of weight and mass.

Mass Resists Acceleration: The property of massive objects to resist changes is nicely shown with this follow-up demonstration.

> DEMONSTRATION: Lie on your back and have an assistant place a blacksmith's anvil on your stomach. Have the assistant strike the anvil rather hard with a sledge hammer. The principles here are the same as the ball and string demo. Both the inertia of the ball and the inertia of the anvil

resist the changes in motion they would otherwise undergo. So the string doesn't break, and your body is not squashed. (Be sure that your assistant is good with the hammer. When I began teaching I used to trust students to the task. In my fourth year the student who volunteered was extra nervous in front of the class and missed the anvil entirely—but not me. The hammer smashed into my hand breaking two fingers. I was lucky I was not harmed more.)

Relate the ideas of tightening a hammer head by slamming the opposite end of the handle on a firm surface, with the bones of the human spine after jogging or even walking around. Interestingly, we are similarly a bit shorter at night. Ask your students to find a place in their homes that they can't quite reach before going to bed—a place that is one or two centimeters higher than their reach.

Then tell them to try again when they awake the next morning. Unforgettable, for you are likely instructing them to discover something about themselves they were not aware of!

Newton's 2nd Law
Briefly review the idea of acceleration and its definition, and state that it is produced by an imposed force. Write this as $a \sim F$ and give examples of doubling the force and the resulting doubling of the acceleration, etc. Introduce the ideas of net force, with appropriate examples—like applying twice the force to a stalled car gives it twice as much acceleration—three times the force, three times the acceleration.

CHECK QUESTION: If one were able to produce and maintain a constant net force of only 1 newton on the Queen Mary 2 ocean liner, what would be its maximum speed? Give multiple choices for an answer: a) 0 m/s; b) 1 m/s; c) less than 1 m/s; d) about 10 m/s; e) close to the speed of light! In the discussion that follows, the key concept is *net* force. Point out the enormous applied forces necessary to overcome the enormous water resistance at high speeds, to yield a *net force of 1 newton*; and the meaning of acceleration—that every succeeding second the ship moves a bit faster than the second before. This would go on seemingly without limit, except for relativistic effects which result in e) being the correct answer.

Falling Objects:
Point out that although Galileo introduced the idea of inertia, discussed the role of forces, and defined acceleration, he never tied these ideas together as Newton did with his second law. Although Galileo is credited as the first to demonstrate that in the absence of air resistance, falling objects fall with equal accelerations, he was not able to say why this is so. The answer is given by Newton's 2nd law.

SKIT: Hold a heavy object like a kilogram weight and a piece of chalk with outstretched hands, ready to drop them. Ask your class which will strike the ground first if you drop them simultaneously. They know. Ask them to imagine you ask the same of a bright youngster, who responds by asking to handle the two objects before giving an answer. Pretend you are the kid judging the lifting of the two objects. "The metal object is heavier than chalk, which means there is more gravity force acting on it, which means it will accelerate to the ground before the chalk does." Write the kids argument in symbol notation on the board. $a \sim F$. Then go through the motions of asking the same of another child, who responds with a good argument that takes inertia rather than weight into account. This kid says, after shaking the metal and chalk back-and-forth in his or her hands, "The piece of metal is more massive than the chalk, which means it has more inertia, than the chalk, which means it will be harder to get moving than the chalk. So the chalk will race to the ground first, while the inertia of the metal causes it to lag behind." Write this kid's argument with, $a \sim 1/m$. State that a beauty of science is that such speculations can be ascertained by experiment. Drop the weight and the chalk to show that however sound each child's argument seemed to be, the results do not support either. Then bring both arguments together with $a \sim F/m$, Newton's 2nd law.

Relate your skit to the case of falling bricks, Figure 4.12, and the falling boulder and feather, Figure 4.13. Once these concepts are clear, ask how the bricks would slide on a frictionless inclined plane, then illustrate with examples such as the time required for a fully loaded roller coaster and an empty roller coaster to

make a complete run. In the absence of friction effects, the times are the same. Cite the case of a Cadillac limousine and Volkswagen moving down a hill in the absence of friction. By now you are fielding questions having to do with air resistance and friction. (Avoid getting into the buoyancy of falling objects—information overload.)

> DEMONSTRATION: After you have made clear the cases with no friction, then make a transition to practical examples that involve friction—leading off with the dropping of sheets of paper, one crumpled and one flat. Point out that the masses and weights are the same, and the only variable is air resistance. Bring in the idea of net force again, asking what the net force is when the paper falls at constant speed. (If you left the Chapter 3 demo of the falling book and paper on top of it unexplained, reintroduce it here.)

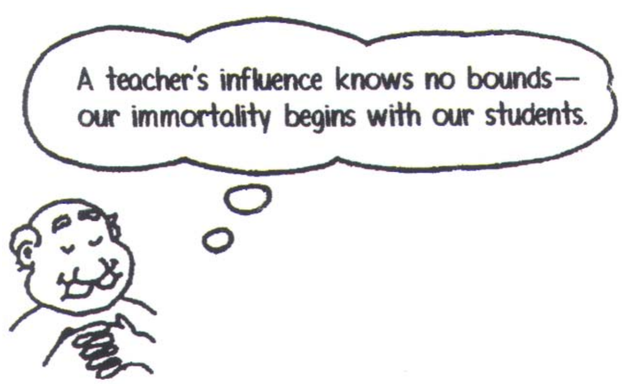
> CHECK QUESTIONS: What is the acceleration of a feather that "floats" slowly to the ground? The net force acting on the feather? If the feather weighs 0.0 N, how much air resistance acts upward against it? [Acceleration is zero at terminal speed, and air resistance = weight of object.]

These questions lead into a discussion of the parachutists in Figure 4.15. When the decrease of acceleration that builds up to terminal velocity is clear, return to the point earlier about the Cadillac and Volkswagen moving down an incline, only this time in the presence of air resistance. Then ask whether or not it would be advantageous to have a heavy cart or a light cart in a soap-box-derby race. Ask which would reach the finish line first if they were dropped through the air from a high-flying balloon. Then consider the carts on an inclined plane.

For your information, the terminal velocity of a falling baseball is about 150 km/h (95 mi/h), and for a falling Ping-Pong ball about 32 km/h (20 mi/h).

Make the distinction between how fast something hits the ground and with what force it hits. Dropping a pebble on one foot, and a boulder on the other makes this clear. Although they both hit at the same speed, the heavier boulder elicits the ouch!

So far we have regarded a force as a push or a pull. We will consider a deeper definition of force in the next chapter. Onward!



Answers and Solutions for Chapter 4

Reading Check Questions

1. Acceleration and net force are proportional to each other, not equal to each other.
2. Your push and the force of friction have the same magnitude.
3. Yes. As you increase your push, friction also increases just as much.
4. Once moving, your push has the same magnitude as the force of friction.
5. Static friction is greater than sliding friction for the same object.
6. Friction does not vary with speed.
7. Yes. Fluid friction does vary with speed.
8. Mass is more fundamental than weight.
9. mass; weight.
10. kilogram; newton.
11. A quarter-pound hamburger after it is cooked weighs about 1 newton.
12. The weight of a 1-kg brick is about 10 newtons.
13. Breaking of the top string is due mainly to the ball's weight.
14. Breaking of the lower string is due mainly to the ball's mass.
15. Acceleration is inversely proportional to mass.
16. The acceleration produced by a net force on an object is directly proportional to the net force, is in the same direction as the net force, and is inversely proportional to the mass of the object.
17. No. Weight is proportional to mass, but not *equal* to mass.
18. The acceleration triples.
19. The acceleration decreases to one-third.
20. The acceleration will be unchanged.
21. The acceleration and net force are in the same direction.
22. In free fall, the only force acting on an object is the force of gravity.
23. The ratio of force to mass is g.
24. The ratio of force to mass for both is the same, g.
25. The net force is 10 N.
26. The net force is 6 N; zero.
27. Speed and frontal area affect the force of air resistance.
28. Acceleration is zero.
29. A heavier parachutist must fall faster for air resistance to balance weight.
30. The faster one encounters greater air resistance.

Think and Do

31. Relate how Newton followed Galileo, and so on.

32. The coin hits the ground first; when crumpled, both fall in nearly the same time; from an elevated starting point, the coin hits first. That's because it has less frontal area.

33. When the paper is on top of the dropped book, no air resistance acts on the paper because the book shields it from the air. So the paper and book fall with the same acceleration!

34. In all three kinds of motion they move in unison, in accord with $a = F/m$.

35. The spool will roll to the right! There is an angle at which it will not roll but slide. Any angle larger will roll the spool to the left. But pulled horizontally it rolls in the direction of the pull.

Plug and Chug

36. Weight = (50 kg)(10 N/kg) = 500 N.

37. Weight = (2000 kg)(10 N/kg) = 20,000 N.

38. Weight = (2.5 kg)(10 N/kg) = 25 N; (25 N)(2.2 lb/kg)(10 N/1 kg) = 550 N.

39. (1 N)(1 kg/10 N) = 0.1 kg; (0.1 kg)(2.2 lb/1 kg) = 0.22 lb.

40. N to kg; (300 N)(1 kg/10 N) = 30 kg.

41. $a = F_{net}/m$ = (500 N)/(2000 kg) = 0.25 N/kg = 0.25 m/s^2.

42. $a = F_{net}/m$ = (120,000 N)/(300,000 kg) = 0.4 N/kg = 0.4 m/s^2.

43. $a = F_{net}/m$ = 200 N/40 kg = 5 N/kg = 5 m/s^2.

44. $a = \Delta v/\Delta t$ = (6.0 m/s)/(1.2 m/s^2) = 5.0 m/s^2. .

45. **$a = F_{net}/m$ = (15 N)/(3.0 kg) = 5.0 N/kg = 5.0 m/s^2.**

46. **$a = F_{net}/m$ = (10 N)/(1 kg) = 10 N/kg = 10 m/s^2.**

47. $F_{net} = ma$ = (12 kg)(7.0 m/s^2) = 84 kg·m/s^2 = 84 N.

Think and Solve

48. (1 N)(1 lb/4.45 N) = 0.225 lb.

49. Lillian's mass is (500N)/(10N/kg) = 50 kg. Her weight in pounds, (50 kg)(2.2 lb/kg) = 110 lb.

50. The acceleration of each is the same: $a = F/m$ = 2 N/2 kg = 1 N/1 kg = 1 m/s^2. (Incidentally, from the definition that 1 N = 1 kg·m/s^2, you can see that 1 N/kg is the same as 1 m/s^2.)

51. For the jet: $a = F/m$ = 2(30,000 N)/(30,000 kg) = 2 m/s^2.

52. (a) a = Δv/Δt = (9.0 m/s)/(0.2 s) = 45 m/s^2. (b) $F = ma$ = (100 kg)(45 m/s^2) = 4500 N.

53. (a) The force on the bus is Ma. New acceleration = same force/new mass = $Ma/(M+M/5) = 5Ma/(5M+M)$ $= 5Ma/6M = (5/6)a$.
 (b) New acceleration = $(5/6)a$ = (5/6)(1.2 m/s^2) = 1.0 m/s^2.

Think and Rank

54. a. D, A=B=C; b. A=C, B=D
55. C, B, A
56. a. A=B=C; b. C, A, B
57. a. C, A, B; b. B, A, C

Think and Explain

58. The force you exert on the ball ceases as soon as contact with your hand ceases.

59. Yes, if the ball slows down, a force opposite to its motion is acting—likely air resistance and friction between the ball and alley.

60. Constant velocity means zero acceleration, so yes, no net force acts on the motorcycle. But when moving at constant acceleration there is a net force acting on it.

61. No, inertia involves mass, not weight.

62. Items like apples weigh less on the Moon, so there are more apples in a 1-pound bag of apples there. Mass is another matter, for the same quantity of apples are in 1-kg bag on the Earth as on the Moon.

63. Buy by weight in Denver because the acceleration of gravity is less in Denver than in Death Valley. Buying by mass would be the same amount in both locations.

64. Shake the boxes. The box that offers the greater resistance to acceleration is the more massive box, the one containing the sand.

65. When you carry a heavy load there is more mass involved and a greater tendency to remain moving. If a load in your hand moves toward a wall, its tendency is to remain moving when contact is made. This tends to squash your hand if it's between the load and the wall—an unfortunate example of Newton's first law in action.

66. Mass is a measure of the amount of material in something, not gravitational pull that depends on its location. So although the weight of the astronaut may change with location, mass does not.

67. A massive cleaver is more effective in chopping vegetables because its greater mass contributes to greater tendency to keep moving as the cleaver chops the food.

68. Neither the mass nor the weight of a junked car changes when it is crushed. What does change is its volume, not to be confused with mass and weight.

69. Ten kilograms weighs about 100 N on the Earth (weight = mg = 10 kg $\times$ 10 m/s^2 = 100 N, or 98 N if g = 9.8 m/s^2 is used). On the Moon the weight is 1/6 of 100 N = 16.7 N
(or 16 N if g = 9.8 m/s^2 is used). The mass is 10 kg everywhere.

70. The scale reading will increase during the throw. Your upward force on the heavy object is transmitted to the scale.

71. The change of weight is the change of mass times *g,* so when mass changes by 2 kg, weight changes by about 20 N.

72. One kg of mass weighs 2.2 pounds at the Earth's surface. If you weigh 100 pounds, for example, your mass is (100 lb)/(2.2 kg/lb) = 45 kg. Your weight in newtons, using the relationship weight = mg, is then (45 kg)(10 N/kg) = 450 N.

73. A 1-kg mass weighs 10 N, so 30 kg weigh 300 N. The bag can safely hold 30 kg of apples—if you don't pick it up too quickly.

74. Since the crate remains at rest, the net force on it is zero, which means the force of friction by the floor on the crate will be equal and opposite to your applied force.

75. The second law states the relationship between force and acceleration. If there is no net force, there is no acceleration—which is what Newton's first law states. So Newton's first law is consistent with the second law, and can be considered to be a special case of the second law.

76. Acceleration (slowing the car) is opposite to velocity (direction car moves).

77. Agree. Acceleration (slowing the car) is opposite to velocity (the direction the car is moving).

78. Acceleration is the ratio force/mass (Newton's second law), which in free fall is just weight/mass = $mg/m = g$. Since weight is proportional to mass, the ratio weight/mass is the same whatever the weight of a body.

79. Lifting the opponent decreases the force with which the ground supports him, and correspondingly decreases the force of friction he can muster. The reduced friction limits the opponent's effectiveness.

80. The forces acting horizontally are the driving force provided by friction between the tires and the road, and resistive forces—mainly air resistance. These forces cancel and the car is in dynamic equilibrium with a net force of zero.

81. (a) No. Air resistance is also acting. Free fall means free of all forces other than that due to gravity. A falling object may experience air resistance; a freely falling object experiences only the force due to gravity. (b) Yes. Although getting no closer to the Earth, the satellite is falling (more about this in Chapter 10).

82. The velocity of the ascending coin decreases while its acceleration remains constant (in the absence of air resistance).

83. The only force on a tossed coin, except for air resistance, is mg. So the same mg acts on the coin at all points in its trajectory.

84. The acceleration at the top or anywhere else in free fall is g, 10 m/s^2, downward. The velocity of the rock is momentarily zero while the rate of change of velocity is still present. Or better, by Newton's 2nd

law, the force of gravity acts at the top as elsewhere; divide this net force by the mass for the acceleration of free fall. That is, $a = F_{net}/m = mg/m = g$.

85. You explain the distinction between an applied force and a net force. It would be correct to say no *net* force acts on a car at rest.

86. When driving at constant velocity, the zero net force on the car results from the driving force that your engine supplies against the friction drag force. You continue to apply a driving force to offset the drag force that otherwise would slow the car.

87. When the apple is held at rest the upward support force equals the gravitational force on the apple and the net force is zero. When the apple is released, the upward support force is no longer there and the net force is the gravitational force, 1 N. (If the apple falls fast enough for air resistance to be important, then the net force will be less than 1 N, and eventually can reach zero if the air resistance builds up to 1 N.)

88. High-speed grains of sand grazing the Earth's atmosphere burn up because of friction against the air.

89. Both forces have the same magnitude. This is easier to understand if you visualize the parachutist at rest in a strong updraft—static equilibrium. Whether equilibrium is static or dynamic, the net force is zero.

90. When anything falls at constant velocity, air resistance and gravitational force are equal in magnitude. Raindrops are merely one example.

91. When a parachutist opens her chute she slows down. That means she accelerates upward.

92. There are usually two terminal speeds, one before the parachute opens, which is faster, and one after, which is slower. The difference has mainly to do with the different areas presented to the air in falling. The large area presented by the open chute results in a slower terminal speed, slow enough for a safe landing.

93. Just before a falling body attains terminal velocity, there is still a downward acceleration because gravitational force is still greater than air resistance. When the air resistance builds up to equal the gravitational force, terminal velocity is reached. Then air resistance is equal and opposite to gravitational force.

94. The terminal speed attained by the falling cat is the same whether it falls from 50 stories or 20 stories. Once terminal speed is reached, falling extra distance does not affect the speed. (The low terminal velocities of small creatures enables them to fall without harm from heights that would kill larger creatures.)

95. The sphere will be in equilibrium when it reaches terminal speed—which occurs when the gravitational force on it is balanced by an equal and opposite force of fluid drag.

96. Air resistance is not really negligible for so high a drop, so the heavier ball does strike the ground first. (This idea is shown in Figure 4.16.) But although a twice-as-heavy ball strikes first, it falls only a little faster, and not twice as fast, which is what followers of Aristotle believed. Galileo recognized that the small difference is due to air friction, and both would fall together when air friction is negligible.

97. The heavier tennis ball will strike the ground first for the same reason the heavier parachutist in Figure 4.15 strikes the ground first. Note that although the air resistance on the heavier ball is smaller relative to the ball's weight, it is actually greater than the air resistance that acts on the other ball. Why? Because the heavier ball falls faster, and air resistance is greater at greater speed.

98. Air resistance decreases the speed of a moving object. Hence the ball has less than its initial speed when it returns to the level from which it was thrown. The effect is easy to see for a feather projected upward by a slingshot. No way will it return to its starting point with its initial speed!

99. The ball rises in less time than it falls. If we exaggerate the circumstance and considering the feather example in the preceding answer, the time for the feather to flutter from its maximum altitude is clearly longer than the time it took to attain that altitude. The same is true for the not-so-obvious case of the ball.

100. Open-ended.

Think and Discuss

101. Yes, as illustrated by a ball thrown vertically into the air. Its velocity is initially upward, and finally downward, all the while accelerating at a constant downward *g*.

102. Neither a stick of dynamite nor anything else “contains” force. We will see later that a stick of dynamite contains *energy*, which is capable of producing forces when an interaction of some kind occurs.

103. No. An object can move in a curve only when a force acts. With no force its path would be a straight line.

104. The only force that acts on a dropped rock on the Moon is the gravitational force between the rock and the Moon because there is no air and therefore no air drag on the rock.

105. A dieting person seeks to lose mass. Interestingly, a person can lose weight by simply being farther from the center of the Earth, at the top of a mountain, for example.

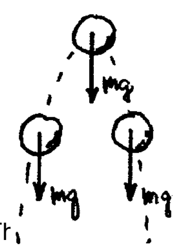
106. Friction between the crate and the truck-bed is the force that keeps the crate picking up the same amount of speed as the truck. With no friction, the accelerating truck would leave the crate behind.

107. Note that 30 N pulls three blocks. To pull two blocks then requires a 20-N pull, which is the tension in the rope between the second and third block. The tension in the rope that pulls only the third block is therefore 10 N. (Note that the net force on the first block,
30 N – 20 N = 10 N, is the force needed to accelerate that block, having one-third of the total mass.)

108. The *net* force on the wagon, your pull plus friction, is zero. So $\Sigma F = 0$.

109. When you stop suddenly, your velocity changes rapidly, which means a large acceleration of stopping. By Newton’s second law, this means the force that acts on you is also large. Experiencing a large force is what hurts you.

110. The force vector *mg* is the same at all locations. Acceleration *g* is therefore the same at all locations also.



111. Th t on the ground is greater. The ground must push up on you with a force greater than the downward force o

112. At the top of your jump your acceleration is *g*. Let the equation for acceleration via Newton’s second law guide your thinking: $a = F/m = mg/m = g$. If you said zero, you’re implying the force of gravity ceases to act at the top of your jump—not so!

113. For a decreasing acceleration the increase in speed becomes smaller each second, but nevertheless, there’s greater speed each second than in the preceding second.

114. The net force is *mg* downward, 10 N (or more precisely, 9.8 N).

115. The net force is 10 N – 2 N = 8 N (or more precisely 9.8 N – 2 N = 7.8 N).

116. Agree with your friend. Although acceleration decreases, the ball is nevertheless gaining speed. It will do so until it reaches terminal speed. Only then will it not continue gaining speed.

117. A sheet of paper presents a larger surface area to the air in falling (unless it is falling edge on), and therefore has a lower terminal speed. A wadded piece of paper presents a smaller area and therefore falls faster before reaching terminal speed.

118. In each case the paper reaches terminal speed, which means air resistance equals the weight of the paper. So air resistance will be the same on each! Of course the wadded paper falls faster for air resistance to equal the weight of the paper.

119. For low speeds, accelerations are nearly the same because air drag is small relative to the weights of the falling objects. From a greater height, there is time for air resistance to build up and more noticeably show its effects.

120. Sliding down at constant velocity means acceleration is zero and the net force is zero. This can occur if friction equals the bear's weight, which is 4000 N. Friction = bear's weight = mg = (400 kg)(10 m/ s^2) = 4000 N.

121. Nowhere is her velocity upward. The upward net force on Nellie during the short time that air resistance exceeds the force of gravity produces a momentary upward net force and upward acceleration. This produces a *decrease* in her downward speed, which is nevertheless still downward.

5 Newton's Third Law of Motion

5.2 Forces and Interactions
5.2 Newton's Third Law of Motion
Defining Your System
5.3 Action and Reaction on Different Masses
5.4 Vectors and the Third Law
5.5 Summary of Newton's Three Laws

The opening photos begin with Darlene Librero and Paul Doherty, my two dear friends at the Exploratorium, Darlene goes back to the earliest days at the Exploratorium when she worked with Frank Oppenheimer. Paul has been the senior scientist there since the 80s. The caption of the tennis ball and racquet makes an important point, often overlooked by many: The racquet cannot hit the ball *unless* the ball simultaneously hits the racquet! Toby Jacobson, who pushes on the pair of scales with wife Bruna, sat with his mom on my Exploratorium Conceptual Physics class when he was 13 years old. Today, both with physics PhDs, Toby and Bruna continue in their love of physics. The touching photo is of my son Paul and his daughter, my granddaughter Gracie. Hooray for Newton's third law!

The personality profile is of the Exploratorium's senior scientist and good friend Paul Doherty.

Up to here a force is seen as a push or a pull. Newton's third law defines it better—as part of an interaction between one body and another. As the tennis ball and racquet attests, you cannot exert a force on something—*unless*, and I pause, that something exerts an equal and opposite force on you. So you can't hit a ball *unless* the ball hits back. You can't exert a force on the floor when you walk, *unless* the floor exerts the same amount of force back on you, etc. In discussing action and reaction emphasize the word "between," for example, the forces *between* Earth and the Moon.

This chapter continues with a treatment of vectors. Trigonometry, no. The parallelogram rule, yes! Vector components are also treated, which will be needed when projectiles are covered in Chapter 10. Treatment of vectors continues in the Practice Book.

Practicing Physics Book:
- Action and Reaction Pairs
- Interactions
- Vectors and the Parallelogram Rule
- Velocity Vectors and Components
- Force and Velocity Vectors
- Force Vectors and the Parallelogram Rule
- Force-Vector Diagrams
- More on Vectors

Problem Solving Book:
Sample Problems and more, also with optional section on trigonometry instruction

Laboratory Manual:
- The Force Mirror *Quantitative Observations of Force Pairs* (Tech Lab)
- Blowout *Newton's Three Laws* (Demonstration)

Next-Time Questions (in the Instructors Resource DVD):
- Reaction Forces
- Apple on a Table
- Scale Reading
- Tug of War
- Tug of War 2
- Leaning Tower of Pisa Drop
- Apple on Table
- Atwood Pulley
- Airplane in the Wind
- No-Recoil Cannon

Hewitt-Drew-It! Screencasts:
- *Newton's Third Law*
- *Newton's Laws Problem*

SUGGESTED LECTURE PRESENTATION

Forces and Interactions

Hold a piece of tissue paper at arms length and ask if the heavyweight champion of the world could hit the paper with 50 pounds of force. Ask your class to check their answer with their neighbors. Then don't give your answer. Instead, continue with your lecture. Reach out to your class and state, "I can't touch you, without you touching me in return—I can't nudge this chair without the chair in turn nudging me—I can't exert a force on a body without that body in turn exerting a force on me." In all these cases of contact there is a *single* interaction between *two* things—contact requires a *pair* of forces, whether they be slight nudges or great impacts, between *two* things. This is Newton's 3rd law of motion. Call attention to the examples of Figure 5.7.

Newton's Third Law of Motion

Extend your arm horizontally and show the class that you can bend your fingers upward only very little. Show that if you push with your other hand, and thereby apply a force to them, or have a student do the same, they will bend appreciably more. Then walk over to the wall and show that the inanimate wall does the same (as you push against the wall). State that everybody will acknowledge that you are pushing on the wall, but only a few realize the fundamental fact that the wall is simultaneously pushing on you also—as evidenced by your bent fingers.

Do as Linda E. Roach does and place a sheet of paper between the wall and your hand. When you push on the paper, it doesn't accelerate—evidence of a zero net force on the paper. You can explain that in addition to your push, the wall must be pushing just as hard in the opposite direction on the paper to produce the zero net force. Linda recommends doing the same with an inflated balloon, whereupon your class can easily see that both sides of the balloon are squashed.

> CHECK QUESTION: Identify the action and reaction forces for the case of a bat striking the ball.

Action and Reaction on Different Masses

Discuss walking on the floor in terms of the single interaction between you and the floor, and the pair of action and reaction forces that comprise this interaction. Contrast this to walking on frictionless ice, where no interaction occurs. Ask how one could get off a pond of frictionless ice. Make the answer easy by saying one has a massive brick in hand. By throwing the brick there is an interaction between the thrower and the brick. The reaction to the force on the brick, the recoiling force, sends one to shore. Or without such a convenient brick, one has clothing. Or if on clothing, one has air in the lungs. One could blow air in jet fashion. Exhale with the mouth facing away from shore, but be sure to inhale with the mouth facing toward shore.

> CHECK QUESTION: Identify the force that pushes a car along the road. [Interestingly enough, the force that pushes cars is provided by the road. Why? The tires push on the road, action and the road pushes on the tires, reaction. So roads push cars along. A somewhat different viewpoint!]

Most people say that the Moon is attracted to Earth by gravity. Ask most people if Earth is also attracted to the Moon, and if so, which pulls harder, Earth or the Moon? You'll get mixed answers. Physicists think differently than most people on this topic. Rather than saying the Moon is attracted to Earth by gravity, a physicist would say there is an attractive gravitational force between Earth and the Moon.

Asking if the Moon pulls as hard on Earth as Earth pulls on the Moon is similar to asking if the distance between New York and Los Angeles is the same as the distance between Los Angeles and New York. Rather than thinking in terms of two distances, we think of a single distance *between* New York and Los Angeles. Likewise there is a single gravitational interaction between Earth and the Moon.

Support this point by showing your outstretched hand where you have a stretched rubber band between your thumb and forefinger. Ask which is pulling with the greater force, the thumb or the finger. Or, as you increase the stretch, which is being pulled with more force toward the other—the thumb toward the finger or the finger toward the thumb. After neighbor discussion, stress the single interaction between things that pull on each other. Earth and the Moon are pulling on each other. Their pulls on each other comprise a single interaction. This point of view makes a moot point of deciding which exerts the greater force, the Moon on Earth or Earth on the Moon, or the ball on the bat or the bat on the ball, et cetera. Pass a box of rubber bands to your class and have them do it.

> DEMONSTRATION: Tug-of-war in class. Have a team of women engage in a tug-of-war with a team of men. If you do this on a smooth floor, with men wearing socks and women wearing rubber-soled shoes, the women will win. This illustrates that the team who wins in this game is the team who pushes harder on the floor. This is featured at the bottom of page 80.

Discuss the firing of a bullet from a rifle, as treated in the chapter. Illustrate Newton's 3rd law with a skit about a man who is given one last wish before being shot, who states that his crime demands more punishment than being struck by a tiny bullet, who wishes instead that the mass of the bullet match the magnitude of his crime (being rational in a rigid totalitarian society), that the mass of the bullet be much much more massive than the gun from which it is fired—and that his antagonist pull the trigger!

Return to your question about whether a heavyweight boxer could hit a piece of tissue paper with a force of 50 pounds or so. Now your class understands (hopefully) that the fist can't produce any more force on the paper than the paper exerts on the fist. The paper doesn't have enough mass to do this, so the answer is no. The fighter can't hit the paper any harder than the paper can hit back. Consider solving Think and Solve 27 in the end matter here.

Philosophically we know that if you try to do one thing, something else happens as a result. So we say you can never do only one thing. Every equation reminds us of that—change a term on one side of an equation and a term on the other correspondingly changes. In this chapter we similarly see that you can never have only one force.

Defining Your System
Discuss the different systems of orange and apple as in Figures 5.8 - 5.11. This is also treated in the Hewitt-Drew-It! Screencast on *Newton's Third law*. Ask students to identify action and reaction parts of the systems of Figures 5.14–5.18. That's wife Lil and me in Figure 5.19. And continuing with the same important concept of "you can't touch without being touched", my brother Steve and his daughter Gretchen do the same in Think and Explain 35 in the back matter. A prior photo of them, when Gretchen was a child, occurred in previous editions. The pushed bricks in the road of Figure 5.20 can illicit class discussion. The photo is clear evidence that the bricks have been pushed, as they push the tires of automobiles!

Vectors and their Components
Section 5.4 illustrates vectors and their components. The physics can be clearly seen without the use of trigonometry. My assumption is that most readers of Conceptual Physics are not trig literate. You can take physics time to teach some trigonometry, but my advise is that you resist that impulse and use class time for the exciting physics beyond this chapter. If your school is typical, there are many math classes, and perhaps your class is the only one focused on physics. In that case, learning trig can occur in the math classes. Your math teaching colleagues are unlikely to teach much physics in their math classes! Since you're the physics person, go physics! ☺

You'll note examples involving vectors are simple ones. Why? Before one gets deeply into any subject, they are better off with an understanding of the simplest examples first. When challenge comes, it should be welcomed. It won't be welcomed if the basics are missing. So go basics!

Think and Discuss 80 in the back matter, of the strongman pulled in opposite directions, is treated in the screencast on *Newton's Third law*. The situation elicits class discussion.

Force and Velocity Vectors

Have your students have a go at the vector exercises in the Practicing Physics book. Take care to avoid force *and* velocity vectors on the same diagram. Having both on a vector diagram is an invitation to confusion—what you don't need.

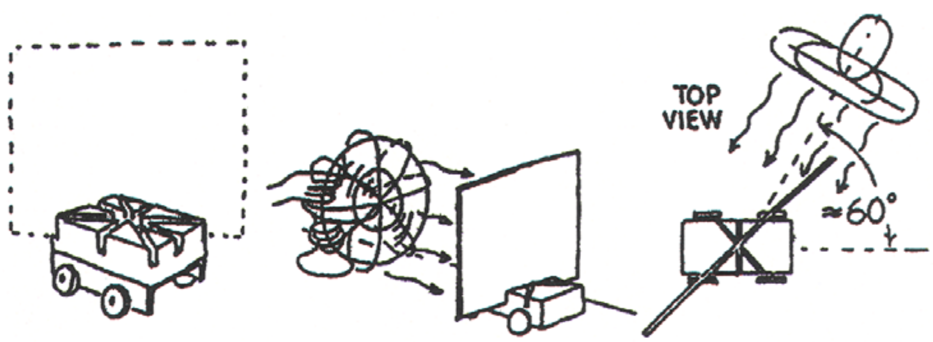
Components of Vectors

For components of vectors, again, the Practicing Physics worksheet on page 27 is instructive. The notion of component vectors will be useful in following chapters, particularly Chapters 6 and 10.

> DEMONSTRATION: To highlight the parallelogram rule for vectors, here's a good one: Have two students hold the ends of a heavy chain. Ask them to pull it horizontally to make it as straight as possible. Then ask what happens if a bird comes along and sits in the middle (as you place a 1-kg hook mass on the middle of the chain!). What happens if another bird comes to join the first (as you suspend another 1-kg mass)? Ask the students to keep the chain level. Now what happens if a flock of birds join the others (as you hang additional masses). This works well!

Invoke the parallelogram rule to show that the chain must be directed slightly upward to provide the needed vertical components to offset the weight.

Appendix D nicely extends vectors, and describes the interesting case of a sailboat sailing into the wind. This and the crossed Polaroids later in Chapter 29 are to my mind, the most intriguing illustrations of vectors and what they can do. An interesting demo is the model sailboat which you can easily build yourself with a small block of wood and a piece of aluminum. Cut slots in the wood and mount it on a car (or ideally, on an air track). A square-foot sheet of aluminum serves as a sail, and wind from a hand-held fan is directed against the sail in various directions. Most impressive is holding the fan in front, but off to the side a bit, so that the cart will sail into the wind. This is indeed an excellent vehicle for teaching vectors and their components!



Answers and Solutions for Chapter 5

Reading Check Questions

1. The force is the wall pushing on your fingers.
2. He can't exert much force on the tissue paper because the paper can't react with the same magnitude of force.
3. A pair of forces are required for an interaction.
4. Whenever one object exerts a force on a second object, the second object exerts and equal and opposite force on the first.
5. Action: bat against ball. Reaction: ball against bat.
6. Yes, and that external net force accelerates the orange system.
7. No, for the pair of forces are internal to the apple-orange system.
8. Yes, an external net force is required to accelerate the system.
9. Yes, the net force is provided by contact with your foot. If two opposite and equal forces act on the ball, the net force on it is zero and it will not accelerate.
10. Yes, you pull upward with the same amount of force on Earth.
11. The different accelerations are due to different masses.
12. The force that propels a rocket is the exhaust gases pushing on the rocket.
13. A helicopter gets its lifting force by pushing air downward, in which case the reaction is the air pushing the helicopter upward.
14. You cannot touch without being touched! And with the same amount of force.
15. The process of determining the components of a vector.
16. The magnitude of the normal force decreases.
17. The friction force has the same magnitude, with the sum of all forces being zero.
18. Moving upward, the vertical component of velocity decreases. The horizontal component remains constant, in accord with Newton's first law.
19. Inertia; acceleration; action and reaction.
20. Newton's third law deals with interactions.

Think and Do

21.Your hand will be pushed upward, a reaction to the air it deflects downward.

22. Each will experience the same amount of force.

Plug and Chug

23. 100 km/h – 75 km/h = 25 km/h north. 100 km/h + 75 km/h = 175 km/h north

24. R = $\sqrt{}(100^2 + 100^2)$ = 141 km/h

25. R = $\sqrt{}(4^2 + 3^2)$ = 5.

26. R = $\sqrt{}(200^2 + 80^2)$ = 215 km/h

Think and Solve

27. a. $a = \Delta v/\Delta t$ =(25 m/s)/(0.05 s) = **500 m/s²**. b. $F = ma$ = (0.003 kg)(500 m/s^2) = 1.5 N, which is about $^1/3$ pound. c. By Newton's third law, the same amount, 1.5 N.

28.The wall pushes on you with **40 N**.
$a = F/m$ = 40 N/80 kg = **0.5 m/s²**.

29.$a = F/m$, where $F = \sqrt{}[(3.0\text{ N})^2 + (4.0\text{ N})^2]$ = 5 N. So $a = F/m$ = 5 N/2.0 kg = **2.5 m/s²**.

30. (a) From the 3rd law $F_{\text{on }2m\text{ puck}} = F_{\text{on m puck}} \Rightarrow 2m(a_{2m}) = m(a_m) \Rightarrow 2m\frac{\Delta v_{2m}}{\Delta t} = m\frac{\Delta v_m}{\Delta t}$ Since the force acts for exactly the same Δt for each mass $\Rightarrow \Delta v 2m = \frac{1}{2}\Delta v_m$. Since both masses start out at rest $\Rightarrow v_{2m} = \frac{1}{2}v_m$.

(b) $v_{2m} = \frac{1}{2}v_m = \frac{1}{2}\left(0.4\,\frac{\text{m}}{\text{s}}\right) = 0.2\,\frac{\text{m}}{\text{s}}$.

Think and Rank

31. A = B = C
32. A, B, C; (b) B, C
33. (a) A = B = C; (b) C, B, A

Think and Explain

34. Action; hammer hits nail. Reaction; nail hits hammer. (b) Action; Earth pulls down on a book. Reaction; book pulls up on Earth. (c) Action; helicopter blade pushes air downward. Reaction; air pushes helicopter blade upward. (In these examples, action and reaction may be reversed—which is called which is unimportant.)

35. In accord with Newton's third law, Steve and Gretchen are touching each other. One may initiate the touch, but the physical interaction can't occur without contact between both Steve and Gretchen. Indeed, you cannot touch without being touched!

36. No, for each hand pushes equally on the other in accord with Newton's third law—you cannot push harder on one hand than the other.

37. (a) Two force pairs act; Earth's pull on apple (action), and apple's pull on Earth (reaction). Hand pushes apple upward (action), and apple pushes hand downward (reaction). (b) With no air resistance, one force pair acts; Earth's pull on apple, and apple's pull on Earth.

38. (a) Action; Earth pulls you downward. Reaction; you pull Earth upward. (b) Action; you touch tutor's back. Reaction; tutor's back touches you. (c) Action; wave hits shore. Reaction; shore hits wave.

39. (a) While the bat is in contact with the ball there are two interactions, one with the bat, and even then, with Earth's gravity. Action; bat hits ball. Reaction; ball hits bat. And, action, Earth pulls down on ball (weight). Reaction; ball pulls up on Earth. (b) While in flight the major interactions are with Earth's gravity and the air. Action; Earth pulls down on ball (weight). Reaction; ball pulls up on Earth. And, action; air pushes ball, and reaction; ball pushes air.

40. In accord with Newton's first law, your body tends to remain in uniform motion. When the airplane accelerates, the seat pushes you forward. In accord with Newton's third law, you simultaneously push backward against the seat.

41. When the ball exerts a force on the floor, the floor exerts an equal and opposite force on the ball—hence bouncing. The force of the floor on the ball provides the bounce.

42. The billions of force pairs are internal to the book, and exert no net force on the book. An external net force is necessary to accelerate the book.

43. The friction on the crate is 200 N, which cancels your 200-N push on the crate to yield the zero net force that accounts for the constant velocity (zero acceleration). No, although the friction force is equal and oppositely directed to the applied force, the two do *not* make an action-reaction pair of forces. That's because both forces *do* act on the same object—the crate. The reaction to your push on the crate is the crate's push back on you. The reaction to the frictional force of the floor on the crate is the opposite friction force of the crate on the floor.

44. When the barbell is accelerated upward, the force exerted by the athlete is greater than the weight of the barbell (the barbell, simultaneously, pushes with greater force against the athlete). When acceleration is downward, the force supplied by the athlete is less.

45. The forces must be equal and opposite because they are the only forces acting on the person, who obviously is not accelerating. Note that the pair of forces do *not* comprise an action-reaction pair, however, for they act on the *same* body. The downward force, the man's weight, *Earth pulls down on man*, has the reaction *man pulls up on Earth*, not the floor pushing up on him. And the upward force of the floor on the man has the reaction of man against the floor, not the interaction between the man and Earth. (If you find this confusing, you may take solace in the fact that Newton himself had trouble applying his 3rd law to certain situations. Apply the rule, A on B reacts to B on A, as in Figure 5.7.)

46. When you pull up on the handlebars, the handlebars simultaneously pull down on you. This downward force is transmitted to the pedals.

47. When the climber pulls the rope downward, the rope simultaneously pulls the climber upward—the direction desired by the climber.

48. When you push the car, you exert a force on the car. When the car simultaneously pushes back on you, that force is on you—not the car. You don't cancel a force on the car with a force on you. For cancellation, the forces have to be equal and opposite and act on the same object.

49. The strong man can exert only equal forces on both cars, just as your push against a wall equals the push of the wall on you. Likewise for two walls, or two freight cars. Since their masses are equal, they will undergo equal accelerations and move equally.

50. As in the preceding exercise, the force on each cart will be the same. But since the masses are different, the accelerations will differ. The twice-as-massive cart will undergo only half the acceleration of the less massive cart.

51. In accord with Newton's 3rd law, the force on each will be of the same magnitude. But the effect of the force (acceleration) will be different for each because of the different mass. The more massive truck undergoes less change in motion than the Civic.

52. Both will move. Ken's pull on the rope is transmitted to Joanne, causing her to accelerate toward him. By Newton's third law, the rope pulls back on Ken, causing him to accelerate toward Joanne.

53. The winning team pushes harder against the ground. The ground then pushes harder on them, producing a net force in their favor.

54. The tension in the rope is 250 N. With no acceleration, each must experience a 250-N force of friction via the ground. This is provided by pushing against the ground with 250 N.

55. No. The net force on the rope is zero, meaning tension is the same on both ends, in accord with Newton's third law.

56. The forces on each are the same in magnitude, and their masses are the same, so their accelerations will be the same. They will slide equal distances of 6 meters to meet at the midpoint.

57. The writer apparently didn't know that the reaction to exhaust gases does not depend on a medium for the gases. A gun, for example, will kick if fired in a vacuum. In fact, in a vacuum there is no air drag and a bullet or rocket operates even better.

58. The slanted streaks are composed of two components. One is the vertical velocity of the falling rain. The other is the horizontal velocity of the car. At 45° these components are equal, meaning the speed of falling drops equals the speed of the car. (We saw this question back in Chapter 3.)

59. To climb upward means pulling the rope downward, which moves the balloon downward as the person climbs.

60. The other interaction is between the stone and the ground on which it rests. The stone pushes down on the ground surface, say action, and the reaction is the ground pushing up on the stone. This upward force on the stone is called the *normal force*.

61. (a) The other vector is upward as shown.
(b) It is called the normal force.

62. (a) As shown.
(b) Yes.
(c) Because the stone is in equilibrium.

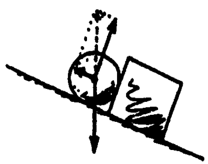
63. (a) As shown.
(b) Upward tension force is greater resulting in an upward net force.

64. As shown.

65. The acceleration of the stone at the top of its path, or anywhere where the net force on the stone is *mg*, is *g*, downward.

66. (a) Weight and normal force only.
(b) As shown.

67. (a) As shown.



(b) Note the resultant of the two normal forces is equal and opposite to the stone's weight.

68. Vector *f* will have the same magnitude as the vector sum of *mg* and *N*. If *f* is less, then a net force acts on the shoe and it accelerated down the incline.

69. The magnitudes of *mg* and *N* will be equal.

70. When the rope is vertical, *S* is zero. If the rope were vertical, *S* would be at an angle such that its vertical component would be equal and opposite to *mg*.

71. No force acts horizontally on the ball so the initial horizontal velocity remains constant as the ball moves through the air in accord with Newton's first law of inertia.

72. Earth pulls downward on the ball, action: the ball pulls upward on Earth, reaction. So the reaction force is the ball's upward pull on Earth. Acceleration all along the path is *g*
($a = F/m = mg/m = g$).

Think and Discuss

73. The answer is given in the equation $a = F/m$. As fuel is burned, the mass of the rocket becomes less. As *m* decreases as *F* remains the same, *a* increases! There is less mass to be accelerated as fuel is consumed.

74. Action: your foot against the ball. Reaction: the ball against your foot. Both forces have the same magnitude, in accord with Newton's third law.

75. Yes, it's true. The Earth can't pull you downward without you simultaneously pulling Earth upward. The acceleration of Earth is negligibly small, and not noticed, due to its enormous mass.

76. The scale will read 100 N, the same as it would read if one of the ends were tied to a wall instead of tied to the 100-N hanging weight. Although the net force on the system is zero, the tension in the rope within the system is 100 N, as would show on the scale reading.

77. Yes, a baseball exerts an external force on the bat, opposite to the bat's motion. This external force decelerates the oncoming bat.

78. The rapid deceleration of the speeding ball on the player's glove produces the force on the player's glove. In this sense, deceleration produces force (cause and effect can sometimes be a matter of interpretation).

79. The forces do not cancel because they act on different things—one acts on the horse, and the other acts on the wagon. It's true that the wagon pulls back on the horse, and this prevents the horse from running as fast as it could without the attached wagon. But the force acting on the wagon (the pull by the horse minus friction) divided by the mass of the wagon, produces the acceleration of the wagon. To accelerate, the horse must push against the ground with more force than it exerts on the wagon and the wagon exerts on it. So tell the horse to push backward on the ground.

80. Tension would be the same if one end of the rope were tied to a tree. If two horses pull in the same direction, tension in the rope (and in the strongman) is doubled.

6 Momentum

Rising physics star Derek Muller rises to the occasion in the first of the photos that open this chapter. And the personal profile is of Derek also. The second photo is of friend from school days, physics teacher Howie Brand. The physics he shows applies nicely to the Pelton wheel. The photo below is of grandson Alex.

This chapter begins where Chapter 5 leaves off. Newton's 2nd and 3rd laws lead directly to momentum and its conservation. We emphasize the impulse-momentum relationship with applications to many examples that have been selected to engage the students' interest. In your classroom I suggest the exaggerated symbol technique as shown in Figures 6.5, 6.6, and 6.8. Draw a comparison between momentum conservation and Newton's 3rd law in explaining examples such as rocket propulsion. You might point out that either of these is fundamental—i.e., momentum conservation may be regarded as a consequence of Newton's 3rd law, or equally, Newton's 3rd law may be regarded as a consequence of momentum conservation.

The increased impulse that occurs for bouncing collisions is treated very briefly and is expanded in the next chapter. Angular momentum is postponed to Chapter 8.

Interesting fact: The time of contact for a tennis ball on a racquet is about 5 milliseconds, whether or not a player "follows through." The idea that follow-through in tennis, baseball, or golf appreciably increases the duration of contact is useful pedagogy and gets the point of extended time across. But it is not supported by recent studies. Follow-through is more important in guiding one's behavior in applying maximum force to supply the impulse.

The swinging ball apparatus (Newton's cradle) shown in the sketch is popular for demonstrating momentum conservation. But any thorough analysis of it ought to be postponed to the next chapter when energy is treated. This is because the question is often raised, "Why cannot two balls be raised and allowed to swing into the array, and one ball emerge with twice the speed?" Be careful. Momentum would indeed be conserved if this were the case. But the case with different numbers of balls emerging never happens. Why? Because energy would not be conserved. For the two-balls-one-ball case, the KE after would be twice as much as the KE before impact. KE is proportional to the square of the speed, and the conservation of both momentum and KE cannot occur unless the numbers of balls for collision and ejection are the same. Consider postponing this demo until the next chapter.

A system is not only isolated in space, but in time also. When we say that momentum is conserved when one pool ball strikes the other, we mean that momentum is conserved during the brief duration of interaction when outside forces can be neglected. After the interaction, friction quite soon brings both balls to a halt. So when we isolate a system for purposes of analysis, we isolate both in space and in time. System identification is developed in *Systems*, in the Practicing Physics Book.

You may want to assign an "Egg Drop" experiment. Students design and construct a case to hold an egg that can and will be dropped from a three-or-four story building without breaking. The design cannot include means to increase air resistance, so all cases should strike the ground with about the same speed. By requiring the masses of all cases to be the same, the impulses of all will be the same upon impact. The force of impact, of course, should be minimized by maximizing the time of impact. Or do as Peter Hopkinson does (Think and Explain 56), and simply have students toss eggs into cloth sheets, suspended so the eggs don't hit the floor after impact. Either of these projects stir considerable interest, both for your students and others who are not (yet?) taking your class.

In 2009 40-year old Paul Lewis from the UK survived a 10,000-foot skydiving fall after his parachute failed to open. Amazingly, he landed on the roof of an aircraft hanger that broke his fall and flexed sufficiently to reduce impact. That's a wonderful $Ft = \Delta mv$ in action!

An economy air track is available from Arbor Scientific (P4-2710).

Practicing Physics Book:
• Changing Momentum
• Systems

Problem Solving Book:
Many problems on impulse, momentum, and the impulse-momentum relationship

Laboratory Manual:
• Bouncy Board *Impact Time and Impact Force* (Activity)

Next-Time Questions include:
• Car Crash
• Ice Sail craft
• Ball Catch

Hewitt-Drew-It! Screencasts:
•*Momentum*
•*Conservation of Momentum*
•*Fish-Lunch Problem*
•*Freddy-Frog Momentum Problem*

This chapter is important in its own right, and serves as a foundation for the concept of energy in the next chapter.

SUGGESTED LECTURE PRESENTATION

Momentum

Begin by stating that there is something different between a Mack truck and a roller skate—they each have a different inertia. And that there is still something different about a moving Mack truck and a moving roller skate—they have different momenta. Define and discuss momentum as inertia in motion.

> CHECK QUESTION: After stating that a Mack truck will always have more inertia than an ordinary roller skate, ask if a Mack truck will always have more momentum than a roller skate. [Only when *mv* for the truck is greater than *mv* for the skate.]

Cite the case of the supertanker shown in Figure 6.2, and why such huge ships normally cut off their power when they are 25 or so kilometers from port. Because of their huge momentum (due mostly to their huge mass), about 25 kilometers of water resistance are needed to bring them to a halt.

Impulse and Momentum

Derive the impulse-momentum relationship. In Chapter 3 you defined acceleration as $a = \Delta v/t$ (really Δt, but you likely used t as the "time interval"). Then later in Chapter 4 you defined acceleration in terms of the force needed, $a = F/m$. Now simply equate; $a = a$, or $F/m = \Delta v/t$, with simple rearrangement you have, $Ft = \Delta mv$ (as in the footnote in the textbook on page 92).

Then choose your examples in careful sequence: First, those where the objective is to increase momentum—pulling a slingshot or arrow in a bow all the way back, the effect of a long cannon for maximum range, driving a golf ball. Second, those examples where small forces are the objective when decreasing momentum—pulling your hand backward when catching a ball, driving into a haystack versus a concrete wall, falling on a surface with give versus a rigid surface. Then lastly, those examples where the objective is to obtain large forces when deceasing momentum—karate. Karate is more properly called "tae kwon do."

Point of confusion: In boxing, one "follows-through" whereas in karate one "pulls back." But this is not so—a karate expert does not pull back upon striking his target. He or she strikes in such a way that the hand is made to *bounce* back, yielding up to twice the impulse to the target (just as a ball bouncing off a wall delivers nearly twice the impulse to the wall than if it stuck to the wall).

> CHECK QUESTION: Why is falling on a wooden floor in a roller rink less dangerous than falling on the concrete pavement? [Superficial answer: Because the wooden floor has more "give." Emphasize that this is the beginning of a fuller answer—one that is prompted if the question is reworded as follows:] Why is falling on a floor with more give less dangerous than falling on a floor with less give? [Answer: Because the floor with more give allows a greater time for the impulse that reduces the momentum of fall to zero. The greater time occurs because Δ*momentum* means less force.]

The loose coupling between railroad cars (Think and Discuss 88) makes good lecture topic. Discuss the importance of loose coupling in bringing a long train initially at rest up to speed, and its importance in braking the train as well. In effect the time factor in impulse is extended. The force needed to produce motion is therefore decreased.
(I compare this to taking course load in proper sequence, rather than all at once where for sure one's wheels would likely spin.)

Conservation of Momentum

Distinguish between external and internal forces and progress to the conservation of momentum. Show from the impulse-momentum equation that no change in momentum can occur in the absence of an external net force.

> DEMONSTRATION: Show momentum conservation with an air-track performance. Doing so can be the focus of your lecture presentation.

Defining Your System

Momentum is not conserved in a system that experiences an external net force. This is developed in *Systems* in the Practicing Physics book (next page, which is credited to Cedric Linder, the instructor profiled in Chapter 2). The momentum of a system is conserved only when no external impulse is exerted on the system. As the example of the girl jumping from the Earth's surface suggests, momentum is always conserved if you make your system big enough. Likewise when you jump up and down.
The momentum of the universe is without change.

The numerical example of lunchtime for the fish in Figure 6.17 should clarify the vector nature of momentum—particularly for the case of the fishes approaching each other. Going over this should be helpful—Think and Solve 35, and Think and Rank 42 on pages 104 and 105, for example. Vehicles, rather than fish, are treated similarly.

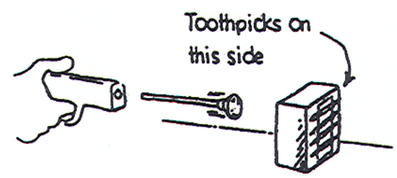
Bouncing

When discussing bouncing, tell how the inventor of the Pelton wheel, Lester Pelton, made a fortune from applying some simple physics to the old paddle wheels. Fortunately for him, he patented his ideas and was one of the greatest financial beneficiaries of the Gold Rush Era in San Francisco.

Bouncing does not necessarily increase impact force. That depends on impact time. Point out that bouncing involves some reversing of momentum, which means greater momentum change, and hence greater impulse. If the greater impulse is over an extended time (bouncing from a circus net), impact force is small. If over a short time (plant pot bouncing from your head), impact force is large. Damage from an object colliding with a person may depend more on energy transfer than on momentum change, so in some cases damage can be greater in an inelastic collision without bouncing.

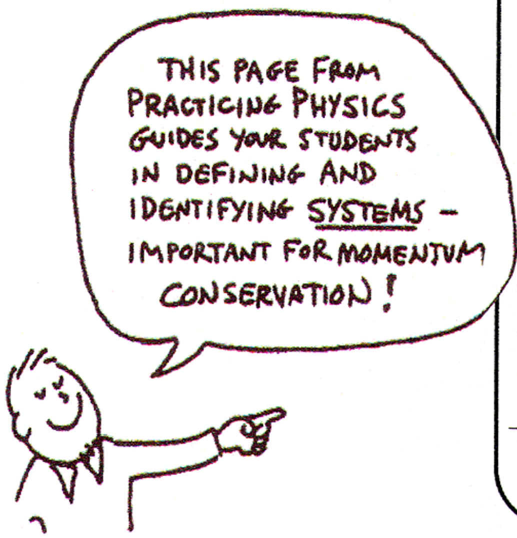
Consider the demo of swinging a dart against a wooden block, as Howie Brand does in the photo that opens this chapter, showing the effect of bouncing. A weak point of this demonstration is the fact that if the dart securely sticks to the block, then the center of gravity of the block is changed to favor non-tipping. This flaw is neatly circumvented by the following demo by Rich Langer of Beaumont High School in St. Louis, MO, which considers sliding rather than tipping.

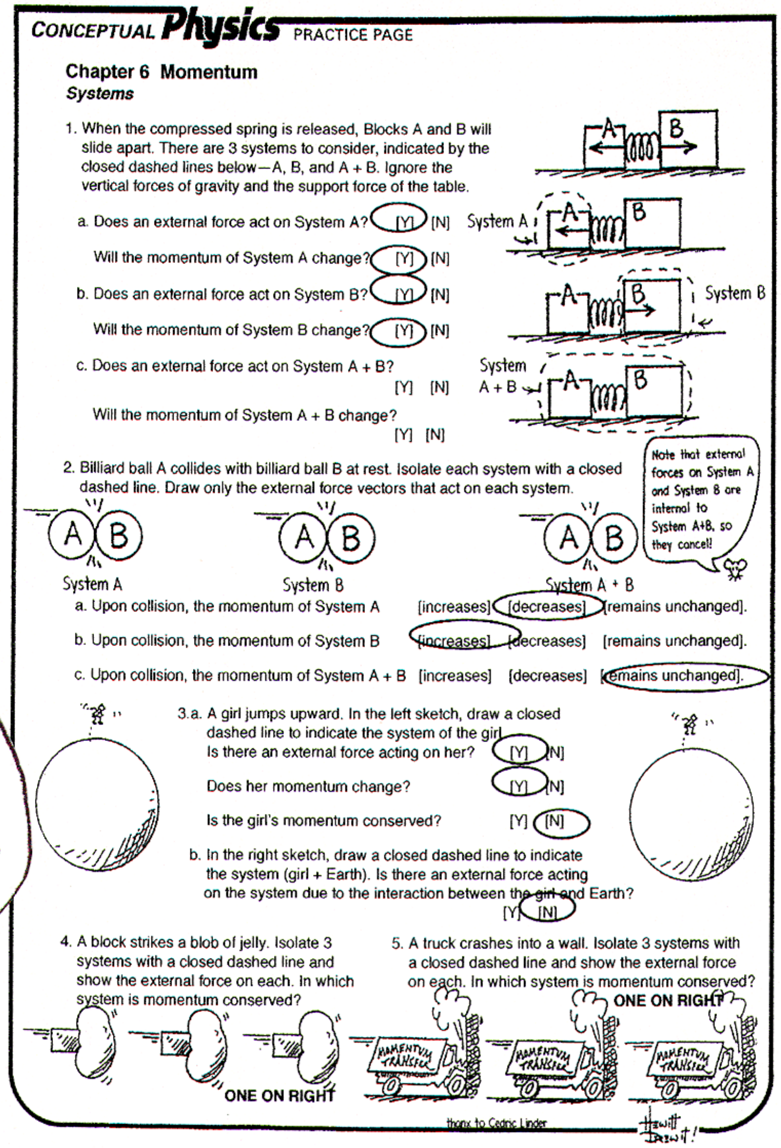
DEMONSTRATION: Toy dart gun and block of wood. Tape some toothpicks to only one side of the block, so a suction-cup dart won't stick to it. First fire the dart against the smooth side of the block. The dart sticks and the block slides an observed distance across the table. Then repeat, but with the block turned around so the dart hits the toothpick side. When the dart doesn't stick but instead bounces, note the appreciably greater distance the block slides!



Or do as Fred Bucheit does and fashion a pendulum using the "happy-unhappy" rubber balls and let them swing into an upright board. When the less-elastic ball makes impact, with very little bounce, the board remains upright. But when the more-elastic ball makes impact, it undergoes a greater change in momentum as it bounces. This imparts more impulse to the board, and it topples.

Think and Discuss 94-96 may need your elaboration if you wish to go this deep in your lecture. Simply removing the sail, as 94 suggests, is the option used by propeller-driven aircraft. Consider suddenly producing a sail in the airstream produced by the propeller of an airplane. The result would be a loss of thrust, and if bouncing of the air occurred, there would be a reverse thrust on the craft. This is precisely what happens in the case of jet planes landing on the runway. Metal "sails" move into place behind the engine in the path of the ejected exhaust, which cause the exhaust to reverse direction. The resulting reverse thrust appreciably slows the aircraft.





CONCEPTUAL **Physics** PRACTICE PAGE

Chapter 6 Momentum
Systems

1. When the compressed spring is released, Blocks A and B will slide apart. There are 3 systems to consider, indicated by the closed dashed lines below—A, B, and A + B. Ignore the vertical forces of gravity and the support force of the table.

   a. Does an external force act on System A? [Y] [N]

   Will the momentum of System A change? [Y] [N]

   b. Does an external force act on System B? [Y] [N]

   Will the momentum of System B change? [Y] [N]

   c. Does an external force act on System A + B? [Y] [N]

   Will the momentum of System A + B change? [Y] [N]

2. Billiard ball A collides with billiard ball B at rest. Isolate each system with a closed dashed line. Draw only the external force vectors that act on each system.

   a. Upon collision, the momentum of System A [increases] [decreases] [remains unchanged].

   b. Upon collision, the momentum of System B [increases] [decreases] [remains unchanged].

   c. Upon collision, the momentum of System A + B [increases] [decreases] [remains unchanged].

3.a. A girl jumps upward. In the left sketch, draw a closed dashed line to indicate the system of the girl.
   Is there an external force acting on her? [Y] [N]

   Does her momentum change? [Y] [N]

   Is the girl's momentum conserved? [Y] [N]

   b. In the right sketch, draw a closed dashed line to indicate the system (girl + Earth). Is there an external force acting on the system due to the interaction between the ~~girl and~~ Earth? [Y] [N]

4. A block strikes a blob of jelly. Isolate 3 systems with a closed dashed line and show the external force on each. In which system is momentum conserved?

   ONE ON RIGHT

5. A truck crashes into a wall. Isolate 3 systems with a closed dashed line and show the external force on each. In which system is momentum conserved?

   ONE ON RIGHT

thanx to Cedric Linder

Hewitt Drew it!

Answers and Solutions for Chapter 6

Reading Check Questions

1. The moving skateboard has more momentum since only it is moving.
2. Impulse is force x time, not merely force.
3. Impulse can be increased by increasing force or increasing time of application.
4. More speed is imparted because the force on the cannonball acts for a longer time.
5. The impulse-momentum relationship is derived from Newton's second law.
6. For greatest increase in momentum, use both the largest force for the longest time.
7. Less force will occur if momentum is decreased over a long time.
8. When the momentum of impact is quick, less time means more force.
9. By rolling with the punch, more time of impact occurs, which means a less forceful punch.
10. Choice (c) represents the greatest change in momentum.
11. Choice (c) also represents the greatest impulse.
12. Only external forces produce changes in momentum, so sitting in a car and pushing on the dash is an internal force, and no momentum change of the car occurs. Likewise with the internal forces within a baseball.
13. Yes, the statement is correct.
14. To say a quantity is conserved is to say its magnitude before an event is the same as its magnitude after the event. Momentum in a collision, for example is the same before and after providing no external forces act.
15. Momentum would not be conserved if force, and therefore impulse, was not a vector quantity.
16. Momentum is conserved in both an elastic and an inelastic collision.
17. Car B will have the speed of Car A before the collision.
18. After collision, the cars will move at half the initial speed of Car A.
19. Since they are same-magnitude vectors at right angles to each other, the combined momentum is $\sqrt{2}$ kg·m/s.
20. The total momentum before and after collision is the same, $\sqrt{2}$ kg·m/s.

Think and Do

21. Open ended.

Plug and Chug

22. Momentum (p) = mv = (8 kg)(2 m/s) = 16 kg·m/s.

23. $p = mv$ = (50 kg)(4 m/s) = 200 kg·m/s.

24. I = (10 N)(2.5 s) = 25 N·s.

25. I = (10 N)(5 s) = 50 N·s.

26. $I = \Delta mv$ = (8 kg)(2 m/s) = 16 kg·m/s = 16 N·s.

27. $I = \Delta mv$ = (50 kg)(4 m/s) = 200 kg·m/s = 200 N·s.

28. From $mv_{bef} + 0 = (m + m)v_{aft}$; $v_{aft} = mv_{bef}/2m = v_{bef}/2$ = (3 m/s)/2 = 1.5 m/s.

Think and Solve

29. The bowling ball has a momentum of (10 kg)(6 m/s) = 60 kg·m/s, which has the magnitude of the impulse to stop it. That's 60 N·s. (Note that units N·s = kg·m/s.)
30. From $Ft = \Delta mv$, $F = \dfrac{\Delta mv}{t}$ = [(1000 kg)(20 m/s)]/10 s = 2000 N.
31. From $Ft = \Delta mv$, $F = \dfrac{\Delta mv}{t}$ = [(75 kg)(25 m/s)]/0.1 s = 18,750 N.
32. From the conservation of momentum,

    Momentum$_{dog}$ = momentum$_{Judy + dog}$
    (15 kg)(3.0 m/s) = (40.0 kg + 15 kg)v
    45 kg m/s = (55 kg) v , so v = 0.8 m/s.

33. Momentum after collision is zero, which means the net momentum before collision must have been zero. So the 1-kg ball must be moving twice as fast as the 2-kg ball so that the magnitudes of their momenta are equal.

34. Let m be the mass of the freight car, and $4m$ the mass of the diesel engine, and v the speed after both have coupled together. Before collision, the total momentum is due only to the diesel engine, $4m$(5 km/h), because the momentum of the freight car is 0. After collision, the combined mass is $(4m + m)$, and combined momentum is $(4m + m)v$. By the conservation of momentum equation:

$\text{Momentum}_{\text{before}} = \text{momentum}_{\text{after}}$

$4m(5\text{ km/h}) + 0 = (4m + m)v$

$v = \dfrac{(20m\cdot\text{km/h})}{5m} = 4\text{ km/h}$

(Note that you don't have to know m to solve the problem.)

35. $\text{Momentum}_{\text{before}} = \text{momentum}_{\text{after}}$

$(5\text{ kg})(1\text{ m/s}) + (1\text{ kg})v = 0$

$5\text{ m/s} + v = 0$

$v = -5\text{ m/s}$

So if the little fish approaches the big fish at 5 m/s, the momentum after will be zero.

36. By momentum conservation,

asteroid mass × 800 m/s = Superman's mass × v.

Since asteroid's mass is 1000 times Superman's,

$(1000m)(800\text{ m/s}) = mv$

v = 800,000 m/s. This is nearly 2 million miles per hour!

37. Momentum conservation can be applied in both cases.

(a) For head-on motion the total momentum is zero, so the wreckage after collision is motionless.

(b) As shown in Figure 6.18, the total momentum is directed to the northeast—the resultant of two perpendicular vectors, each of magnitude 20,000 kg·m/s. It has magnitude 28,200 kg·m/s. The speed of the wreckage is this momentum divided by the total mass, v = (28,200 kg·m/s)/(2000 kg) = 14 m/s.

38. (a,b) From $Ft = \Delta p = mv \Rightarrow F = \dfrac{mv}{t} = \dfrac{(1\text{ kg})(2\text{ m/s})}{(0.2\text{s})} = 10\text{ kg}\cdot\text{m/s}^2 = 10\text{ N}$.

Think and Rank

39. a. B, D, C, A
    b. B, D, C, A
40. a. B=D, A=C
    b. D, C, A=B
41. a. A, B, C
    b. A, B, C
    c. C, B, A
    d. A, B, C
42. C, A, B

Think and Explain

43. The momentum of a supertanker is enormous, which means enormous impulses are needed for changing motion—which are produced by applying modest forces over long periods of time. Due to the force of water resistance, over time it coasts 25 kilometers to sufficiently reduce the momentum.

44. When you are brought to a halt in a moving car, an impulse, the product of force and time, reduces your momentum. During a collision, padded dashboards increase the time of impact while reducing the force of impact. The impulse equals your change in momentum.

45. Air bags lengthen the time of impact thereby reducing the force of impact.

46. The extra thickness extends the time during which momentum changes and reduces impact force.

47. Stretching ropes extend the time during which momentum decreases, thereby decreasing the jolting force of the rope. Note that bringing a person to a stop more gently does *not* reduce the impulse. It only reduces the force.

48. The steel cord will stretch only a little, resulting in a short time of stop and a correspondingly large force. Ouch!

49. Bent knees will allow more time for momentum to decrease, therefore reducing the force of landing.

50. The time during which the stopping force acts is different for the different situations. Stopping time is least on concrete and most on water, hence the different impact speeds. So there are three concepts; speed at impact, time of impact, and force of impact—which are all related by the impulse-momentum relationship.

51. An extended hands allow more time for reducing the momentum of the ball to zero, resulting in a smaller force of impact on your hand.

52. The time during which the ball stops is small, producing a greater force.

53. Crumpling allows more time for reducing the momentum of the car, resulting in a smaller force of impact on the occupants.

54. The blades impart a downward impulse to the air and produce a downward change in the momentum of the air. The air at the same time exerts an upward impulse on the blades, providing lift. (Newton's third law applies to impulses as well as forces.)

55. Its momentum is the same (its weight might change, but not its mass).

56. The egg hitting the sagging sheet has a longer impact time, which decreases the force that would otherwise break it.

57. The large momentum of the spurting water is met by a recoil that makes the hose difficult to hold, just as a shotgun is difficult to hold when it fires birdshot.

58. Not a good idea. The gun would recoil with a speed ten times the muzzle velocity. Firing such a gun in the conventional way would not be a good idea!

59. Impulse is force $\times$ time. The forces are equal and opposite, by Newton's third law, and the times are the same, so the impulses are equal and opposite.

60. The momentum of recoil of Earth is 10 kg m/s. Again, this is not apparent because the mass of the Earth is so enormous that its recoil velocity is imperceptible. (If the masses of Earth and person were equal, both would move at equal speeds in opposite directions.)

61. The momentum of the falling apple is transferred to the Earth. Interestingly, when the apple is released, the Earth and the apple move toward each other with equal and oppositely directed momenta. Because of the Earth's enormous mass, its motion is imperceptible. When the apple and Earth hit each other, their momenta are brought to a halt—zero, the same value as before.

62. There is usually greater speed and therefore impact on a catcher's mitt than the mitts of other players. That's why extra padding is used to prolong the time of the impulse to stop the ball and lessen the catching force.

63. The lighter gloves have less padding, and less ability to extend the time of impact, and therefore result in greater forces of impact for a given punch.

64. In jumping, you impart the same momentum to both you and the canoe. This means you jump from a canoe that is moving away from the dock, reducing your speed relative to the dock, so you don't jump as far as you expected to.

65. The swarm will have a net momentum of zero if the swarm stays in the same location; then the momenta of the many insects cancel and there is no net momentum in any given direction.

66. To get to shore, the person may throw keys, coins or an item of clothing. The momentum of what is thrown will be accompanied by the thrower's oppositely-directed momentum. In this way, one can recoil towards shore. (One can also inhale facing the shore and exhale facing away from the shore.)

67. If no momentum is imparted to the ball, no oppositely directed momentum will be imparted to the thrower. Going through the motions of throwing has no net effect. If at the beginning of the throw you begin recoiling backward, at the end of the throw when you stop the motion of your arm and hold onto the ball, you stop moving too. Your position may change a little, but you end up at rest. No momentum given to the ball means no recoil momentum gained by you.

68. Regarding Question 66: If one throws clothing, the force on the clothes will be paired with an equal and opposite force on the thrower. This force can provide recoil toward shore. Regarding Question 67: According to Newton's third law, whatever forces you exert on the ball, first in one direction, then in the other, are balanced by equal forces that the ball exerts on you. Since the forces on the ball give it no final momentum, the forces it exerts on you also give no final momentum.

69. Both recoiling carts have the same amount of momentum. So the cart with twice the mass will have half the speed of the less massive cart. That is, $2m(v/2) = mv$.

70. An impulse is responsible for the change in momentum, resulting from a component of gravitational force parallel to the inclined plane.

71. Momentum is not conserved for the ball itself because an impulse is exerted on it (gravitational force $\times$ time). So the ball gains momentum. Only in the *absence* of an external force does momentum not change. If the whole Earth and the rolling ball are taken together as a system, then the gravitational interaction between Earth and the ball are internal forces and no external impulse acts. Then the change of momentum of the ball is accompanied by an equal and opposite change of momentum of Earth, which results in no change in momentum.

72. A system is any object or collection of objects. Whatever momentum such a system has, in the absence of external forces, that momentum remains unchanged—what the conservation of momentum is about.

73. For the system comprised of only the ball, momentum changes, and is therefore not conserved. But for the larger system of ball + Earth, momentum is conserved for the impulses acting are internal impulses. The change of momentum of the ball is equal and opposite to the change of momentum of the recoiling Earth.

74. For the system comprised of ball + Earth, momentum is conserved for the impulses acting are internal impulses. The momentum of the falling apple is equal in magnitude to the momentum of the Earth toward the apple.

75. If the system is the stone only, its momentum certainly changes as it falls. If the system is enlarged to include the stone plus the Earth, then the downward momentum of the stone is cancelled by the equal but opposite momentum of the Earth "racing" up to meet the stone.

76. Yes, because you push upward on the ball you toss, which means the ball pushes downward on you, which is transmitted to the ground. So normal force increases as the ball is thrown (and goes back to equal mg after the ball is released). Likewise, in catching the ball you exert an upward force while stopping it, which is matched by a downward force by your feet on the ground, which increases the normal force.

77. By Newton's 3rd law, the force on the bug is equal in magnitude and opposite in direction to the force on the car windshield. The rest is logic: Since the time of impact is the same for both, the amount of impulse is the same for both, which means they both undergo the same change in momentum. The change in momentum of the bug is evident because of its large change in speed. The same change in momentum of the considerably more massive car is not evident, for the change in speed is correspondingly very small. Nevertheless, the magnitude of $m\Delta V$ for the bug is equal to $M\Delta v$ for the car!

78. In accord with Newton's third law, the forces on each are equal in magnitude, which means the impulses are likewise equal in magnitude, which means both undergo equal changes in momentum.

79. The magnitude of force, impulse, and change in momentum will be the same for each. The MiniCooper undergoes the greater deceleration because its mass is less.

80. Cars brought to a rapid halt experience a change in momentum, and a corresponding impulse. But greater momentum change occurs if the cars bounce, with correspondingly greater impulse and therefore greater damage. Less damage results if the cars stick upon impact than if they bounce apart.

81. The direction of momentum is to the left, for the momentum of the 0.8-kg car is greater. By magnitude, net momentum = (0.5)(1) – (0.8)(1.2) = -0.46.

82. The combined momentum is $\sqrt{2}$ times the magnitude of that of each cart before collision.

83. Momentum conservation is being violated. The momentum of the boat before the hero lands on it will be the same as the momentum of boat + hero after. The boat will slow down. If, for example, the masses of the hero and boat were the same, the boat should be slowed to half speed; $mv_{\text{before}} = 2m(v/2)_{\text{after}}$. From an impulse-momentum point of view, when the hero makes contact with the boat, he is moved along with the boat by a friction force between his feet and the boat surface. The equal and opposite friction force on the boat surface provides the impulse that slows the boat. (Here we consider only horizontal forces and horizontal component of momentum.)

84. Yes, you exert an impulse on a ball that you throw. You also exert an impulse on the ball when you catch it. Since you change its momentum by the same amount in both cases, the impulse you exert in both cases is the same. To catch the ball and then throw it back again at the same speed requires twice as much impulse. On a skateboard, you'd recoil and gain momentum when throwing the ball, you'd also gain the same momentum by catching the ball, and you'd gain twice the momentum if you did both—catch and then throw the ball at its initial speed in the opposite direction.

85. The impulse will be greater if the hand is made to bounce because there is a greater change in the momentum of hand and arm, accompanied by a greater impulse. The force exerted on the bricks is equal and opposite to the force of the bricks on the hand. Fortunately, the hand is resilient and toughened by long practice.

Think and Discuss

86. The impulse required to stop the heavy truck is considerably more than the impulse required to stop a skateboard moving with the same speed. The *force* required to stop either, however, depends on the time during which it is applied. Stopping the skateboard in a split second results in a certain force. Apply less than this amount of force on the moving truck and given enough time, the truck will come to a halt.

87. When a boxer hits his opponent, the opponent contributes to the impulse that changes the momentum of the punch. When punches miss, no impulse is supplied by the opponent—all effort that goes into reducing the momentum of the punches is supplied by the boxer himself. This tires the boxer. This is very evident to a boxer who can punch a heavy bag in the gym for hours and not tire, but who finds by contrast that a few minutes in the ring with an opponent is a tiring experience.

88. Without this slack, a locomotive might simply sit still and spin its wheels. The loose coupling enables a longer time for the entire train to gain momentum, requiring less force of the locomotive wheels against the track. In this way, the overall required impulse is broken into a series of smaller impulses. (This loose coupling can be very important for braking as well.)

89. The internal force of the brake brings the wheel to rest. But the wheel, after all, is attached to the tire which makes contact with the road surface. It is the force of the road on the tires that stops the car.

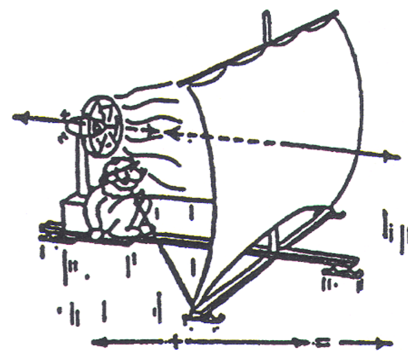
90. If the rocket and its exhaust gases are treated as a single system, the forces between rocket and exhaust gases are internal, and momentum in the rocket-gases system is conserved. So any momentum given to the gases is equal and opposite to momentum given to the rocket. A rocket attains momentum by giving momentum to the exhaust gases.

91. When two objects interact, the forces they exert on each other are equal and opposite and these forces act simultaneously, so the impulses are equal and opposite. Therefore their changes of momenta are equal and opposite, and the total change of momentum of both objects is zero.

92. Let the system be the car and the Earth together. As the car gains downward momentum during its fall, Earth gains equal upward momentum. When the car crashes and its momentum is reduced to zero, Earth stops its upward motion, also reducing its momentum to zero.

93. This exercise is similar to the previous one. If we consider Bronco to be the system, then a net force acts and momentum changes. In this case, momentum is not conserved. If, however we consider the system to be Bronco and the world (including the air), then all the forces that act are internal forces and momentum is conserved. Momentum is conserved only in systems not subject to external forces.

94. The craft moves to the right. This is because there are two horizontal impulses that act on the craft: One is that of the wind against the sail, and the other is that of the fan recoiling from the wind it produces. These impulses are oppositely directed, but are they equal in magnitude? No, because of bouncing. The wind bounces from the sail and produces a greater impulse than if it merely stopped. This greater impulse on the sail produces a net impulse in the forward direction, toward the right. We can see this in terms of forces as well. Note in the sketch there are two force pairs to consider: (1) the fan-air force pair, and (2) the air-sail force pair. Because of bouncing, the air-sail pair is greater. The net force on the craft is forward, to the right. The principle described here is applied in thrust reversers used to slow jet planes after they land. Also, you can see that after the fan is turned on, there is a net motion of air to the left, so the boat, to conserve momentum, will move to the right.



95. If the air is brought to a halt by the sail, then the impulse against the sail will be equal and opposite to the impulse on the fan. There will be no net impulse and no change in momentum. The boat will remain motionless. Bouncing counts!

96. Removing the sail and turning the fan around is the best means of propelling the boat! Then maximum impulse is exerted on the craft. If the fan is not turned around, the boat is propelled backward, to the left. (Such propeller-driven boats are used where the water is very shallow, as in the Florida Everglades.)

97. Bullets bouncing from the steel plate experience a greater impulse. The plate will be moved more by bouncing bullets than by bullets that stick.

98. In terms of force: When Freddy lands on the skateboard he is brought up to the skateboard's speed. This means a horizontal force provided by the board acts on Freddy. By action-reaction, Freddy exerts a force on the board in the opposite direction—which slows the skateboard. In terms of momentum conservation: Since no external forces act in the horizontal direction, the momentum after the skateboard catches Freddy is equal to the momentum before. Since mass is added, velocity must decrease.

99. Agree with the first friend because after the collision the bowling ball *will* have a greater momentum than the golf ball. Note that before collision the momentum of the system of two balls is all in the moving golf ball. Call this +1 unit. Then after collision the momentum of the rebounding golf ball is nearly –1 unit. The momentum (not the speed!) of the bowling ball will have to be nearly +2 units. Why? Because only then is momentum conserved. Momentum before is +1 unit: momentum after is (+2 – 1) = +1.

100. We assume the equal strengths of the astronauts means that each throws with the same speed. Since the masses are equal, when the first throws the second, both the first and second move away from each other at equal speeds. Say the thrown astronaut moves to the right with velocity V, and the first recoils with velocity $-V$. When the third makes the catch, both she and the second move to the right at velocity $V/2$ (twice the mass moving at half the speed, like the freight cars in Figure 6.14). When the third makes her throw, she recoils at velocity V (the same speed she imparts to the thrown astronaut) which is added to the $V/2$ she acquired in the catch. So her velocity is $V + V/2 = 3V/2$, to the right—too fast to stay in the game. Why? Because the velocity of the second astronaut is $V/2 - V = -V/2$, to the left—too slow to catch up with the first astronaut who is still moving at $-V$. The game is over. Both the first and the third got to throw the second astronaut only once!

101. Impulse is greater for reflection, which is in effect, bouncing. The vanes therefore recoil more from the silvered sides. The vanes in the sketch therefore rotate clockwise as viewed from above. (This rotation is superseded by a counter rotation when air is present, which is the case for most radiometers. The black surface absorbs radiation and is heated, which warms the nearby air. The surface is pushed away from the warmed air resulting in a recoil that spins the vanes counterclockwise.)

102. Their masses are the same; half speed for the coupled particles means equal masses for the colliding and the target particles. This is like the freight cars of equal mass that collide as shown in Figure 6.14.

103. If a ball does not hit straight on, then the target ball flies off at an angle (to the left, say) and has a component of momentum perpendicular to the ball's initial momentum. To offset this, the striking ball cannot be simply brought to rest, but must fly off in the other direction (say, the right). It will do this in such a way that its sideways component of momentum is equal and opposite to that of the target ball. This means the total sideways momentum is zero—what it was before collision. (Inspect Figure 6.19 and see how the sideways components of momentum cancel to zero.)

104. The chunks have equal and opposite momenta, with the smaller-mass chunk having greater speed ($mV = -Mv$).

7 Energy

Swedish physics teacher Christine Lindstrom heads the photo openers for this chapter, followed by Neil de Grasse Tyson, whose profile is in Chapter 30. I see Neil as the new Carl Sagan, both for his devotion to astrophysics, his keen wit, and the message he conveys about science to the public. Photo 3 is of friends who started a small physics products company in 1981, which I've watched grow since then. Today Vernier Software and Technology, based in Portland, is a major supplier of quality equipment for classroom and lab physics. Photo 4 is an impressive array of photovoltaic cells at Nellis Air Force Base near Las Vegas, NV, that supply about 25% of the Base's electrical needs. On days when air conditioning isn't needed, the panels supply 100% of the Base's needs. The panels were installed in just 26 weeks in 2007 by the SunPower Corporation. The system generates 14.2 megawatts and is the largest photovoltaic instillation in the U.S (though only the 25th largest in the world). Nearly all the bigger ones are in Spain. Germany, however leads the world in photovoltaic power, interestingly, not in the brightest part of sunshine reaching Earth. Germany also leads in wind turbine power, not the windiest part of the world. Citizen resolve is the explanation. Hooray for Germany and other parts of the world who take alternative energies seriously. Robots in space, of course, nicely feed on sunshine.

The profile on Emilie du Chatelet cites the controversy in England and continental Europe about the "oomph" of objects in contact. Emilie helped settle the controversy by distinguishing between momentum (v) and kinetic energy (v^2), an interesting story.

The section, Recyled Energy, on page 119 interestingly advocates using the thermal energy generated by power plants to heating homes and other buildings. New York City and Copenhagen are two cities that do this quite successfully. Rooftop energy is contrasted in Figures 7.24 and 7.25 where water and sunlight are successfully caught and employed. I have been advocating dry-rock geothermal power (Figure 7.26) for nearly every edition of Conceptual Physics, going back more than a quarter century. Why it hasn't come to the forefront puzzles me. Is the fact that there's no fuel to sell a factor? The Internet will provide the latest in which of the several power contenders rises to the occasion.

Not mentioned in the text are biofuels and the prospects for algae-based fuel oil. Algae can be grown on nonagricultural land, absorb carbon dioxide, and the oils they produce can be refined into conventional transportation fuels that can be distributed using existing infrastructures. Given that the energy market is $1 trillion a year globally, biofuels will likely be a substantial player.

Helen Yan, one of my proud teaching protégés, shows pulley systems in Figure 7.20 on page 121. Helen was my student before continuing physics at U.C. Berkeley and San Francisco State University. In addition to her "rocket-science" occupation at Lockheed Martin in Sunnyvale, CA, she teaches the same conceptual physics course at CCSF that she took from me many years ago.

Another protégé of mine is Tenny Lim, drawing a bow in Figure 7.10. Tenny is also a "rocket scientist" (Figure 7.5) and lead designer of the descent stage that lowered Curiosity onto the Martian surface in 2012 (her profile is in Chapter 10). David Willey points out that only about 60% to 75% of the PE of a drawn bow goes into the KE of an arrow, depending on the type of bow. The rest of the energy heats the bow. Similarly, only about 30% of the energy of firearms is transferred to the projectiles they fire. The rest heats the firearm. This poses a problem with sustained fire in machine guns, where the bore thermally expands so bullets no longer take the rifling and tip over and over in flight just as though they were fired from a smooth bore. Hence the water cooling for machine guns.

Practicing Physics Book:
• Work and Energy • Momentum and Energy
• Conservation of Energy • Energy and Momentum

Problem Solving Book:
Many problems on energy

Laboratory Manual:
• An Uphill Climb *Work on an Inclined Plane* (Experiment)
• The Fountain of Fizz *Physics in the Soda Pop Geyser* (Demonstration)
• Dropping the Ball *Conservation of Energy During Free Fall* (Experiment)

Next-Time Questions (in the Instructor Resource DVD):
• Bumpy Tracks • Ball Toss
• Roller Coaster • Cannonball
• Long Cannon •Falling Balls
•Skidding Distance •Oomph

Hewitt-Drew-It! Screencasts:
•*Work and Potential Energy* •*Potential and Kinetic Energy*
•*Work-Energy Theorem* •*Conservation of Energy*
•*Energy of Acrobats* •*Ballistic Pendulum*
•*Machines and Energy*

SUGGESTED LECTURE PRESENTATION

Begin by standing on a chair against a wall with an extended heavy pendulum bob held at the tip of your nose. Say nothing. Release the bob and let it swing out, then back to your nose. Don't flinch. Then comment on your confidence in physical laws and lead into a distinction between potential and kinetic energy. Point out where the bob is moving fastest it is lowest, and where it is highest it doesn't move at all. The bob transforms energy of motion to energy of position in cyclic fashion. Allow the pendulum to swing to-and-fro while you're talking. Its motion decays. Why? Then point out the transformation of energy from the moving bob to the molecules of air that are encountered, and to the molecules in the bending string or wire at the pivot point. The energy of the pendulum will end up as heat energy. I quip that on a very hot day, somebody, somewhere, is swinging a giant pendulum to-and-fro.

Work

Define work and compare it to impulse of the previous chapter. In both case, the effect of exerting a force on something depends on how long the force acts. In the previous chapter, how long was meant as time, and we spoke of impulse. In this chapter, how long is meant as distance, and we speak of work. Cite the examples of the drawn slingshot and the long barreled cannon, where the added length produces greater speed. We described this greater speed in terms of greater momentum. Now we describe this greater speed in terms of greater energy—that is, greater KE.

CHECK QUESTION: Is work done when a weightlifter (Figure 7.3) holds a barbell stationary above her head? [Yes and no. With each contraction of the weightlifter's heart, a force is exerted

through a distance on her blood and so does work on the blood. But this work is not done on the barbell.]

Work-Energy Theorem
When discussing whether or not work is done, be sure to specify *done on what*. If you push a stationary wall, you may be doing work on your muscles (that involve forces and distances in flexing), but you do no work *on the wall*. Key point: If work is done on something, then the energy of that something changes. Distinguish between the energy one expends in doing things, and the work that is actually done *on* something.

CHECK QUESTION: When a car slows down due to air resistance, does its KE decrease? [Most certainly!]

CHECK QUESTION: Which is greater, 1 joule or 1 newton? [Whoops! The comparison is silly, for they're units of completely different things—work and force.] An idea about the magnitude of 1 joule is that it's the work done in vertically lifting a quarter-pound hamburger with cheese (approximately 1 N) one meter.

Power
A watt of power is the work done in vertically lifting a quarter-pound hamburger with cheese (approximately 1 N) one meter in one second.

Potential Energy
Return to your pendulum: With the pendulum at equilibrium show how the force necessary to pull it sideways (which varies with the angle made by the string) is very small compared to the force necessary to lift it vertically (its weight). Point out that for equal elevations, the arced path is correspondingly longer than the vertical path—with the result that the product of the applied force and distance traveled—the work done—is the same for both cases. (Without overdoing it, this is a good place to let your students know about integral calculus—how calculus is required to add up the work segments that continuously increase in a nonlinear way.) Then discuss the work needed to elevate the ball in Figure 7.6.

CHECK QUESTIONS: Does a car hoisted for lubrication in a service station have PE? How much work will raise the car twice as high? Three times as high? How much more PE will it have in these cases?

You can give the example of dropping a bowling ball on your toe—first from a distance of a couple of centimeters above your toe, then to various distances up to 1 m. Each time, the bowling ball would do more work on your toe because it would transfer more gravitational potential energy when released.

Kinetic Energy
Relate force × distance = ΔKE to examples of pushing a car, and then to braking a car as treated in the text. You may do Problem 3 (about skidding distance as a function of speed) at this point.

To a close approximation, skidding force is independent of speed. Hence change in KE is approximately equal to change in skidding distance. When the car's brakes are applied, the car's kinetic energy is changed into internal energy in the brake pads, tire, and road as they become warmer.

You may or may not at this point preview future material by relating the idea of the KE of molecules and the idea of temperature. State that molecules in a substance having the same temperature have the same average KE. If the masses of the molecules are the same, then it follows that the speeds of the molecules are the same. But what if the masses are different, for example in a sample of gas composed of light and heavy molecules at the same temperature? Which molecules would move faster? (If you shook a container of billiard balls mixed with Ping-Pong balls so that both kinds of balls had the same kinetic energy, which would move faster in the container? If an elephant and a mouse run with the same kinetic energy, which means that both will do the same amount of work if bumping into the door of a barn, can you say which of the two is running faster?) You might consider the demonstration of inhaling helium and talking at this

point—particularly if you are not including the chapters on sound in your course design. Relate the higher temperature due to the faster moving helium molecules to the higher temperature in a bugle when faster moving air is blown through it.

Energy Conservation

Discuss Figures 7.9 and 7.11 and then return to your pendulum. Explain how the kinetic energy and hence, the speed of the bob at the bottom of its swing is equal to the speed it would have if dropped vertically through the same height.

> CHECK QUESTION: Refer to Figure 7.6 in "inclines" (a) and (b): How does the speed of the ball compare at ground level when released from equal elevations? [It is impressive that the speeds will be the same. The lesser acceleration down the sloped ramp is compensated by a longer time. But return to the situation and ask how the *times* to reach the bottom compare and be prepared for an incorrect response, "The same!" (NOT true!) Quip and ask if the colors and temperatures will also be the same. Straight-forward physics can be confusing enough!]

> DEMONSTRATION: Preview electricity and magnetism and bring out the horseshoe magnet hand-cranked generator that lights up the lamp shown ahead in photo 5 that opens Chapter 25 (Sheron Snyder producing light). Have student volunteers attest to the fact that more work is needed to turn the crank when the lamp is connected than when it is not. Then relate this to Think and Discuss 101 (about the car burning more fuel with lights on).

When gasoline combines with oxygen in a car's engine, the chemical potential energy stored in the fuel is converted mainly into molecular KE (thermal energy). Some of this energy in effect is transferred to the piston and some of this causes motion of the car.

We think of electric cars as something new. But they were more popular than gasoline-driven cars in the late 19th and early 20th century. They could go all day on a single charge and move a driver around a city with ease. They required no hand crank to start and had no gears to shift. But back then speed limits were set below 20 mph to accommodate horse-drawn carriages. After World War I these limits were lifted and gasoline powered cars began to dominate. Sooner of later when most cars go electric, we'll be going full-circle!

Go over the Check Yourself question about fuel economy on page 117—very important. (I pose the same question on my exams, which to the student is the *definition* of what's important!) This is a pre-hybrid question about cars. As a side point, gas economy is increased when tires are inflated to maximum pressures, where less flattening of the tire occurs as it turns. The very important point of this exercise is the upper limit possible.

I extend this idea of an upper limit to the supposed notion that certain gadgets attached to automobile engines will give phenomenal performance—so much in fact, (tongue in cheek) that the oil companies have gobbled up the patents and are keeping them off the market. Charlatans stand ready to benefit from this public perception, and offer the public a chance to invest in their energy producing machines. They prey on people who are ignorant of or do not understand the message of the energy conservation law. You can't get something for nothing. You can't even break-even, because of the inevitable transformation of available energy to heat. For more on such charlatans, read Bob Park's book, *Voodoo Science*.

Scams that sell energy-making machines rely on funding from deep pockets and shallow brains!

Solar Power

Government subsidies for solar power have made Europe the world's solar capitol. Even the first large solar plant in the U.S, Solar One in Nevada, belongs to Acciona, a Spanish company that generates electricity that it sells to NV Energy, the regional utility. Nevada One uses solar thermal, where sunlight is reflected onto long rows of pipes that make steam to run a 64-megawatt power plant. The mirrors were made in Germany.

Another method of getting electricity from sunshine is employed by SunCatchers, huge mirrors at Sandia National Labs in New Mexico that power Stirling engines held at the focal points of the arrays. Electricity is made by pistons in the engines. It is the most efficient system for converting photon energy to grid-ready AC power.

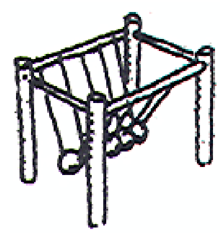
Nearly all big solar plants lack a storage system, a means of storing some of the heat produced during daylight hours for release when the Sun isn't shining. Check the commercial solar plant near Granada in Spain where sunlight from mirrors is used to heat molten salt. In the evening the salt cools and gives back heat to make steam. In this way, molten salt is used for storage. As the book mentions, energy can be stored in compressed air, which a plant in Alabama is using, and which has been used in Germany for decades. Another way is with batteries. With a storage system of one kind or another, electricity can be generated continuously on demand.

Solar photovoltaic panels are expensive to produce and normally provide efficiencies of 10 to 20%. Parabolic troughs that turn heat to steam get about 24%. Researchers can produce PV panels somewhat more than 40% efficient. Check the Internet for current information.

Efficiency
It should be enough that your students become acquainted with the idea of efficiency, so I don't recommend setting the plow too deep for this topic. The key idea to impart is that of useful energy. To say that an incandescent lamp is 10% efficient is to say that only 10% of the energy input is converted to the useful form of light. All the rest goes to heat. But even the light energy converts to heat upon absorption. So all the energy input to an incandescent lamp is converted to heat. This means that it is a 100% efficient *heater* (but not a 100% device for emitting light)! Much more efficient light sources are treated in Chapter 23 and 30 (CFLs and LEDs).

Dark Energy: Not discussed in the text is the current serious speculation of dark energy, which is postulated to be speeding up the expanding universe. You may want to discuss this current finding, which may be one of the most important discoveries in science in the past quarter century.

NEXT-TIME QUESTION: Think and Discuss 120, when you've shown the swinging ball apparatus, Newton's cradle, in class (available from Arbor Scientific. P1-6001.)



Answers and Solutions for Chapter 7

Reading Check Questions

1. Energy is most evident when it is changing.
2. Force multiplied by distance is work.
3. No work is done in pushing on a stationary wall, as in Figure 7.4.
4. It is the same, for the product of each is the same; (50 kg)(2 m) = (25 kg)(4 m).
5. Energy enables an object to do work.
6. The same power when both are raised in the same time; Twice the power for the lighter sack raised in half the time.
7. It would have twice because distance raised is twice.
8. Twice-as-massive car has twice the PE.
9. PE is significant when it changes, does work or transforms to energy of another form.
10. Four times as much (as $2^2 = 4$).
11. Four times as much work; 4 times as much stopping distance (as $2^2 = 4$).
12. ΔKE = work done = (100 N – 70 N)(10 m) = (30 N)(10 m) = 300 N·m = 300 J.
13. Speed has little or no effect on friction.
14. Its gain in KE will equal its decrease in PE, 10 kJ.
15. Immediately before hitting the ground its initial PE becomes KE. When it hits the ground its energy becomes thermal energy.
16. The source of the energy of sunshine is fusion power in the Sun.
17. Recycled energy is the reemployment of energy that otherwise would be wasted.
18. A machine can multiply input force or input distance, but NEVER input energy.
19. As force is increased, distance is decreased by the same factor.
20. The end moving 1/3 as far can exert 3 times the input force, 150 N.
21. Efficiency would be 100%.
22. Efficiency will be 60%.
23. The Sun is the source of these energies.
24. Radioactivity is the source of geothermal energy.
25. Like electricity, hydrogen is a carrier of energy, not a source. That’s because it takes energy to separate hydrogen from molecules.

Think and Do

26. The temperature of the sand is more after shaking than before. You do work on the sand in shaking it, which increases its temperature.

27. Some of the basketball’s energy is transferred to the tennis ball by compression. During decompressing, the basketball pushes the tennis ball upward, while the tennis ball pushes the basketball downward. So PE of the bounced basketball is less and PE of the tennis ball is more, but both add to equal the original PEs of the balls before dropped.

Plug and Chug

28. $W = Fd$ = (5 N)(1.2 m) = 6 N·m = 6 J.
29. $W = Fd$ = (2.0 N)(1.2 m) = 2.4 N·m = 2.4 J.
30. $W = Fd$ = (20 N)(3.5 m) = 70 N·m = 70 J.
31. $W = Fd$ = (500 N)(2.2 m) = 1100 N·m = 1100 J, which is also the gain in PE.
32. $P = W/t$ = (100 J)/(2 s) = 50 W.
33. $P = W/t = Fd/t$ = (500 N)(2.2 m)/(1.4 s) = 786 W.
34. PE = mgh = (3.0 kg)(10 N/kg)(2.0 m) = 60 N·m = 60 J.
35. PE = mgh = (1000 kg)(10 N/kg)(5 m) = 50,000 N·m = 50,000 J.
36. KE = $\frac{1}{2} mv^2$ = $\frac{1}{2}$(1.0 kg)(3.0 m/s)^2 = 4.5 kg(m/s)^2 = 4.5 J.
37. KE = $\frac{1}{2} mv^2$ = $\frac{1}{2}$(84 kg)(10 m/s)^2 = 4200 kg(m/s)^2 = 4200 J.
38. $W = \Delta$KE = $\Delta\frac{1}{2} mv^2$ = $\frac{1}{2}$(3.0 kg)(4.0 m/s)^2 = 24 J.
39. From $W = \Delta$KE, ΔKE = Fd = (5000 N)(500 m) = 2,500,000 J.
40. Efficiency = energy output/energy input x 100% = (40 J)/(100 J) = 0.40 or 40%

Think and Solve

41. Work = ΔE = Δmgh = 300 kg $\times$ 10 N/k $\times$ 6 m = **18,000 J**.

42. (a) You do $F \times d$ = 100 N × 10 m = 1000 J of work.
(b) Because of friction, net work on the crate is less. ΔKE = Net work = net force × distance = (100 N – 70 N)(10 m) = 300 J.
(c) So the rest, 700 J, goes into heating the crate and floor.

43. At three times the speed, it has 9 times (3^2) the KE and will skid 9 times as far—135 m. Since the frictional force is about the same in both cases, the distance has to be 9 times as great for 9 times as much work done by the pavement on the car.

44. PE + KE = Total E; KE = 10,000 J – 1000 J = 9000 J.

45. From $F \times d = F' \times d/4$, we see $F' = 4F$ = 200 N.

46. Your input work is 50 J, so 200-N × h = 50 J. h = 50/200 = 0.25 m.

47. $(F \times d)_{in} = (F \times d)_{out}$
$F \times$ 2 m = 5000 N × 0.2 m
F = [(5000 N)(0.2 m)]/2 m = **500 N**.

48. $(F \times d)_{in} = (F \times d)_{out}$
$(100\text{ N} \times 10\text{ cm})_{in} = (? \times 1\text{ cm})_{out}$
So we see that the output force and weight held is **1000 N** (less if efficiency < 100%).

49. Power = Fd/t = (50N)(8m)/(4s) = 100J/1s = 100 watts.

50. The initial PE of the banana is transformed to KE as it falls. When the banana is about to hit the water, all of its initial PE becomes KE.
From $PE_0 = KE_f \Rightarrow mgh = 1/2\, mv^2 \Rightarrow v^2 = 2gh \Rightarrow v = \sqrt{2gh}.$

Think and Rank

51. a. B, A, C
b. C, B, A
c. C, B, A
52. a. C, B=D, A
b. C, B=D, A
c. A, B=D, C
53. a. D, B, C, E, A
b. D, B, C, E, A
c. A, E, C, B, D
54. B=C, A (same as two supporting ropes)

Think and Explain

55. Stopping a lightly loaded truck of the same speed is easier because it has less KE and will therefore require less work to stop. (An answer in terms of impulse and momentum is also acceptable.)
56. You do no work because you haven't exerted more than a negligible force on the backpack in the direction of motion. Also, the energy of the backpack hasn't changed. No change in energy means no work done.

57. Your friend does twice as much work ($4 \times {}^1/2 > 1 \times 1$).

58. Although no work is done on the wall, work is nevertheless done on internal parts of your body (which generate heat).

59. More force is required to stretch the strong spring, so more work is done in stretching it the same distance as a weaker spring.

60. Work done by each is the same, for they reach the same height. The one who climbs in 30 s uses more power because work is done in a shorter time.

61. The PE of the drawn bow as calculated would be an overestimate (in fact, about twice its actual value) because the force applied in drawing the bow begins at zero and increases to its maximum value when fully drawn. It's easy to see that less force and therefore less work is required to draw the bow halfway than to draw it the second half of the way to its fully-drawn position. So the work done is not *maximum force* × *distance drawn*, but *average force* × *distance drawn*. In this case where force varies almost directly with distance (and not as the square or some other complicated factor) the average force is simply equal to the initial force + final force, divided by 2. So the PE is equal to the average force applied (which would be approximately half the force at its full-drawn position) multiplied by the distance through which the arrow is drawn.

62. When a rifle with a long barrel is fired, more work is done as the bullet is pushed through the longer distance. A greater KE is the result of the greater work, so of course, the bullet emerges with a greater velocity. (Note that the force acting on the bullet is not constant, but decreases with increasing distance inside the barrel.)

63. Agree, because speed itself is relative to the frame of reference (Chapter 3). Hence $\frac{1}{2}mv^2$ is also relative to a frame of reference.

64. The KE of the tossed ball relative to occupants in the airplane does not depend on the speed of the airplane. The KE of the ball relative to observers on the ground below, however, is a different matter. KE, like velocity, is relative.

65. You're both correct, with respect to the frames of reference you're inferring. KE is relative. From your frame of reference she has considerable KE for she has a great speed. But from her frame of reference her speed is zero and KE also zero.

66. The energy goes mostly into frictional heating of the air.

67. Without the use of a pole, the KE of running horizontally cannot easily be transformed to gravitational PE. But bending a pole stores elastic PE in the pole, which *can* be transformed to gravitational PE. Hence the greater heights reached by vaulters with very elastic poles.

68. The KE of a pendulum bob is maximum where it moves fastest, at the lowest point; PE is maximum at the uppermost points. When the pendulum bob swings by the point that marks half its maximum height, it has half its maximum KE, and its PE is halfway between its minimum and maximum values. If we define PE = 0 at the bottom of the swing, the place where KE is half its maximum value is also the place where PE is half its maximum value, and KE = PE at this point. (By energy conservation: Total energy = KE + PE.)

69. If the ball is given an initial KE, it will return to its starting position with that KE (moving in the other direction!) and hit the instructor. (The usual classroom procedure is to release the ball from the nose at rest. Then when it returns it will have no KE and will stop short of bumping the nose.)

70. Yes to both, relative to Earth, because work was done to lift it in Earth's gravitational field and to impart speed to it.

71. In accord with the theorem, once moving, no work is done on the satellite (because the gravitational force has no component parallel to motion), so no change in energy occurs. Hence the satellite cruises at a constant speed.

72. According to the work-energy theorem, twice the speed corresponds to 4 times the energy, and therefore 4 times the driving distance. At 3 times the speed, driving distance is 9 times as much.

73. The answers to both (a) and (b) are the same: When the direction of the force is perpendicular to the direction of motion, as is the force of gravity on both the bowling ball on the alley and the satellite in circular orbit, there is no force component in, or parallel to, the direction of motion and no work is done by the force.

74. On the hill there is a component of gravitational force parallel to the car's motion. This component of force does work on the car. But on the level, there is no component of gravitational force parallel to the direction of the car's motion, so the force of gravity does no work in this case.

75. The string tension is everywhere perpendicular to the bob's direction of motion, which means there is no component of tension parallel to the bob's path, and therefore no work done by the tension. The force of gravity, on the other hand, has a component parallel to the direction of motion everywhere except at the bottom of the swing, and does work, which changes the bob's KE.

76. The fact that the crate pulls back on the rope in action-reaction fashion is irrelevant. The work done on the crate by the rope is the horizontal component of rope force that acts on the crate multiplied by the distance the crate is moved by that force—period. How much of this work produces KE or thermal energy depends on the amount of friction acting.

77. The 100 J of potential energy that doesn't go into increasing her kinetic energy goes into thermal energy—heating her bottom and the slide.

78. A Superball will bounce higher than its original height if thrown downward, but if simply dropped, no way. Such would violate the conservation of energy.

79. When a Superball hits the floor some of its energy is transformed to heat. This means it will have less kinetic energy after the bounce than just before and will not reach its original level.

80. Kinetic energy is a maximum as soon as the ball leaves the hand. Potential energy is a maximum when the ball has reached its highest point.

81. The design is impractical. Note that the summit of each hill on the roller coaster is the same height, so the PE of the car at the top of each hill would be the same. If no energy were spent in overcoming friction, the car would get to the second summit with as much energy as it starts with. But in practice there is considerable friction, and the car would not roll to its initial height and have the same energy. So the maximum height of succeeding summits should be lower to compensate for friction.

82. You agree with your second classmate. The coaster could just as well encounter a low summit before or after a higher one, so long as the higher one is enough lower than the initial summit to compensate for energy dissipation by friction.

83. Sufficient work occurs because with each pump of the jack handle, the force she exerts acts over a much greater distance than the car is raised. A small force acting over a long distance can do significant work.

84. Einstein's $E = mc^2$. (More on this in Chapters 34 and 35).

85. When the mass is doubled with no change in speed, both momentum and KE are doubled.

86. When the velocity is doubled, the momentum is doubled and the KE is increased by a factor of four. Momentum is proportional to speed, KE to speed squared.

87. Both have the same momentum, but the faster 1-kg one has the greater KE.

88. The momentum of the car is equal in magnitude but opposite in direction in the two cases—not the same since momentum is a vector quantity.

89. Zero KE means zero speed, so momentum is also zero.

90. Yes, if we're talking about only you, which would mean your speed is zero. But a system of two or more objects can have zero net momentum, yet have substantial total KE.

91. Not at all. For two objects of the same KE, the one of greater mass has greater momentum. (The mathematical relationship is $p^2 = 2m \times \text{KE}$.)

92. Net momentum before the lumps collide is zero and after collision is zero. Momentum is indeed conserved. Kinetic energy after is zero, but was greater than zero before collision. The lumps are warmer after colliding because the initial kinetic energy of the lumps transforms into thermal energy. Momentum has only one form. There is no way to "transform" momentum from one form to another, so

it is conserved. But energy comes in various forms and can easily be transformed. No single form of energy such as KE need be conserved.

93. Scissors and shears are levers. The applied force is normally exerted over a short distance for scissors so that the output force is exerted over a relatively long distance (except when you want a large cutting force like cutting a piece of tough rope, and you place the rope close to the "fulcrum" so you can multiply force). With metal-cutting shears, the handles are long so that a relatively small input force is exerted over a long distance to produce a large output force over a short distance.

94. Energy is transformed into nonuseful forms in an inefficient machine, and is "lost" only in the loose sense of the word. In the strict sense, it can be accounted for and is therefore not lost.

95. An engine that is 100% efficient would not be warm to the touch, nor would its exhaust heat the air, nor would it make any noise, nor would it vibrate. This is because all these are transfers of energy, which cannot happen if all the energy given to the engine is transformed to useful work. (Actually, an engine of 100% efficiency is not even possible in principle. We discuss this in Chapter 18.)

96. Your friend is correct, for changing KE requires work, which means more fuel consumption and decreased air quality.

97. In accord with energy conservation, a person who takes in more energy than is expended stores what's left over as added chemical energy in the body—which in practice means more fat. One who expends more energy than is taken in gets extra energy by "burning" body fat. An undernourished person who performs extra work does so by consuming stored chemical energy in the body—something that cannot long occur without losing health—and life.

Think and Discuss

98. Once used, energy cannot be regenerated, for it dissipates into less useful forms in the environment—inconsistent with the term "renewable energy." Renewable energy refers to energy derived from renewable resources—trees, for example.

99. As world population continues to increase, energy production must also increase to provide decent standards of living. Without peace, cooperation, and security, global-scale energy production likely decreases rather than increases.

100. Both will have the same speed. This is easier to see here because both balls convert the same PE to KE. (Think energy when solving motion problems!)

101. Yes, a car burns more gasoline when its lights are on. The overall consumption of gasoline does not depend on whether or not the engine is running. Lights and other devices are run off the battery, which "runs down" the battery. The energy used to recharge the battery ultimately comes from the gasoline.

102. Except for the very center of the plane, the force of gravity acts at an angle to the plane, with a component of gravitational force along the plane—along the block's path. Hence the block goes somewhat against gravity when moving away from the central position, and moves somewhat with gravity when coming back. As the object slides farther out on the plane, it is effectively traveling "upward" against Earth's gravity, and slows down. It finally comes to rest and then slides back and the process repeats itself. The block slides back and forth along the plane. From a flat-Earth point of view the situation is equivalent to that shown in the sketch.

103. Solar energy is merely energy from the Sun. Solar power, like power in general, is the *rate* at which energy is transferred. Solar power is therefore the same from hour to hour, whereas the amount of solar energy depends on the amount of time energy is transferred.

104. If KEs are the same but masses differ, then the ball with smaller mass has the greater speed. That is, $^1/2\, Mv^2 = {}^1/2\, mV^2$. Likewise with molecules, where lighter ones move faster on the average than more massive ones. (We will see in Chapter 15 that temperature is a measure of average molecular KE—lighter molecules in a gas move faster than same-temperature heavier molecules.)

105. A car with windows open experiences more air drag, which causes more fuel to be burned in maintaining motion. This may more than offset the saving from turning off the air conditioner.

106. A machine can multiply force or multiply distance, both of which can be of value.

107. Your friend may not realize that mass itself is congealed energy, so you tell your friend that much more energy in its congealed form is put into the reactor than is taken out from the reactor. About 1% of the mass that undergoes fission is converted to energy of other forms.

108. The work that the rock does on the ground is equal to its PE before being dropped, mgh = 100 joules. The force of impact, however, depends on the distance that the rock penetrates into the ground. If we do not know this distance we cannot calculate the force. (If we knew the time during which the impulse occurs we could calculate the force from the impulse-momentum relationship—but not knowing the distance or time of the rock's penetration into the ground, we cannot calculate the force.)

109. When we speak of work done, we must understand work done *on what, by what*. Work is done on the car by applied forces that originate in the engine. The work done by the road in reacting to the backward push of the tires is equal to the product of the applied force and the distance moved, not the *net* force that involves air resistance and other friction forces. When doing work, we think of applied force; when considering acceleration, we think of net force. Actually, the frictional forces of the internal mechanisms in the car, and to some extent the road itself are doing negative work on the car. The zero total work explains why the car's speed doesn't change.

110. When air resistance is a factor, the ball will return with less speed (as discussed in Chapter 4). It therefore will have less KE. You can see this directly from the fact that the ball loses mechanical energy to the air molecules it encounters, so when it returns to its starting point and to its original PE, it will have less KE. This does not contradict energy conservation, for energy is transformed, not destroyed.

111. The ball strikes the ground with the *same* speed, whether thrown upward or downward. The ball starts with the same energy at the same place, so they will have the same energy when they reach the ground. This means they will strike with the same speed. This is assuming negligible air resistance, for if air resistance is a factor, then the ball thrown upward will lose more energy to the air in its longer path and strike with somewhat less speed. Another way to look at this is to consider Figure 3.8 back on page 50; in the absence of air resistance, the ball thrown upward will return to its starting level with the same speed as the ball thrown downward. Both hit the ground at the same speed (but at different *times*).

112. Tension in the string supporting the 10-kg block is 100 N (which is the same all along the string). So Block B is supported by two strands of string, each 100 N, which means the mass of Block B is twice that of Block A. So Block B has a mass of 20 kg.

113. The other 15 horsepower is supplied by electric energy from the batteries (which are ultimately recharged using energy from gasoline).

114. In a conventional car, braking converts KE to heat. In a hybrid car, braking charges up the batteries. In this way, braking energy can soon be transformed to KE.

115. The question can be restated; Is $(30^2 - 20^2)$ greater or less than $(20^2 - 10^2)$? We see that $(30^2 - 20^2)$ = (900 - 400) = 500, which is considerably greater than $(20^2 - 10^2)$ = (400 - 100) = 300. So KE changes more for a given Δv at the higher speed.

116. If an object has KE, then it must have momentum—for it is moving. But it can have potential energy without being in motion, and therefore without having momentum. And every object has "energy of being"—stated in the celebrated equation $E = mc^2$. So whether an object moves or not, it has some form of energy. If it has KE, then with respect to the frame of reference in which its KE is measured, it also has momentum.

117. (a) In accord with Newton's second law, the component of gravitational force that is parallel to the incline in B produces an acceleration parallel to the incline. (b) In accord with the work-energy theorem, that parallel force component multiplied by the distance the ball travels is equal to the change in the ball's KE.

118. The physics here is similar to that of the ball on the horizontal alley in the previous problem. (a) Tension in the string is everywhere perpendicular to the arc of the pendulum, with no component of tension force parallel to its motion. (b) In the case of gravity, a component of gravitational force on the pendulum exists parallel to the arc, which does work and changes the KE of the pendulum. (c) When the pendulum is at its lowest point, however, there is no component of gravitational force parallel to motion. At that instant of motion, gravity does no work (as it doesn't when the pendulum hangs at rest when the sting is vertical).

119. This is very similar to the previous two problems. In circular orbit, the force of gravity is everywhere perpendicular to the satellite's motion. With no component of force parallel to its motion, no work is done and its KE remains constant.

120. There is more to the "swinging balls" problem than momentum conservation, which is why the problem wasn't posed in the previous chapter. Momentum is certainly conserved if two balls strike with momentum $2mv$ and one ball pops out with momentum $m(2v)$. That is, $2mv = m2v$. We must also consider KE. Two balls would strike with $2(^1/2\ mv^2) = mv^2$. The single ball popping out with twice the speed would carry away twice as much energy as was put in:
$^1/2\ m(2v)^2 = {}^1/2\ m(4\ v^2) = 2mv^2$. So popping out with twice its initial energy is clearly a conservation of energy no-no!

121. In the popular sense, conserving energy means not wasting energy. In the physics sense energy conservation refers to a law of nature that underlies natural processes. Although energy can be wasted (which really means transforming it from a more useful to a less useful form), it cannot be destroyed. Nor can it be created. Energy is transferred or transformed, without gain or loss. That's what a physicist means in saying energy is conserved.

122. The rate at which energy can be supplied is more central to consumers than the amount of energy that may be available, so "power crisis" more accurately describes a short-term situation where demand exceeds supply. (In the long term, the world may be facing an energy crisis when supplies of fuel are insufficient to meet demand.)

8 Rotational Motion

The photo openers credit four influential educators: Paul Stokstad, the founder of Pasco, a supplier of high-quality physics apparatus, Jacque Fresco, my original inspiration guiding me to physics (who is featured in this chapter's personality profile), late friend Mary Beth Monroe, who was very active in the organization AAPT (American Association of Physics Teachers), and CCSF physics instructor Diana Lininger Markham.

It is often said that rotational motion is analogous to linear motion and therefore should not be difficult to learn. Really? Consider the numerous distinctions between motions that are (1) linear, (2) rotational, (3) revolutional, (4) radial, (5) tangential, and (6) angular. I remember as a student being told that rotational motion would be easy to learn since it is an extension of linear motion. But alas, at that time my grasp of linear motion was anything but a secure foundation. Many students are still grappling with speed, velocity, and acceleration. And we have centripetal and centrifugal forces, real and fictitious, not to mention torques. So there is a myriad of ideas and material to understand in this chapter. Is it any wonder why students find rotational motion a steep hill to climb? Since a study of rotational motion is considerably more complex than a study of linear motion, caution your students to be patient with themselves if they don't immediately comprehend what has taken centuries to master. To keep coverage manageable, the chapter does not treat rotational kinetic energy.

One of the most intriguing examples of $v = r\omega$ is the beveled shape of railroad wheels. A train is able to round a corner in the same way a tapered glass rolls in a circle along a tabletop. Or the way a person with one leg shorter than the other tends to walk in a circle when lost in the woods. This is the feature of the box Wheels on Railroad Trains. Fascinating, especially when demonstrated with a pair of tapered cups taped at their wide ends that roll along a pair of metersticks. At CCSF, Will Maynez built a beautiful "roller coaster" along which a set of tapered wheels faithfully follow the curved track. Most impressive!

Martha Lietz at Niles West High School does a nice activity with torques. She places the ends of a board on two bathroom scales and sets the scales to zero. Then she challenges her students to calculate where a person of a given weight should stand on the board so one scale would read 75 pounds. The scale displays are covered when students do this, until they think they are in the proper position. Whole-body physics!

Although torques is a vector quantity, I don't emphasize it in this chapter. For example I omit entirely the "right hand rule," where fingers of the right hand represent the motion of a rotating body and the thumb represents the positive vector of motion. I have always felt that the reason for this and other hand rules in introductory physics courses has been to provide some instructors the opportunity to write tricky exam questions. Wisdom in general, and in physics teaching, is knowing what can be overlooked. I suggest you overlook the vector nature of torque, which continuing students can get into in a follow-up course.

A nice activity for demonstrating centripetal force was introduced to me by physics teacher Howie Brand: Have a small group of students around a small table (ideally circular) blow air through straws at a Ping-Pong

ball so that it will move in a circular path. They will experience the fact that the ball must be blown radially inward.

Rotation often involves what is called the Coriolis effect. As the name implies, it is an effect and not a force. It occurs only in situations involving rotation. Our Earth rotates. A cannon fired northward from the equator has a horizontal component of velocity equal to the tangential speed of the rotating Earth at that point. But it lands at a location far enough north where Earth's tangential speed is less. Hence it misses the true-north target. Likewise firing from any latitude to another. It "seems" as if the shell were deflected by some force. Toss a ball from a rotating carousel and you'll see the ball deflect from a straight-line path. But a non-rotating observer sees the path as straight. The effect is dramatic with winds that tend to flow *around* regions of high and low pressure, running parallel to the lines of constant pressure on a weather map (isobars), instead of flowing in a direct path. In the Northern Hemisphere, air flowing radially inward across the isobars toward the low pressure deflects to the right. In the Southern Hemisphere, the deflection is to the left.

A common misconception is that water flowing down a drain turns in one direction in the Northern hemisphere and in the opposite direction in the Southern Hemisphere. This is not so in something as small as a kitchen sink. But yes for larger parcels of air. The Coriolis force that is strong enough to direct winds of hurricanes when acting over hundreds of miles, is far too weak to stir a small bowl of water as it runs down a drain. To say it does is to say that one side of the bowl is moving at a different speed relative to Earth's axis than the other side. It does. But how much? That's the amount of your Coriolis force.

The classic oldie but goodie PSSC film, "Frames of Reference" goes well with this chapter.

This chapter can be skipped or skimmed if a short treatment of mechanics is desired. Note that this chapter has more figures than any in the book—54 of them.

Practicing Physics Book:
• Torques
• Torques and Rotation
• Acceleration and Circular Motion
• The Flying Pig
• Banked Airplanes
• Banked Track
• Leaning On
• Simulated Gravity and Frames of Reference

Problem Solving Book:
Many problems with a bit of trigonometry are employed.

Laboratory Manual:
• Twin-Baton Paradox A Puzzle, With a *Twist* (Activity)
• It's All in the Wrist *Experiencing Torque "Firsthand"* (Activity)
• Will it Go Round in Circles? *Accelerating at Constant Speed* (Demonstration)
• Sit On It and Rotate *Take Physics for a Spin* (Activity)

Next-Time Questions (in the Instructor Resource DVD):
• Falling Metersticks • Woman on the Plank • Trucks on a Hill • Tether Ball • Rotating Disk
• Kagan Roll • Wrench Pull • Two Spheres • Rolling Cans • Can Spurt • Berry Shake • Normal Forces
• Broom Balance • Centrifugal Force • Skateboard Lift • Post Wrap

Hewitt-Drew-It! Screencasts:
•*Circular Motion* •*RR Wheels* •*Centripetal Force* •*Centrifugal Force* •*Torque* •*Balanced Torques*
•*Torques on a Plank* •*Skateboard Torques* •*Angular Momentum*

The suggested lecture should take two or three class periods.

SUGGESTED LECTURE PRESENTATION

Cite the difference between rotational and linear speed—examples of riding at various radial positions on a merry-go-round, or the various speeds of different parts of a rotating turntable. A couple of coins on a turntable, one close to the axis and the other near the edge, dramatically show the greater speed of the outer one. Cite the motion of "tail-end Charlie" at the skating rink.

Circular Motion

Only for a rigid rotating system such as a solid turntable or a stiff spoke does the equation $v = r\omega$ apply—the greater the distance from the axis of rotation, the greater the linear speed. Don't be surprised to find students applying this relationship to a nonrigid system, such as a system of planets. They are confused about Mercury, which orbits relatively fast about the Sun, and Neptune, which orbits very slow. Horses running around a circular track obey $v = r\omega$ only if they are constrained, like joined by a giant nonflexible spoke.

Railroad Train Wheels (RR Wheels)

A fascinating application of $v = r\omega$ is presented in the box on railroad train wheels. Fasten a pair of cups with wide ends connected, and with small ends connected, and roll them along a pair of metersticks. Very impressive! That's my niece, Professor Cathy Candler, in Figure 8.8. The screencast on RR Wheels nicely ties together the taper of cups with the taper of the rims of RR wheels.

Side point: Toilet tissue rolls are smaller in diameter than rolls of toilet tissue years ago. Since more tissue makes a complete circle on the outer part of the roll, decreasing the diameter only slightly means appreciably less tissue per roll.

While we're on the subject of circles, you might ask why manhole covers are round (asked in the Check Point on page 138 of the textbook). The answer is so that some moron type doesn't drop them accidentally into the manhole. If they were square, they could be tipped up on edge and dropped through the hole on the diagonal. Similarly with ovals. But a circular hole will defy the most determined efforts. Of course there is a lip around the inside of the manhole that cover rests on, making the diameter of the hole somewhat less than the diameter of the cover.

Rotational Inertia

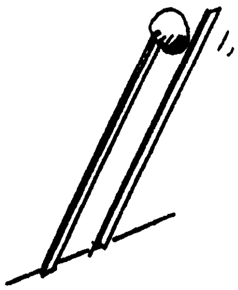
Compare the idea of inertia and its role in linear motion to rotational inertia (moment of inertia) in rotational motion. The difference between the two involves the role of *distance* from a rotational axis. The greater the distance of mass concentration, the greater the resistance to rotation. Discuss the role of the pole for the tightrope walker in Figure 8.10. A novice tightrope walker might begin with the ends of the pole in supporting slots, similar to the training wheels on a beginner's bicycle. If the pole has adequate rotational inertia, the slots mainly provide psychological comfort as well as actual safety. Just as the training wheels could be safely removed without the rider's knowledge, the slots could be safely removed without the walker's knowledge.

Show how a longer pendulum has a greater period and relate this to the different strides of long and short-legged people. Imitate these strides yourself—or at least with your fingers walking across the desk.

> DEMONSTRATION: This is a good one. Have two 1 meter pipes, one with two lead plugs in the center, the other with plugs in each end. They appear identical. Weigh both to show the same weight. Give one to a student (with plugs in ends) and ask her to rotate it about its center (like in Figure 8.9). Have another student do the same with the pipe that has the plugs in the middle. Then have them switch. Good fun. Then ask for speculations as to why one was noticeably more difficult to rotate than the other.

> DEMONSTRATION: As in Check Point 1 on page 138, have students try to balance on a finger a long stick with a massive lead weight at one end. Try it first with the weight at the fingertip, then with the weight at the top. Or you can use a broom, or long-handled hammer. Relate this to the ease with which a circus performer balances a pole full of people doing acrobatics, and cite how much more difficult it would be for the performer to balance an empty pole!

Also relate this demonstration and the continued adjustments you have to execute to keep the object balanced to the similar adjustments that must be made in keeping a rocket vertical when it is first fired. Amazing! As Tenny Lim and Mark Clark demonstrate in Figure 8.35, the Segway Transporter employs the same physics. The Segway behaves as we do—when it leans forward it increases its speed to keep its CG above a point of support.

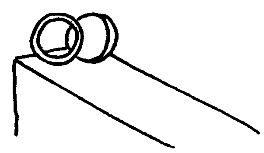


DEMONSTRATION (As in Check Point 2 on page 138): Fasten a mass to the end of a meterstick. A blob of clay works fine. Set it on end on your lecture table, along with another meterstick with no attached mass. When you let go of the sticks, they'll topple to the tabletop. Ask which stick will reach the tabletop first. [The plain stick wins due to the greater rotational inertia of the clay-top stick. There is more to this than simply greater rotational inertia, for torque is increased as well. If the clay is located at the middle of the stick, the effects of greater torque and greater rotational inertia balance each other and both sticks fall together.]

Discuss the variety of rotational inertias shown in Figure 8.15. Stress the formulas are for comparison, and point out why the same formula applies to the pendulum and the hoop (all the mass of each is at the same distance from the rotational axis). State how reasonable the smaller value is for a solid disk, given that much of its mass is close to the rotational axis.

The rotational inertia of a thin-walled hollow sphere, missing from the drawings in Figure 8.15, is given by Sanjay Rebello in Figure 8.16. Sanjay was an enormous help in developing the PowerPoint presentations of Conceptual Physics. Thanx Sanjay!

DEMONSTRATION: Place a hoop and disk at the top of an incline and ask which will have the greater acceleration down the incline. Do not release the hoop and disk until students have discussed this with their neighbors. Try other shapes after your class makes reasoned estimates.



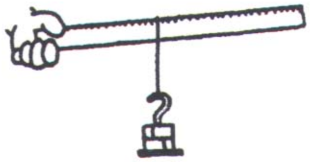
Center of Mass and Torque

Depart a bit from the order of the chapter and begin a discussion of center of mass before treating torque. Do this by tossing a small metal ball across the room, stating it follows a smooth curved path—a parabola. Then pick up an irregularly shaped piece of wood, perhaps an L-shape, and state that if this were thrown across the room it would not follow a smooth path, but would wobble all over the place—a special place, the place presently being discussed—the center of mass, or center of gravity. Illustrate your definition with figures of different shapes, first those where the center of mass lies within the object and then to shapes where the center of mass lies outside the objects.

CHECK QUESTION: Where is the center of mass of a donut?

Consider the motion of a basketball tossed across the room when a heavy weight is attached to one side. The wobble is evident. Likewise for suns with planet, a welcome feature to astronomy types.

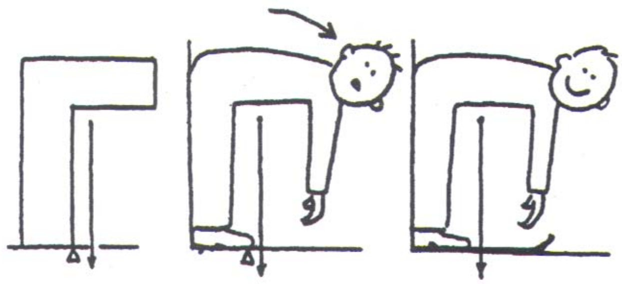
Ask your students if they "have" a CG. Acknowledge that the CG in men is generally higher than in women (1%-2%), mainly because women tend to be proportionally smaller in the upper body, and heavier in the pelvis. On the average it lies about 6 inches above the crotch, a bit below the bellybutton. Interestingly enough, the reason for the bellybutton being where it is relates to CG. A fetus turning in its mother's womb would rotate about its CG, the likely place for its umbilical cord. Standing erect with heavy side down simulates an average woman. Standing with heavy side up, simulates an average man. A baseball bat likewise makes this point. Interestingly, When we bend over, of course, the CG extends beyond the physical body.



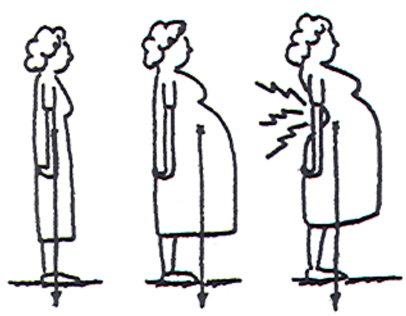
Pass around a meterstick with a weight that can be suspended at different places. This is "Torque Feeler," an important activity that can be done in your classroom as Mary Beth Monroe shows in the chapter photo opener. Students hold the meterstick horizontally and note that different torques

when the weight's distance is varied. The difference between force and torque is felt! How nice when students can feel physics!

Place an L-shaped body on the table and show how it topples—because its center of mass lies outside a point of support. Sketch this on the board. Then stand against a wall and ask if it is possible for one to bend over and touch their toes without toppling forward. Attempt to do so. Sketch this next to the L-shape as shown. By now your board looks like the following:



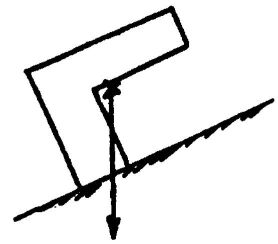
Discuss a remedy for such toppling, like longer shoes or the wearing of snowshoes or skis. Sketch a pair of skis on the feet of the person in your drawing. Seem to change the subject and ask why a pregnant woman often gets back pains. Sketch a woman before and after getting pregnant, showing how the CG shifts forward—beyond a point of support for the same posture. (This whole idea goes over much better in lecture than as reading material, so is not found in this edition. So now you can introduce it as a fresh idea in class.) Make a third sketch showing how a woman can adjust her posture so that her CG is above the support base bounded by her feet, sketching lastly, the "marks of pain." Ask the class how she could prevent these pains, and if someone in class doesn't volunteer the idea of wearing skis, do so yourself and sketch skis on her feet in the second drawing.



Lead your class into an alternate solution, that of carrying a pole on her shoulder, near the end of which is a load. Erase the skis and sketch in the pole and load as shown. Acknowledge the objection that she would have to increase the mass of the load as the months go by, and ask what else can be done. Someone should volunteer that she need only move the load closer to the end, which in effect shifts the overall CG in a favorable direction. This routine is effective and sparks much class interest. However, you must be very careful that you don't offend your students, particularly your female students. Whenever you single out any "minority"(?) you run the risk of offending members of that minority group or those sensitive to the feelings of members of that group. We instructors, whether male or female ourselves, are for the most part conscious of this and therefore make our examples as general as possible—mixing "shes" and "hes" whenever these pronouns come up. But in the case of a person becoming pregnant, it's a definite "she." Any classroom laughter that your presentation elicits should be, after all, directed to the situation and not particularly toward the woman. In any event, we are in sad shape when we cannot laugh at ourselves occasionally.

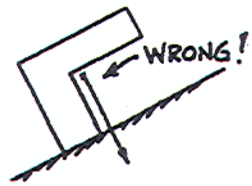
> CHECK QUESTION: Why does a hiker with a heavy backpack lean forward when standing or walking?

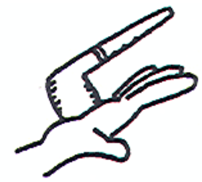
Return to your chalkboard sketches of L-shaped objects and relate their tipping to the torques that exist. Point out the lever arms in the sketches.



CHECK QUESTION: An L-shaped object with CG marked by the X rests on an incline as shown. Draw this on your paper and mark it appropriately to determine whether the object will topple or not.

Comment: Be prepared for some students to sketch in the "vertical" line through the CG perpendicular to the slope as shown.

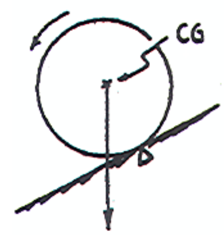




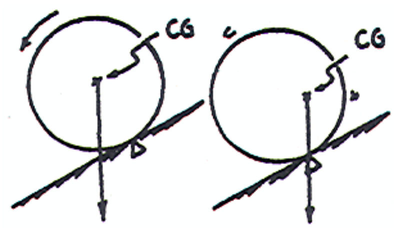
A simple example of this is to balance a pipe (smoking kind) on your hand when held at an angle.

Cite examples involving the CG in animals and people—how the long tails of monkeys enable them to lean forward without losing balance—and how people lean backwards when carrying a heavy load at their chests, and how the coolie method with the load distributed in two parts suspended at the ends of a pole supported in the middle is a better way.

Ask why a ball rolls down a hill. State that "because of gravity" is an incomplete answer. Gravity would have it slide down the hill. The fact it rolls, or rotates, is evidence of an unbalanced torque. Sketch this on your chalkboard.



DEMONSTRATION: Show how a "loaded disk" rolls *up* an inclined plane. After class speculation, show how the disk remains at rest on the incline. Modify your chalkboard sketch to show how both the CG with respect to the support point is altered, and the absence of a lever arm and therefore the absence of a torque.



On rolling: Cliff birds lay eggs that are somewhat pear-shaped. This shape assures that the eggs roll in circles, and don't easily roll off precarious nesting places.

Discuss wrenches and clarify lever arm distances (Figure 8.20). Cite how a steering wheel is simply a modified wrench, and why trucks and heavy vehicles before the advent of power steering used large-diameter steering wheels.

DEMONSTRATION: Attempt to stand from a seated position without putting your feet under the chair. Explain with center of gravity and torques.

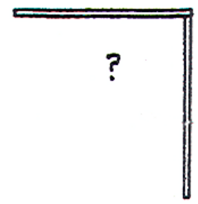
DEMONSTRATION: Do as Michael Bimmerle does and stick a piece of masking tape on an easy-to-move door. Place the tape near the middle and when you pull the door, the tape becomes unstuck. Progressively move the tape closer toward the edge away from the hinges and the tape sticks better. Near the edge the tape will stick and open the door without pulling off. More torque for less force.

Seesaws

Extend rotation to seesaws, as in Figures 8.18 and 8.19. Explain how participants on a seesaw can vary the net torque by not only sliding back and forth, but by leaning. In this way the location of their CGs and hence the lever arm distance is changed. Discuss the boy playing by himself in the park (Think and Discuss 111), and how he is able to rotate up and down by leaning toward and away from the fulcrum.

DEMONSTRATION: Make a candle seesaw by trimming the wick so both ends are exposed, and balance the candle by a needle through the center. Rest the ends of the needle on a pair of drinking glasses. Light both ends of the candle. As the wax drips, the CG shifts, causing the candle to oscillate.

CHECK QUESTION: To balance a horizontal meterstick on one finger, you'd place your finger at the 50-cm mark. Suppose you suspend an identical meterstick vertically from one end, say the 0-cm end. Where would you place your finger to balance the horizontal stick? [At the 25-cm mark, where equal weights would each be 25 cm distant.]



DEMONSTRATION: Place a heavy plank on your lecture table so that it overhangs. Walk out on the overhanging part and ask why you don't topple. Relate this to a solitary seesaw example. (Note the version of this in the NTQs.) This is also treated in the screencast 'More on Torques.'

Here's a neat application of CG that is not in the text, but is another NTQ. If you gently shake a basket of berries, the larger berries will make their way to the top. In so doing the CG is lowered by the more compact smaller berries settling to the bottom. You can demonstrate this with a Ping-Pong ball at the bottom of a container of dried beans, peas, or smaller objects. When the container is shaken, the Ping-Pong ball surfaces, lowering the CG of the system. This idea can be extended to the Ping-Pong ball in a glass of water. The CG of the system is lowest when the Ping-Pong ball floats. Push it under the surface and the CG is raised. If you do the same with something more dense than water, the CG is lowest when it is at the bottom.

Centripetal Force

Whirl an object tied to the end of a string overhead and ask if there is an outward or an inward force exerted on the whirling object. Explain how no outward or centrifugal force acts on the whirling object (the only outward directed force is the reaction force *on the string*, but not on the object). Emphasize also that centripetal force is not a force in its own right, like gravity, but is the name for any force that pulls an object into a curved path.

DEMONSTRATION: Swing a bucket of water in a vertical circle and show that the water doesn't spill (when centripetal force is at least equal to the weight of the water). All your students have heard of this demonstration, but only a few have actually seen it done. Why doesn't the water fall at the top of the path? [The answer is intriguing—it does! You have to pull the bucket down as fast as the water falls. Similarly, a space shuttle above falls—just as much as the round Earth curves! Nothing holds the water up; nothing holds the satellite up.] Both are falling—nice physics!

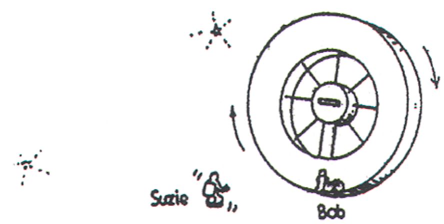
The "trick" of this demonstration is to pull the bucket down as fast as the water falls so both fall the same vertical distance in the same time. Too slow a swing produces a wet teacher. As said, the water in the swinging bucket is analogous to the orbiting of a satellite. Both the swinging water and a satellite such as the

orbiting space shuttle are falling. Because of their tangential velocities, they fall in a curve; just the right speed for the water in the bucket, and just the right greater speed for the space shuttle. Tying these related ideas together is good teaching!

CHECK QUESTION: A motorcycle runs on the inside of a bowl-shaped track (sketched in Think and Explain 89). Is the force that holds the motorcycle in a circular path an inward- or outward-directed force? [It is an inward-directed force—a centripetal force. An outward-directed force acts on the inner wall, which may bulge as a result, but no outward-directed force acts on the motorcycle.]

Centrifugal Force in a Rotating Frame

The concept of centrifugal force is useful when viewed from a rotating frame of reference. Then it seems as real as gravity to an occupant—like inside a rotating space habitat. State how it differs from a real force in that there is no agent such as mass. The magnetic force on a magnet, for example, is caused by the presence of another magnet; the force on a charge is caused by the presence of another charge. Whereas a real force is an interaction between one body and another, there is no reaction counterpart to centrifugal force. Distinguish centrifugal force from the action-reaction pairs of forces at the feet of an astronaut in a rotating habitat.



Discuss rotating space habitats. Show how *g* varies with both the radial distance from the hub and the rotational rate of the structure. The Earth has been the cradle of humankind; but humans do not live in the cradle forever. We will likely leave our cradle and inhabit structures of our own building; structures that will serve as lifeboats for the planet Earth. Their prospect is exciting.

DEMONSTRATION: Do as Diana Lininger Markham does in the chapter opening photos and swing a drink in an overhead circle without spilling a drop. The surface of the liquid remains parallel to the dish when freely swinging. (I witnessed this method of carrying cups of tea or other beverages though crowded areas without spilling while visiting Turkey—very impressive.) A smaller gadget that does the same, *SpillNot*, (P4-2500) is available from Arbor Scientific.

Angular momentum

Just as inertia and rotational inertia differ by a radial distance, and just as force and torque also differ by a radial distance, so momentum and angular momentum also differ by a radial distance. Relate linear momentum to angular momentum for the case of a small mass at a relatively large radial distance—an object you swing overhead.

For the more general case, angular momentum is simply the product of rotational inertia I and angular velocity ω. This is indicated in Figure 8.52.

DEMONSTRATION: With weights in your hand, rotate on a platform as shown in Figure 8.52. Simulate the slowing down of the Earth when ice caps melt and spread out.

DEMONSTRATION: Show the operation of a gyroscope—either a model or a rotating bicycle wheel as my late son James demonstrates in Figure 8.50.

Regarding the falling cat of Figure 8.54, J. Ronald Galli of Weber State University in Utah cautions that a falling cat bends its spine to swing about and twist in an opposite direction to land feet first—all the while maintaining a total angular momentum of zero.

Regarding Think and Explains 93 through 97: When answering these, demonstrate again on the rotating platform, holding the weights over your head to simulate Earth washing toward the equator, melting ice caps spreading toward the equator by lowering your hands in an outstretched position to simulate Earth and water

flowing toward the equator. To simulate the effects of skyscraper construction, hold the weights short of fully stretched, then extend your arms full-length.

Going Further with Rolling

Rolling things have two kinds of kinetic energy: That due to linear motion, and that due to rotational motion. So an object rolling down an incline will lag behind a freely sliding object because part of a rolling object's kinetic energy is in rotation. If this is clear, then the following question is in order for your better students.

> NEXT-TIME QUESTION: Which will roll with the greater acceleration down an incline, a can of water or a frozen can of ice? Double credit for a good explanation of what is seen. [The can of liquid will undergo appreciably more acceleration because the liquid is not made to rotate with the rotating can. It in effect "slides" rather than rolls down the incline, so practically all the KE at the bottom is in linear speed with next-to none in rotation. Fine, one might say, then if the liquid doesn't rotate, the can ought to behave as an empty can, with the larger rotational inertia of a "hoop" and lag behind. This brings up an interesting point: The issue is not which can has the greater rotational inertia, but which has the greater rotational inertia compared to its mass (note the qualifier in the legend of Figure 8.14). The liquid content has appreciably more mass than the can that contains it; hence the non-rolling liquid serves to increase the mass of the can without contributing to its rotational inertia. It gives the can of liquid a relatively small rotational inertia compared to its mass.]

You can follow through by asking which can will be first in rolling to a stop once they meet a horizontal surface. The can hardest to "get going" is also the can hardest to stop—so given enough horizontal distance, the slowest can down the incline rolls farther and wins the race!

> CHALLENGE: At the bottom of an incline are two balls of equal mass—a solid one and a thin-walled hollow one. Each is given the same initial speed. Which rolls higher up the incline before coming to a stop? [The answer is the hollow ball.] In terms of rotational inertia, whether a ball is hollow or solid makes a big difference. A thin-walled hollow ball, having much of its mass along its radius, has a relatively large rotational inertia ($^2/_3MR^2$). A solid ball, having much of its mass near its center, has less rotational inertia ($^2/_5MR^2$). The ball with the greater rotational inertia out-rolls a lower-inertia ball. Hence the hollow ball rolls farther up the incline before it comes to a stop.

Another way to look at it is in terms of energy. The balls begin their upward travel with kinetic energy of two kinds—translational and rotational. Although their initial translational KEs are the same, the hollow ball begins with more rotational KE due to its greater rotational inertia. So the hollow ball has more total KE at the base of the incline, which means it must have more PE at the top. The hollow ball indeed goes higher.

Does mass make a difference? No. As with the mass of a pendulum bob, or the mass of a freely-falling object, mass makes no difference. Sent rolling up an incline with equal speeds, any hollow ball will out-roll any solid ball. That's right—a tennis ball will roll higher than a bowling ball or a marble.

If you instead release both balls from a rest position at the top of an incline, the hollow ball "out-rests" the solid ball, is slower to gain speed, and lags behind the solid ball. The solid ball reaches the bottom first. Inertia is a resistance to *change*.

Answers and Solutions for Chapter 8

Reading Check Questions

1. Tangential speed is measured in meters per second; rotational speed in RPM (revolutions per minute) or rotations per second.
2. Only tangential speed varies with distance from the center.
3. The wide part has a greater tangential speed than the narrow part.
4. The wide part of the wheel has a greater radius than the narrow part, and hence a greater tangential speed when the wheel rolls.
5. Rotational inertia is the resistance to a change in rotational motion, which is similar to plane inertia which is a resistance to a change in velocity.
6. Rotational inertia also depends on the distribution of mass about an objects axis of rotation.
7. Rotational inertia increases with increasing distance.
8. Smallest when rotation is about the lead; next when at a right angle about the middle, and most when about a right angle at the end.
9. Easier to get swinging when held closer to the massive end.
10. Bent legs have mass closer to the axis of rotation and therefore have less rotational inertia.
11.A solid disk has less rotational inertial and will accelerate more.
12. A torque tends to change the rotational motion of an object.
13. The lever arm is the shortest distance between the applied force and rotational axis.
14. For a balanced system, both clockwise and counterclockwise torques have equal magnitudes.
15. The stick 'wobbles,' spins really, about its CM (or CG).
16. A baseball's CM and CG are at its center. Both are closer to the massive end of a baseball bat.
17. Your CG is beneath the rope.
18. The CM of a soccer ball is at its center.
19. For stable equilibrium the CG must be above a support base, and not extend beyond it.
20. The CG of the tower lies above and within the support base of the tower.
21. In attempting so, your CG extends beyond your support base, so you topple.
22. The direction of the force is inward, toward the center of rotation.
23. The force on the clothes is inward.
24. When the string breaks, no inward force acts and via with the law of inertia, the can moves in a straight line.
25. No force is responsible, for you tend to move forward in a straight line and the car curves into you.
26. It's called fictitious because there is no reaction counterpart to centrifugal force.
27. Rotational motion results in a centrifugal force that behaves like the force of gravity.
28. Linear momentum involves straight-line motion; angular momentum involves rotational motion.
29. The angular momentum of a system remains constant when no net torque acts.
30. Angular momentum remains the same, while her rate of spin doubles.

Think and Do

31. Open ended.

32. You'll note the cups roll off the track!

33. Yes, this happens because the CG hangs below the point of support.

34. Women have lower CGs than men. Their feet are also smaller. So women have the advantage in the toppling contest because their CG is more likely to be above a support base.

35. Facing the wall is more difficult! For both sexes the CG extends beyond the support base defined by the balls of the feet to the wall.
36. Your fingers will meet in the center. When a finger is farther from the center than the other, it presses with less force on the stick and slides. The process alternates until both fingers are at the center.

37. If the coin is on the line to the center of rotation, the 'normal' force on the coin provides a centripetal force to keep it steadily rotating.

Plug and Chug

38. τ = 0.2 m × 50 N = 10 m·N.
39. τ = 0.5 m × 50 N = 25 m·N.
40. F = (2 kg)(3 m/s)^2/2.5 m = 7.2 N.

41. F = (80 kg)(3 m/s)^2/2 m = 360 N.

42. Ang momentum = mvr = (80 kg)(3 m/s)(2 m) = 480 kg·m^2/s.

43. Twice: Ang momentum = mvr = (80 kg)(6 m/s)(2 m) = 960 kg·m^2/s.

Think and Solve

44. In accord with $v = r\omega$, the greater the radius (or diameter), the greater the tangential speed. So the wide part rolls faster. It rolls 9/6 = 3/2 = 1.5 times faster.

45.(a) Torque = force $\times$ lever arm = (0.25 m) (80 N) = 20 N·m.
(b) Force = 200 N. Then (200 N)(0.10 m) = 20 N·m.
(c) Yes. These answers assume that you are pushing perpendicular to the wrench handle. Otherwise, you would need to exert more force to get the same torque.

46.The mass of the rock is 1 kg. (A reverse of the Check Point on page 142.)

47. The 1-kg mass weighs 10 N. At the 50-cm mark, torque = 10 N $\times$ 0.5 m = 5 N·m.
At the 75-cm mark, torque = 10 N $\times$ 0.75 m = 7.5 N·m, and at the 100-cm mark,
torque = 10 N $\times$ 1.0 m = 10 N·m. So at the 75-cm mark the torque is 7.5/5 = 1.5 times as much, and at the 100-cm mark the torque is twice what it is at the 50-cm mark.

48. From $F = mv^2/r$, substituting, $T = mv^2/L$. (a) Rearranging, $m = TL/v^2$.
(b) Substituting numerical values, m = (10N)(2m)/(2m/s)^2 = 5 kg.

49.The artist will rotate 3 times per second. By the conservation of angular momentum, the artist will increase rotation rate by 3. That is
$I\omega_{\text{before}} = I\omega_{\text{after}}$
$I\omega_{\text{before}} = [(^I/3)I(3\omega)]_{\text{after}}$

50. (a) In the absence of an unbalanced external torque the angular momentum of the system is conserved. So (angular momentum)$_{\text{initial}}$ = (angular momentum)$_{\text{final}}$., where angular momentum is mvL.
From $mv_0L = mv_{\text{new}}(0.33L)$ we get $v_{\text{new}} = v_0(L/0.33L) = v_0/0.33 = 3.0v_0$.
(b) $v_{\text{new}} = v_0/(0.33)$ = (1.0 m/s)/(0.33) = 3.0 m/s.

Think and Rank

51. B, C, A
52. C, A, B
53. B, A, C
54. B, C, A
55. C, A, B

Think and Explain

56. Sam's rotational speed ω, RPMs, remains the same, assuming the Ferris wheel is powered and not "free wheeling." Sam's tangential speed, $v = r\omega$ is half because the radial distance r is half. Answers are different because tangential speed v depends on distance from the spin axis, while rotational speed ω does not.

57.Sue's tires have a greater rotational speed for they have to turn more times to cover the same distance.

58.For the same twisting speed ω, the greater distance r means a much greater speed v.

59.The amount of taper is related to the amount of curve the railroad tracks take. On a curve where the outermost track is say 10% longer than the inner track, the wide part of the wheel will also have to be at least 10% wider than the narrow part. If it's less than this, the outer wheel will rely on the rim to stay on the track, and scraping will occur as the train makes the curve. The "sharper" the curve, the more the taper needs to be on the wheels.

60.Yes, rotational inertia is enhanced with long legs. The bird's foot is directly below the bird's CM.

61.Rotational inertia and torque are most predominantly illustrated with this vehicle, and the conservation of angular momentum also plays a role. The long distance to the front wheels means greater rotational

inertia of the vehicle relative to the back wheels, and also increases the lever arm of the front wheels without appreciably adding to the vehicle's weight. As the back wheels are driven clockwise, the chassis tends to rotate counterclockwise (conservation of angular momentum) and thereby lift the front wheels off the ground. The greater rotational inertia and the increased clockwise torque of the more distant front wheels counter this effect.

62. The bowling ball wins. A solid sphere of any mass and size beats both a solid cylinder and a hollow ball of any mass and size. That's because a solid sphere has less rotational inertia per mass than the other shapes. A solid sphere has the bulk of its mass nearer the rotational axis that extends through its center of mass, whereas a cylinder or hollow ball has more of its mass farther from the axis. The object with the least rotational inertia per mass is the "least lazy" and will win races.

63. The ball to reach the bottom first is the one with the least rotational inertia compared with its mass—that's the softball (as in the answer to the previous question).

64. The lever arm is the same whether a person stands, sits, or hangs from the end of the seesaw, and certainly the person's weight is the same. So the net torque is the same also.

65. No, for by definition, a torque requires both force and a lever arm.

66. In the horizontal position the lever arm equals the length of the sprocket arm, but in the vertical position, the lever arm is zero because the line of action of forces passes right through the axis of rotation. (With cycling cleats, a cyclist pedals in a circle, which means they push their feet over the top of the spoke and pull around the bottom and even pull up on the recovery. This allows torque to be applied over a greater portion of the revolution.)

67. No, because there is zero lever arm about the CM. Zero lever arm means zero torque.

68. Friction between the ball and the lane provides a torque, which spins the ball.

69. A rocking bus partially rotates about its CM, which is near its middle. The farther one sits from the CM, the greater is the up and down motion—as on a seesaw. Likewise for motion of a ship in choppy water or an airplane in turbulent air.

70. With your legs straight out, your CG is farther away and you exert more torque sitting up. So sit-ups are more difficult with legs straight out, a longer lever arm.

71. The long drooping pole lowers the CG of the balanced system—the tightrope walker and the pole. The rotational inertia of the pole contributes to the stability of the system also.

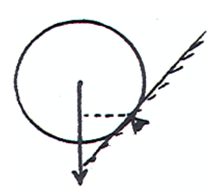
72. You bend forward when carrying a heavy load on your back to shift the CG of you and your load above the area bounded by your feet—otherwise you topple backward.

73. The wobbly motion of a star is an indication that it is revolving about a center of mass that is not at its geometric center, implying that there is some other mass nearby to pull the center of mass away from the star's center. This is one of the ways in which astronomers have discovered planets existing around stars other than our own.

74. Two buckets are easier because you may stand upright while carrying a bucket in each hand. With two buckets, the CG will be in the center of the support base provided by your feet, so there is no need to lean. (The same can be accomplished by carrying a single bucket on your head.)

75. The Earth's atmosphere is a nearly spherical shell, which like a basketball, has its center of mass at its center, i.e., at the center of the Earth.

76. The CG of a ball is not above a point of support when the ball is on an incline. The weight of the ball therefore acts at some distance from the point of support which behaves like a fulcrum. A torque is produced and the ball rotates. This is why a ball rolls down a hill.



77. It is dangerous to pull open the upper drawers of a fully-loaded file cabinet that is not secured to the floor because the CG of the cabinet can easily be shifted beyond the support base of the cabinet. When this happens, the torque that is produced causes the cabinet to topple over.

78.An object is stable when its PE must be raised in order to tip it over, or equivalently, when its PE must be increased before it can topple. By inspection, because of its narrow base the first cylinder undergoes the least change in PE compared to its weight in tipping. So it is the least stable. The third truncated pyramid requires the most work, so it is the most stable.

79.The CG of truck at the left on the lower part of the incline, is not above its support base, and will tip. The CGs of the two other trucks are above their support bases and won't tip. So only the first of the three trucks will tip.

80.In accord with the equation for centripetal force, twice the speed corresponds to four times the force.

81.No—in accord with Newton's first law, in the absence of force a moving object follows a straight-line path.

82.Yes. Letting the equation for centripetal force guide our thinking, increased speed at the same radial distance means greater centripetal force. If this greater centripetal force isn't provided, the car will skid.

83.Newton's first and third laws provide a straight-forward explanation. You tend to move in a straight line (Newton's first law) but are intercepted by the door. You press against the door because the door is pressing against you (Newton's third law). The push by the door provides the centripetal force that keeps you moving in a curved path. Without the door's push, you wouldn't turn with the car—you'd move along a straight line and be "thrown out." Explanation doesn't require invoking centrifugal force.

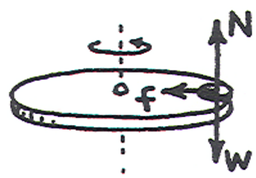
84.On a banked road the normal force, at right angles to the road surface, has a horizontal component that provides the centripetal force. Even on a perfectly slippery surface, this component of the normal force can provide sufficient centripetal force to keep the car on the track.

85.A car can remain on a perfectly slippery banked track if the horizontal component of its normal force is sufficient to provide the required centripetal force.

86.There is no component of force parallel to the direction of motion, which work requires.

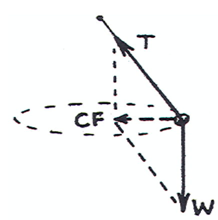
87.In accord with Newton's first law, at every moment her tendency is to move in a straight-line path. But the floor intercepts this path and a pair of forces occur; the floor pressing against her feet and her feet pressing against the floor—Newton's third law. The push by the floor on her feet provides the centripetal force that keeps her moving in a circle with the habitat. She senses this as an artificial gravity.

88.



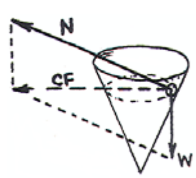
89. (a) Except for the vertical force of friction, no other vertical force except the weight of the motorcycle + rider exists. Since there is no change of motion in the vertical direction, the force of friction must be equal and opposite to the weight of motorcycle + rider. (b) The horizontal vector indeed represents the normal force. Since it is the only force acting in the radial direction, horizontally, it is also the centripetal force. So it's both.

90. The resultant is a centripetal force.



91. As you crawl outward, the rotational inertia of the system increases (like the masses held outward in Figure 8.52). In accord with the conservation of angular momentum, crawling toward the outer rim increases the rotational inertia of the spinning system and decreases the angular speed.

92.



93. Soil that washed down the river is being deposited at a greater distance from the Earth's rotational axis. Just as the man on the turntable slows down when one of the masses is extended, the Earth slows in its rotational motion, extending the length of the day. The amount of slowing, of course, is exceedingly small.

94. Rotational inertia would increase. By angular momentum conservation, the rotation of the Earth would slow (just as a skater spins slower with arms outstretched), tending to make a longer day.

95. In accord with the conservation of angular momentum, as the radial distance of mass increases, the angular speed decreases. The mass of material used to construct skyscrapers is lifted, slightly increasing the radial distance from the Earth's spin axis, which tends to slightly decrease the Earth's rate of rotation, making the days a bit longer. The opposite effect occurs for falling leaves as their radial distance from the Earth's axis decreases. As a practical matter, these effects are entirely negligible!

96. In accord with the conservation of angular momentum, if mass moves closer to the axis of rotation, rotational speed increases. So the day would be ever so slightly shorter.

97. In accord with the conservation of angular momentum, if mass moves farther from the axis of rotation, as occurs with ice caps melting, rotational speed decreases. So the Earth would slow in its daily rotation.

98. Without the small rotor on its tail, the helicopter and the main rotor would rotate in opposite directions. The small rotor on the tail provides a torque to offset the rotational motion that the helicopter would otherwise have.

99. Gravitational force acting on every particle by every other particle causes the cloud to condense. The decreased radius of the cloud is then accompanied by an increased angular speed because of angular momentum conservation. The increased speed results in many stars being thrown out into a dish-like shape.

100. In accord with Newton's first law, moving things tend to travel in straight lines. Surface regions of a rotating planet tend to fly off tangentially, especially at the equator where tangential speed is greatest. More predominantly, the surface is also pulled by gravity toward the center of the planet. Gravity wins, but bulging occurs at the equator because the tendency to fly off is greater there. Hence a rotating planet has a greater diameter at the equator than along the polar axis.

Think and Discuss

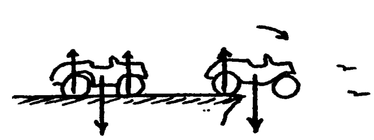
101. Large diameter tires mean you travel farther with each revolution of the tire. So you'll be moving faster than your speedometer indicates. (A speedometer actually measures the RPM of the wheels and displays this as mi/h or km/h. The conversion from RPM to the mi/h or km/h reading assumes the wheels are a certain size.) Oversize wheels give too low a reading because they really travel farther per revolution than the speedometer indicates, and undersize wheels give too high a reading because the wheels do not go as far per revolution.

102. The tangential speeds are equal, for they have the same speed as the belt. The smaller wheel rotates twice as fast because for the same tangential speed, and r half, ω must be twice. $v_{\text{(big wheel)}} = r\omega$; $v_{\text{(small wheel)}} = (r/2 \times 2\omega)$.

103. Two conditions are necessary for mechanical equilibrium, $\Sigma F = 0$ and $\Sigma Torque = 0$.

104. Before leaving the cliff, front and back wheels provide the support base to support the car's weight. The car's CM is well within this support base. But when the car drives off the cliff, the front wheels are the first to leave the surface. This shifts the support base to the region between the rear wheels, so the car tips forward. In terms of torques, before driving off the cliff, the torques are balanced about the CM between the front and back wheels. But when the support force of the front wheels is absent, torque due to the support force of the rear wheels rotates the car forward about its CM making it nose forward as shown. At high speed, the time that this torque acts is less, so less rotation occurs as it falls.

105. Friction by the road on the tires produces a torque about the car's CM. When the car accelerates forward, the friction force points forward and rotates the front of the car upward. When braking, the direction of friction is rearward, and the torque rotates the car in the opposite direction so the rear end rotates upward (and the nose downward).



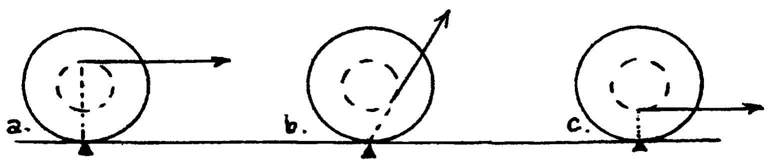
106. If you roll them down an incline, the solid ball will roll faster. (The hollow ball has more rotational inertia compared with its weight.)

107. Don't say the same, for the water slides inside the can while the ice is made to roll along with the can. When the water inside slides, it contributes weight rather than rotational inertia to the can. So the can of water will roll faster. (It will even beat a hollow can.)

108. Lightweight tires have less rotational inertia, and are easier to get up to speed.

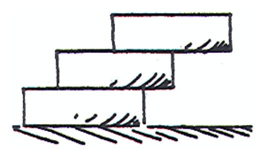
109. Advise the youngster to use wheels with the least rotational inertia—lightweight solid ones without spokes (more like a disk than hooplike).

110. In all three cases the spool moves to the right. In (a) there is a torque about the point of contact with the table that rotates the spool clockwise, so the spool rolls to the right. In (b) the pull's line of action extends through (not about) the point of table contact, yielding no lever arm and therefore no torque; but with a force component to the right; hence the spool slides to the right without rolling. In (c) the torque produces clockwise rotation so the spool rolls to the right.



111. The weight of the boy is counterbalanced by the weight of the board, which can be considered to be concentrated at its CG on the opposite side of the fulcrum. He is in balance when his weight multiplied by his distance from the fulcrum is equal to the weight of the entire board multiplied by the distance between the fulcrum and the midpoint (CG) of the board. (How do the relative weight of boy and board relate to the relative lever arms?)

112. The top brick would overhang $^3/4$ of a brick length as shown. This is best explained by considering the top brick and moving downward; i.e., the CG of the top brick is at its midpoint; the CG of the top two bricks is midway between their combined length. Inspection will show that this is $^1/4$ of a brick length, the overhang of the middle brick. (Interestingly, with a few more bricks, the overhang can be greater than a brick length, and with a limitless number of bricks, the overhang can be made as large as you like.)



113. The track will remain in equilibrium as the balls roll outward and until the ball rolls off the track. This is because the CG of the system remains over the fulcrum. For example, suppose the billiard ball has twice the mass of the golf ball. By conservation of momentum, the twice-as-massive ball will roll outward at half the speed of the lighter ball, and at any time be half as far from the starting point as the lighter ball. So there is no CG change in the system of the two balls. So the torques produced by the weights of the balls multiplied by their relative distances from the fulcrum are equal at all points—because at any time the less massive ball has a correspondingly larger lever arm.

114. The center of mass of the bird is slightly below its beak, the point at which it rests on Diana's finger. So the bird is "hanging" on Diana's finger. This is accomplished by lead or some very dense metal embedded in the wing tips of the bird.

115. The equator has a greater tangential speed than latitudes north or south. When a projectile is launched from any latitude, the tangential speed of the Earth is imparted to the projectile, and unless corrections are made, the projectile will miss a target that travels with the Earth at a different tangential speed. For example, if the rocket is fired south from the Canadian border toward the Mexican border, its Canadian component of speed due to the Earth's turning is smaller than Earth's tangential speed further south. The Mexican border is moving faster and the rocket falls behind. Since the Earth turns toward the east, the

rocket lands west of its intended longitude. (On a merry-go-round, try tossing a ball back and forth with your friends. The name for this alteration due to rotation is the Coriolis effect.)

116. Acceleration caused this force. His body was accelerated by support at his head, but his brain was not so supported. In effect, the back of his head exerted a force on his head, with the cause being too-great an acceleration.

9 Gravity

Dutch friend Ed Van den Berg uses balls to pose questions about the inverse-square law in the opening photo to this chapter. I am still moved by photos of astronauts performing space walks! Photo 3 shows Eric Mazur engaging students in class. When engagement occurs between professor and student, learning can occur. Without this engagement, likely less learning occurs. Hats off to Eric! Tomas Brage, physics department head at Lund University in Sweden shows a version of the Cavendish apparatus to measure G.

The personality profile is of Eric Mazur.

This chapter begins with a historical approach and ends on an astronomical theme. It offers a good place to reiterate the idea of a scientific theory, and comment on the all-too common and mistaken idea that because something has the status of scientific theory, it is somehow short of being valid. This view is evident in those who say, "But it's *only* a theory." Bring the essence of the first and last footnotes in the chapter into your discussion (about scientific homework and being unable to see radically new ways of viewing the world). The last chapter on *Cargo Cult Science* of Feynman's book, *Surely You're Joking Mr. Feynman* (Norton, 1985), expands nicely on this. (When I first read this delightful book I allowed myself only one chapter per day—to extend the pleasure. It's THAT good!)

Kepler's 3rd law follows logically from Newton's law of gravitation. Equate the force of gravity between planet m and the Sun M to the centripetal force on m. Then,

$$\frac{GmM}{r^2} = \frac{mv^2}{r} = \frac{m(2\pi r/T)^2}{r}$$

where the speed of the planet is 2π per period T. Cancel and collect terms,

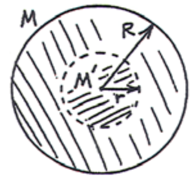
$$\frac{GM}{4\pi^2} = \frac{r^3}{T^2}$$

This is Kepler's 3d law, for $GM/4\pi^2$ is a constant.

The idea of the force field is introduced in this chapter and is a good background for the electric field treated later in Chapter 22. The gravitational field here is applied to regions outside as well as inside the Earth.

In the text I say without explanation that the gravitational field increases linearly with radial distance inside a planet of uniform density. Figure 9.24 shows that the field increases linearly from zero at its center to maximum at the surface. This is also without explanation. The text states that "perhaps your instructor will provide the explanation." Here it is: We know that the gravitational force F between a particle m and a

spherical mass M, when m is outside M is simply $F = GmM/d^2$. But when m is inside a uniform density solid sphere of mass M, the force on m is due only to the mass M' contained within the sphere of radius $r < R$, represented by the dotted line in the figure. Contributions from the shell $> r$ cancel out (Figure 9.25, and again for the analogous case of the electric field in Figure 22.20, later in the book). So, $F = GmM'/r^2$. From the ratio of M'/M, you can show that $M' = Mr^3/R^3$. [That is, $M'/M = V'/V = (^4/_3\, \pi r^3)/(^4/_3\, \pi R^3) = r^3/R^3$.] Substitute M' in Newton's equation for gravitation and we get $F = GmMr/R^3$. All terms on the right are constant except r. So $F = kr$; force is linearly proportional to radial distance when $r < R$.



Interestingly enough, the condition for simple harmonic motion is that the restoring force be proportional to displacement, $F = kr$. Hence the simple harmonic motion of one who falls in the tunnel through the Earth. (Hence also the simple harmonic motion of one who slides without friction to-and-fro along any straight line tunnel through any part of the Earth. The displacement is then the component $r \sin \theta$.) The period of simple harmonic motion, $T = 2\pi\sqrt{(R^3/GM)}$ is the same as that of a satellite in close circular orbit about the Earth. Note that it is independent of the length of the tunnel. I treat falling through a vertical tunnel in the screencast *Tunnel Through Earth*.

You can compare the pull of the Moon that is exerted on you with the pull exerted by more local masses, via the gravitational equation. Consider the ratio of the mass of the Moon to its distance squared:

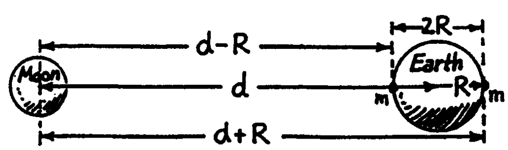
$$7.4 \times 10^{22}\ \text{kg}/(4 \times 10^5\ \text{km})^2 = 5 \times 10^{12}\ \text{kg/km}^2.$$

This is a sizeable ratio, one that buildings in your vicinity cannot match. (City buildings of greatest mass are typically on the order of 10^6 or 10^7 kilograms.) However, if you stand 1 kilometer away from the foot of a mountain of mass 5×10^{12} kilograms (about the mass of Mount Kilimanjaro), then the pull of the mountain and the pull of the Moon are about the same on you. Simply put, with no friction you would tend to gravitate from your spot toward the mountain—but you experience no tendency at all to gravitate from your spot toward the Moon! That's because the spot you stand on undergoes the same gravitational acceleration toward the Moon as you do. Both you and the whole Earth are accelerating toward the Moon. Whatever the lunar force on you, it has no tendency to pull you off a weighing scale—which is the essence of Think and Discuss 97 and 98. This is not an easy notion to grasp—at first.

Not covered in this edition is the inverse-cube nature of tidal forces. This follows from subtracting the tidal force on the far side of a body from the tidal force on the near side. Consider a kilogram of water on the side of the Earth nearest the Moon that is gravitationally attracted to the Moon with a greater force than a kilogram of water on the side of the Earth farthest from the Moon. The difference in force per kilogram of mass, $\Delta F/m$, which we'll call the tidal force T_F is

$$T_F = F_{d+R} - F_{d-R}$$
$$= GM\left[\frac{1}{(d+R)^2} - \frac{1}{(d-R)^2}\right] = \frac{4GMdR}{(d^2 - R^2)^2}$$

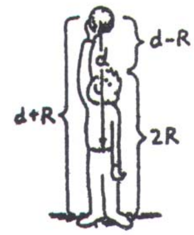
where M is the Moon's mass, (d+R) is the distance to the far side of Earth, (d-R) is the distance to the near side.



When d is very much greater than R, the $(d^2-R^2)^2$ is very nearly equal to d^4. Then the inverse-cube nature of tidal force is evident, for

$$T_F \sim \frac{4GMR}{d^3}\ .$$

Some interesting results occur when calculating the tidal force of the Moon on planet Earth. T_F is 2.2×10^{-6} N/kg. In contrast T_F of an overhead Moon on a person on Earth is 3×10^{-13} N/kg, a hundred million times weaker because of the tiny differences in pulls across the body. The tidal force of the Earth on the same person is 6×10^{-6} N/kg, more than the Moon's influence. And as the text reports, the tidal force due to a 1-kg mass held 1 m above your head is about 200 times as much effective as the Moon! Have those who believe the tidal effects of planets influence people make the calculations themselves.



A brief treatment of black holes is included in this chapter. The idea that light is influenced by a gravitational field isn't treated until Chapter 36, so may merit further explanation. You'll probably want to acknowledge that light bends in a gravitational field as does a thrown baseball. We say light travels in straight lines much for the same reason that some people say that a high-speed bullet doesn't curve downward in the first part of its trajectory. Over short distances the bullet doesn't *appear* to drop only because of its high speed and the short time involved. Likewise for light's speed, which we don't notice because of the vast distance it travels in the brief time it's in the strong part of Earth's gravitational field. Look ahead to the treatment of this idea in Figure 36.6.

Black holes at the center of galaxies are bigger than those found in binary star systems. The biggest recently reported galactic black holes have equivalent masses of some 10 to 40 billion Suns.

Dark matter is briefly mentioned in this chapter and is discussed in Chapter 11. Present consensus among astrophysicists is that dark energy is working against the force of gravity to accelerate the expansion of the universe. These findings downplay the oscillating universe scenario speculated about in the earlier editions of this text (although there remains speculation that the present outward acceleration may change to rapid deceleration and lead to a Big Crunch). The concepts of dark matter and dark energy are at the forefront of physics at this point, and are quite mysterious. Dark matter is out of sight, but not out of mind.

This chapter is prerequisite to the following chapter on satellite motion. It also provides useful background information for Chapter 22 (the inverse-square law, and the analogy between a gravitational and electric field) and Chapter 36 (general relativity). This chapter may be skipped without complicating the treatment of material in Chapters other than 22 and 36. It's an especially interesting chapter because the material is high interest, historical, quite understandable, and closely related to areas of space science that are currently in the public eye.

Practicing Physics Book:
• Inverse-Square Law • Our Ocean Tides

Problem Solving Book:
Some 30 problems

Laboratory Manual:
No labs for this chapter

Next-Time Questions:
• Earth-Moon Cable
• Moon Tides
• Solar Black Hole
• Earth Rise
• Normal Force and Weight
• Giant Plane
• Body Tide
• Gravity Force on Shuttle
• Weight

Hewitt-Drew-It! Screencasts:
• *Weight/Weightlessness*
• *Gravity*
• *Gravity Inside Earth*
• *Tunnel Through Earth*
• *Ocean Tides*

SUGGESTED LECTURE PRESENTATION

Begin by briefly discussing the simple codes and patterns that underlie the complex things around us, whether musical compositions or DNA molecules, and then briefly describe the harmonious motion of the solar system, the Milky Way and other galaxies in the universe—stating that the shapes of the planets, stars, and galaxies, and their motions are all governed by an extremely simple code, or if you will, a pattern. Then write the gravitational equation on the board. Give examples of bodies pulling on each other to convey a clear idea of what the symbols in the equation mean and how they relate. (Acknowledge that many other texts and references use the symbol *r* instead of the *d* in this text. The *r* is used to indicate the radial distance from a body's CG, and to emphasize the center-to-center rather than surface-to-surface nature for distance, and to prepare for *r* as a displacement vector. We don't set our plow that deep, however, and use *d* for distance.)

Inverse-Square Law

Discuss the inverse-square law and go over Figures 9.5 and 9.6 or their equivalents with candlelight or radioactivity.

Plot to scale an inverse-square curve on the board, showing the steepness of the curve—$^1/_4$, $^1/_9$, and $^1/_{16}$, for twice, three times, and four times the separation distance. This is indicated in Figures 9.5 and 9.6. (You may return to the curve of Figure 9.6 when you explain tides.)

> CHECK QUESTIONS: A photosensitive surface is exposed to a point source of light that is a certain distance away. If the surface were instead exposed to the same light four times as far away, how would the intensity upon it compare? A radioactive detector registers a certain amount of radioactivity when it is a certain distance away from a small piece of uranium. If the detector is four times as far from the uranium, how will the radioactivity reading compare?

> CHECK QUESTIONS: How is the gravitational force between a pair of planets altered when one of the planets is twice as massive? When both are twice as massive? When they are twice as far apart? When they are three times as far apart? Ten times as far apart? [The screencast on *Gravity* explains this.]

> CHECK QUESTION: What do you say to a furniture mover who claims that gravity increases with increased distance from the Earth, as evident to him when he's carrying heavy loads up flights of stairs?

Weight and Weightlessness

Note that we define weight as a support force. Even in a gravity-free region inside a rotating toroid, you'd experience weight. So weight needn't always be related to gravity. Discuss weightlessness and relate it to the queasy feeling your students experience when in a car that goes too fast over the top of a hill. State that this feeling is what an astronaut is confronted with all the time in orbit! Ask how many of your class would still welcome the opportunity to take a field trip to Cape Canaveral and take a ride aboard an orbiting vehicle. What an exciting prospect!

A marvelous space station called Skylab was in orbit in the 1970s. When it underwent unavoidable orbital decay the space shuttle was not yet in operation to give it the boost it needed to keep it in orbit. Quite unfortunate. But fortunately, there is movie footage of antics of astronauts aboard Skylab. The NASA film is "Zero *g*," which I showed every semester in my classes. It not only is fascinating in its shots of astronaut acrobatics in the orbiting lab, but illustrates Newton's laws as they apply to intriguing situations. The film shows the good sense of humor of the astronauts. A must! Also check out the screencast on *Weight/ Weightlessness*.

Discuss the differences in a baseball game on the Moon, and your favorite gravity-related topics.

Tides: Begin your treatment of tides by asking the class to consider the consequences of someone pulling your coat. If they pulled only on the sleeve, for example, it would tear. But if every part of your coat were

pulled equally, it and you would accelerate—but it wouldn't tear. It tears when one part is pulled harder than another—or it tears because of a *difference* in forces acting on the coat. In a similar way, the spherical Earth is "torn" into an elliptical shape by differences in gravitational forces by the Moon and Sun.

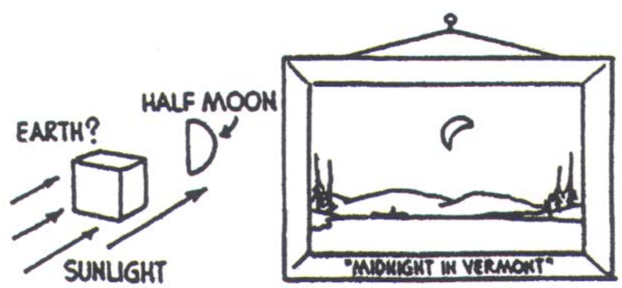
> CHECK QUESTION: Why do the tides not occur at the same time each day? [As the Earth takes 24 hours to rotate, the Moon advances in its orbit one hour ahead of the Earth. If the Moon didn't move in its orbit, the high-tide bulge would be at the same time each day as the Earth spins beneath the water.]

Misconceptions About the Moon: This is an appropriate place for you to dispel two popular misconceptions about the Moon. One is that since one side of the Moon's face is "frozen" to the Earth it doesn't spin like a top about its polar axis; and two, that the crescent shape commonly seen is *not* the Earth's shadow. To convince your class that the Moon spins about its polar axis, simulate the situation by holding your eraser at arms length in front of your face. Tell your class that the eraser represents the Moon and your head represents the Earth. Rotate slowly keeping one face of the eraser in your view. Call attention to the class that from your frame of reference, the eraser doesn't spin as it rotates about you—as evidenced by your observation of only one face, with the backside hidden. But your students occupy the frame of reference of the stars. (Each of them *is* a star.) From their point of view they can see all sides of the eraser as it rotates because it spins about its own axis as often as it rotates about your head. Show them how the eraser, if not slowly spinning and rotationally frozen with one face always facing the same stars, would show all of its sides to you as it circles around you. See one face, then wait 14 days later and the backside is in your view. The Moon's spin rate is the same as its rotational rate .

Misconception 2: Draw a half moon on the board. The shadow is along the diameter and is perfectly straight. If that were the shadow of the Earth, then the Earth would have to be flat, or be a big block shape! Discuss playing "flashlight tag" with a suspended basketball in a dark room that is illuminated by a flashlight in various locations. Ask your class if they could estimate the location of the flashlight by only looking at the illumination of the ball. Likewise with the Moon illuminated by the Sun!

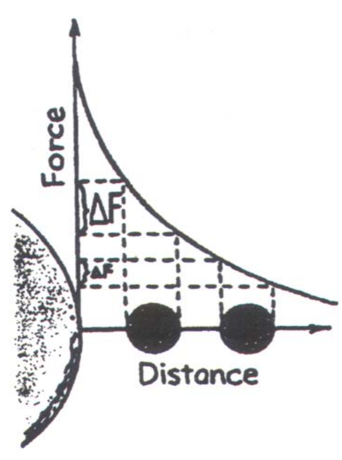
Sketch the picture on the right on the board and ask what is wrong with it.

[Answer: The Moon is in a daytime position as evidenced by the upper part of the Moon being illuminated. This means the Sun must be above. Dispel notions that the crescent shape of the Moon is a partial eclipse by considering a half moon and the shape of the Earth to cast such a shadow.]



Back to Tides

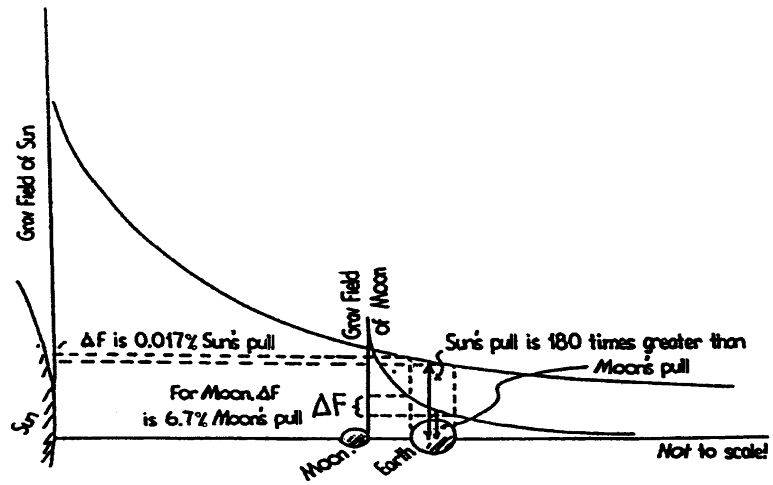
Explain tides via the accelerating ball of Jell-O as in Figure 9.14. Equal pulls result in an undistorted ball as it accelerates, but unequal pulls cause a stretching. This stretching is evident in the Earth's oceans, where the side nearest the Moon is appreciably closer to the Moon than the side farthest away. Carefully draw Figure 9.16 on the board, which explains why closeness is so important for tides. The figure shows that the magnitude of ΔF rather than F itself is responsible for tidal effects. Hence the greater attraction of the distant Sun produces only a small *difference* in pulls on the Earth, and compared to the Moon makes a small contribution to the tides on Earth.



Explain why the highest high tides occur when the Earth, Moon, and Sun are aligned—at the time of a new and a full Moon.

Discuss tides in the molten Earth and in the atmosphere.

Amplify Figure 9.16 with a comparison of ΔFs for both the Sun and the Moon as sketched at the upper right.



Clearly ΔF is smaller for the larger but farther Sun.

The text treats tides in terms of forces rather than fields. In terms of the latter, tidal forces are related to differences in gravitational *field* strengths across a body, and occur only for bodies in a nonuniform gravitational field. The gravitational fields of the Earth, Moon, and Sun, for example, are inverse-square fields—stronger near them than farther away. The Moon obviously experiences tidal forces because the near part to us is in a stronger part of the Earth's gravitational field than the far part. But even an astronaut in an orbiting space shuttle strictly speaking experiences tidal forces because parts of her body are closer to the Earth than other parts. This tidal force, the difference between the forces on near and far parts of her body, follow an inverse-cube law (in this manual as derived earlier). The micro differences produce **microtides**. Farther away in deep space, the differences are less. Put another way, the Earth's gravitational field is more uniform farther away. The "deepness" of a deep-space location can in fact be defined in terms of the amount of microtides experienced by a body there. Or equivalently, by the uniformity of any gravitational field there. There are no microtides in a body located in a strictly uniform gravitational field.

If there are microtides of an astronaut in orbit, would such microtides are even greater on the Earth's surface? The answer is yes. This brings up Exercise 42 that concerns **biological tides**. Interestingly enough, microtides in human bodies are popularly attributed to not the Earth, but the Moon. This is because popular knowledge cites that the Moon raises the ocean an average of 1 meter each 12 hours. Point out that the reason the tides are "stretched" by 1 meter is because part of that water is an Earth diameter closer to the Moon than the other part. In terms of fields, the near part of the Earth is in an appreciably stronger part of the Moon's gravitational field than the far part. To the extent that part of our bodies are closer to the Moon than other parts, there would be lunar microtides—but enormously smaller than the microtides produced by not only the Earth, but massive objects in one's vicinity.

Is there a way to distinguish between a gravity-free region and orbital free-fall inside the International Space Station? The answer is yes. Consider a pair of objects placed side by side. If the ISS were floating in a gravity-free region, the two objects would remain as placed over time. Since the ISS orbits the Earth, however, each object is in its own orbit about the Earth's center, in its own orbital plane. All orbital planes pass through the center of the Earth and intersect, which means that depending on the proximity of the objects, they may collide by the time the ISS makes a quarter orbit—a little more than 23 minutes! If the

pair of objects are placed one in front of the other, with respect to their direction of motion, there will be no such effect since they follow the same orbital path in the same orbital plane. If the objects are one above the other, one farther from Earth, they will migrate in seemingly strange ways relative to each other because they are in distinct orbits with different PEs. Gravity makes itself present to astronauts by secondary effects that are not directly related to weight. See the “Bob Biker” Practice Pages 49 and 50 for Chapter 8.

> CHECK QUESTION: Consider the tiny tidal forces that DO act on our bodies, as a result of parts of our bodies experiencing slightly different gravitational forces. What planetary body is most responsible for microtides in our bodies? [The Earth, by far. When we are standing, there is a greater difference in Earth gravity on our feet compared to our heads than the corresponding differences in gravity due to farther away planetary bodies.]

Simulated Gravity in Space Habitats

The tallness of people in outer space compared to the radius of their rotating space habitats is very important. A *gravitational gradient* is appreciable in a relatively small structure. If the rim speed is such that the feet are at Earth-normal one *g*, and the head is at the hub, then the gravitational gradient is a full 1-*g*. If the head is halfway to the hub, then the gradient is $^1/_2$-*g*, and so forth. Simulated gravity is directly proportional to the radius. To achieve a comfortable $^1/_{100}$-*g* gradient, the radius of the structure must be 100 times that of one’s height. Hence the designs of large structures that rotate to produce Earth-normal gravity.

Tidal forces reach an extreme in the case of a **black hole**. The unfortunate fate of an astronaut falling into a black hole is not encountering the singularity, but the tidal forces encountered far before getting that close. Approaching feet first, for example, his closer feet would be pulled with a greater force than his midsection, which in turn would be pulled with a greater force than his head. The tidal forces would stretch him and he would be killed before these forces literally pulled him apart.

Gravitational Fields

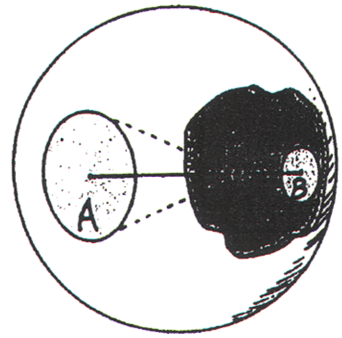
Introduce the idea of force/mass for a body, and the gravitational force field. Relate the gravitational field to the more visible magnetic field as seen via iron filings (Look ahead to Figures 24.2 and 22.4). Since the field strength of the gravitational field is simply the ratio of force per mass, it behaves as force—it follows an inverse-square relationship with distance. Pair this with student viewing of my screencast on *Earth’s Gravity*, where the field strength inside a planet is treated. Follow this with *Tunnel Through Earth*.

It’s easy to convince your students that the gravitational force on a body located at the exact center of the tunnel would be zero—a chalkboard sketch showing a few symmetrical force vectors will do this. Hence the gravitational field at the Earth’s center is zero. Then consider the magnitude of force the body would experience between the center of the Earth and the surface. A few more carefully drawn vectors will show that the forces don’t cancel to zero. The gravitational field is between zero and the value at the surface. You’d like to easily show that it’s half for an Earth of uniform density, to establish the linear part of the graph of Figure 9.24. Careful judgment should be exercised at this point. For most classes I would think the geometrical explanation would constitute “information overload” and it would be best to simply say “It can be shown by geometry that halfway to the center the field is half that at the surface…” and get on with your lecture. For highly motivated students it may be best to develop the geometrical explanation (given earlier in this manual). Then the pedagogical question is raised; how many students profit from your display of the derivation and how many will not?

Class time might better be spent on speculating further about the hole drilled through the Earth. Show with the motion of your hand how if somebody fell in such a tunnel they would undergo simple harmonic motion—and that this motion keeps perfect pace with a satellite in close circular orbit about the Earth. The time for orbit, nearly 90 minutes, is the time to make a to and fro trip in the tunnel. Consider going further and explain how ideally the period of oscillation of a body traveling in such a tunnel under the influence of only gravity would be the same for any straight tunnel—whether from New York to Australia, or from New York to Hawaii or China. You can support this with the analogy of a pendulum that swings through different amplitudes with the same period. In non-vertical tunnels, of course, the object must slide rather than drop without friction. But the period is the same, and timetables for travel in this way would be quite simple; any one-way trip would take nearly 45 minutes. See the screencast *Tunnel Through Earth*.

Gravitational Field Inside a Hollow Planet

Consider the case of a body at the center of a completely *hollow* planet. Again, the field at the center is zero. Then show that the field everywhere inside is zero—by careful explanation of the following sketch. [Consider sample point P, twice as far from side A than side B. A solid cone defines area A and area B. Careful thought shows A has 4 times the area of B, and therefore has 4 times as much mass as B. That would mean 4 times as much gravitational pull, but being twice as far has only $^1/4$ as much pull. $^1/4$ of 4 gives the same gravitational pull as the pull toward B. So the forces cancel out (as they of course do in the center). The forces cancel everywhere inside the shell provided it is of uniform composition. If you stress this material (which will likely be on the heavy-duty side for many students) the following Check Question will measure the worth of your lecture effort.]



CHECK QUESTION: Sketch a graph similar to that in Figure 9.24 to represent the gravitational field inside and outside a hollow sphere. (The graphical answers should look like the following: A thin shelled planet is on the left, a thick shelled one is on the right.)

Speculate about the living conditions of a civilization inside a hollow planet. Expanding on Exercise 54 that considers a hollow planet, consider what happens to the *g* field inside when a massive spaceship lands on the outside surface of the hollow planet. The situation is interesting!

Black Holes

Begin by considering an indestructible person standing on a star, as in Figure 9.27. Write the gravitational equation next to your sketch of the person on the star, and show how only the radius changes in the equation as the star shrinks, and how the force therefore increases. Stress that the force on the person who is able to remain at distance *R* as the star shrinks experiences no change in force—the field there is constant as the star shrinks, even to a black hole. It is near the shrinking surface where the huge fields exist.

CHECK QUESTION: Consider a satellite companion to a star that collapses to become a black hole. How will the orbit of the companion satellite be affected by the star's transformation to a black hole? [Answer is not at all. No terms in the gravitation equation change. What does happen, though, is that matter streams from the visible star to the black hole companion, emitting x-rays as it accelerates toward the black hole, providing evidence of its existence.]

Cosmological Constant

It was long believed that gravity is only attractive. Newton worried that it would cause the universe to collapse and assumed God kept that from happening. Einstein sought a natural explanation and added a constant term to his gravity equation to give a repulsion to stabilize the universe. This was term called the *cosmological constant*. A few years later, after discovery that the universe is expanding, Einstein dropped it, calling it his "biggest blunder." However, in 1998 it was discovered that the expansion of the universe is accelerating under the action of some yet unidentified energy field called **dark energy**, which carries about 68 percent of the energy and mass of the universe. The cosmological constant is thought to be the source of the dark energy. However, calculations give a result that is fifty orders of magnitude greater than what is observed. This "cosmological constant problem" is one of the biggest unanswered questions in physics.

Answers and Solutions for Chapter 9

Reading Check Questions

1. Newton discovered that gravity is universal.
2. The Newtonian synthesis is the union between terrestrial laws and cosmic laws.
3. The Moon falls away from the straight line it would follow if there were no gravitational force acting on it.
4. Every body in the universe attracts every other body with a force that, for two bodies, is directly proportional to the product of their masses and inversely proportional to the square of the distance between their centers:

   $$F = G\frac{m_1 m_2}{d^2}$$

5. The gravitational force between is 6×10^{-11} N.
6. The gravitational force is about 10 N, or more accurately, 9.8 N.
7. Actually the mass of Earth could then be calculated, but calling it "weighing of Earth" seemed more dramatic.
8. The force of gravity is one-fourth as much.
9. Thickness is one-fourth as much.
10. You're closer to Earth's center at Death Valley, below sea level, so you weigh more there than on any mountain peak.
11. Springs would be more compressed when accelerating upward; less compressed when accelerating downward.
12. No changes in compression when moving at constant velocity.
13. Your weight is measured as *mg* when you are firmly supported in a gravitational field of *g* and in equilibrium.
14. In an upward accelerating elevator your weight is greater than *mg*, in free fall your weight is zero.
15. The occupants are without a support force.
16. Tides depend on the difference in pulling strengths.
17. One side is closer.
18. Spring tides are higher.
19. Yes, interior tides occur in Earth and are caused by unequal forces on opposite sides of Earth's interior.
20. At the time of a full or new moon, Sun, Moon, and Earth are aligned.
21. No, for no lever arm would exist between Earth's gravitational pull and the Moon's axis.
22. A gravitational field is a force field about any mass, and can be measured by the amount of force on a unit of mass located in the field.
23. At Earth's center, its gravitational field is zero.
24. Half way to the center, the gravitational field is half that at the surface.
25. Anywhere inside a hollow planet the gravitational field of the planet is zero.
26. Einstein viewed the curve in a planet's path as a result of the curvature of space itself.
27. Your weight would increase.
28. Field strength increases as the star surface shrinks.
29. A black hole is invisible because even light cannot escape it.
30. Perturbations of Uranus' orbit not accounted for by any known planet led to the discovery of Neptune.

Think and Do

31. Open ended.
32. Hold it half way from your eye and it covers the same area of eyesight as the unfolded bill, nicely illustrating the inverse-square law.

Plug and Chug

33. $F = G\frac{m_1 m_2}{d^2} = 6.67 \times 10^{-11} \text{N} \cdot \text{m}^2/\text{kg}^2 \times \frac{(1\text{kg})(6 \times 10^{24}\text{ kg})}{(6.4 \times 10^6 \text{m})^2} = 9.8 \text{ N}.$

34. $F = G\frac{m_1 m_2}{d^2} = 6.67 \times 10^{-11} \text{ N} \cdot \text{m}^2/\text{kg}^2 \times \frac{(1 \text{ kg})(6 \times 10^{24} \text{ kg})}{[2(6.4 \times 10^6 \text{ m})]^2} = 2.5 \text{ N}.$

35. $F = G\frac{m_1 m_2}{d^2} = 6.67 \times 10^{-11}\ \text{N}\cdot\text{m}^2/\text{kg}^2 \times \frac{(6.0 \times 10^{24}\ \text{kg})(7.4 \times 10^{22}\ \text{kg})}{(3.8 \times 10^{8}\ \text{m})^2} = 2.1 \times 10^{20}$ N.

36. $F = G\frac{m_1 m_2}{d^2} = 6.67 \times 10^{-11}\ \text{N}\cdot\text{m}^2/\text{kg}^2 \times \frac{(6.0 \times 10^{24}\ \text{kg})(2.0 \times 10^{30}\ \text{kg})}{(1.5 \times 10^{11}\ \text{m})^2} = 3.6 \times 10^{22}$ N.

37. $F = G\frac{m_1 m_2}{d^2} = 6.67 \times 10^{-11}\ \text{N}\cdot\text{m}^2/\text{kg}^2 \times \frac{(3.0\ \text{kg})(6.4 \times 10^{23}\ \text{kg})}{(5.6 \times 10^{10}\ \text{m})^2} = 4.1 \times 10^{-8}$ N.

38. $F = G\frac{m_1 m_2}{d^2} = 6.67 \times 10^{-11}\ \text{N}\cdot\text{m}^2/\text{kg}^2 \times \frac{(3.0\ \text{kg})(100\ \text{kg})}{(0.5\ \text{m})^2} = 8.0 \times 10^{-8}$ N.

The obstetrician exerts about twice as much gravitational force.

Think and Solve

39. From $F = GmM/d^2$, three times d squared is 9 d^2, which means the force is one ninth of surface weight.

40. From $F = GmM/d^2$, $(2m)(2M) = 4\ mM$, which means the force of gravity between them is 4 times greater.

41. From $F = G2m2M/(2d^2) = 4/4\ (GmM/d^2)$, with the same force of gravitation.

42. From $F = GmM/d^2$, if d is made 10 times smaller, $1/d^2$ is made 100 times larger, which means the force is 100 times greater.

43. $g = \frac{GM}{d^2} = \frac{(6.67 \times 10^{-11})(6.0 \times 10^{24})}{[(6380 + 200)\text{x}10^{3}]^2}$ = 9.24 N/kg or 9.24 m/s^2; 9.24/9.8 = 0.94 or 94%.

44. (a) Substitute the force of gravity in Newton's second law: $a = \frac{F}{m} = \frac{GmM/d^2}{m} = G\frac{M}{d^2}$.

(b) Note that m cancels out. Therefore the only mass affecting your acceleration is the mass M of the planet, not your mass.

Think and Rank

45. B=C, A, D
46. C, B, A
47 a. B, A=C, D b. D, A=C, B
48. C, B, A
49. B, A, C

Think and Explain

50. Nothing to be concerned about on this consumer label. It simply states the universal law of gravitation, which applies to *all* products. It looks like the manufacturer knows some physics and has a sense of humor.

51. This goes back to Chapter 4: A heavy body doesn't fall faster than a light body because the greater gravitational force on the heavier body (its weight), acts on a correspondingly greater mass (inertia). The ratio of gravitational force to mass is the same for every body—hence all bodies in free fall accelerate equally.

52. In accord with the law of inertia, the Moon would move in a straight-line path instead of circling both the Sun and Earth.

53. The force of gravity is the same on each because the masses are the same, as Newton's equation for gravitational force verifies.

54. The force of gravity is the same on each because the masses are the same, as Newton's equation for gravitational force verifies. When dropped the crumpled paper falls faster only because it encounters less air resistance than the sheet.

55. The force decreases as the square of increasing distance, or force increases with the square of decreasing distance.

56. The forces between the apple and Earth are the same in magnitude. Force is the same either way, but the corresponding accelerations of each are different.

57. In accord with Newton's 3^{rd} law, the weight of the Earth in the gravitational field of Larry is 300 N; the same as the weight of Larry in Earth's gravitational field.

58. Less, because an object there is farther from Earth's center.

59. Letting the equation for gravitation guide your thinking, twice the diameter is twice the radius, which corresponds to 1/4 the astronaut's weight at the planet's surface.

60. Letting the equation for gravitation guide your thinking, twice the mass means twice the force, and twice the distance means one-quarter the force. Combined, the astronaut weighs half as much.

61. Your weight would decrease if the Earth expanded with no change in its mass and would increase if the Earth contracted with no change in its mass. Your mass and the Earth's mass don't change, but the distance between you and the Earth's center does change. Force is proportional to the inverse square of this distance.

62. A person is weightless when the only force acting is gravity, and there is no support force. Hence the person in free fall is weightless. But more than gravity acts on the person falling at terminal velocity. In addition to gravity, the falling person is "supported" by air resistance.

63. The high-flying jet plane is not in free fall. It moves at approximately constant velocity so a passenger experiences no net force. The upward support force of the seat matches the downward pull of gravity, providing the sensation of weight. The orbiting space vehicle, on the other hand, is in a state of free fall. No support force is offered by a seat, for it falls at the same rate as the passenger. With no support force, the force of gravity on the passenger is not sensed as weight.

64. Gravitational force is indeed acting on a person who falls off a cliff, and on a person in a space shuttle. Both are falling under the influence of gravity.

65. In a car that drives off a cliff you "float" because the car no longer offers a support force. Both you and the car are in the same state of free fall. But gravity is still acting on you, as evidenced by your acceleration toward the ground. So, by definition, you would be weightless (until air resistance becomes important).

66. The two forces are the normal force and *mg*, which are equal when the elevator doesn't accelerate, and unequal when the elevator accelerates.

67. The pencil has the same state of motion that you have. The force of gravity on the pencil causes it to accelerate downward alongside of you. Although the pencil hovers relative to you, it and you are falling relative to the Earth.

68. The jumper is weightless due to the absence of a support force.

69. You disagree, for the force of gravity on orbiting astronauts is almost as strong as at Earth's surface. They feel weightless because of the absence of a support force.

70. In a rotating habitat (as discussed in Chapter 8) rotation provides the required support force. The weight experienced would be a centrifugal force.

71. Your weight equals *mg* when you are in equilibrium on a horizontal surface and the only forces acting on you are *mg* downward and an equal-and-opposite normal force *N* upward.

72. The scale shows the normal force acting on you, which on an incline is less than the normal force that occurs on a firm horizontal surface. The force of gravity on you is *mg* whatever the support force. But for *mg* to align with the normal force, the scale must be supported on a horizontal surface. If you want to know how strongly gravity is pulling on you, you need to put your scale on a horizontal surface.

73. The force due to gravity, *mg*, does not vary with jouncing. Variations in the scale reading are variations in the support force *N*, not in *mg*.

74. Just as differences in tugs on your shirt will distort the shirt, differences in tugs on the oceans distort the ocean and produce tides.

75. The gravitational pull of the Sun on the Earth is greater than the gravitational pull of the Moon. The tides, however, are caused by the *differences* in gravitational forces by the Moon on opposite sides of the Earth. The difference in gravitational forces by the Moon on opposite sides of the Earth is greater than the corresponding difference in forces by the stronger pulling but much more distant Sun.

76. No torque occurs when the Moon's long axis is aligned with Earth because there is no lever arm. A lever arm exists when the Moon's CG and CM are not aligned with Earth.

77. No. Tides are caused by differences in gravitational pulls. If there are no differences in pulls, there are no tides.

78. Ocean tides are not exactly 12 hours apart because while the Earth spins, the Moon moves in its orbit and appears at its same position overhead about every 25 hours, instead of every 24 hours. So the two-high-tide cycle occurs at about 25-hour intervals, making high tides about 12.5 hours apart.

79. Lowest tides occur along with highest tides, spring tides. So the tide cycle consists of higher-than-average high tides followed by lower-than-average low tides (best for digging clams!).

80. Whenever the ocean tide is unusually high, it will be followed by an unusually low tide. This makes sense, for when one part of the world is having an extra high tide, another part must be donating water and experiencing an extra low tide. Or as the hint in the exercise suggests, if you are in a bathtub and slosh the water so it is extra deep in front of you, that's when it is extra shallow in back of you—"conservation of water!"

81. Because of its relatively small size, different parts of the Mediterranean Sea and other relatively small bodies of water are essentially equidistant from the Moon (or from the Sun). So one part is not pulled with any appreciably different force than any other part. This results in extremely tiny tides. Tides are caused by appreciable differences in pulls.

82. Tides are produced by *differences* in forces, which relate to differences in distance from the attracting body. One's head is appreciably closer than one's feet to the overhead melon. The greater proportional difference for the melon out-tides the more massive but more distant Moon. One's head is not appreciably closer to the Moon than one's feet.

83. In accord with the inverse-square law, twice as far from the Earth's center diminishes the value of *g* to 1/4 its value at the surface or 2.5 m/s^2.

84. For a uniform-density planet, *g* inside at half the Earth's radius would be 5 m/s^2. This can be understood via the spherical shell idea discussed in the chapter. Halfway to the center of the Earth, the mass of the Earth in the outer shell can be neglected—the gravitational contribution of all parts of the shell cancels to zero. Only the mass of the Earth "beneath" contributes to acceleration, the mass in the sphere of radius $r/2$. This sphere of half radius has only $^1/8$ the volume and only $^1/8$ the mass of the whole Earth (volume varies as r^3). This effectively smaller mass alone would find the acceleration due to gravity $^1/8$ that of *g* at the surface. But consider the closer distance to the Earth's center as well. This twice-as-close distance alone would make *g* four times as great (inverse-square law). Combining both factors, $^1/8$ of 4 = $^1/2$, so the acceleration due to gravity at $r/2$ is $g/2$.

85. Your weight would be less down in the mine shaft. One way to explain this is to consider the mass of the Earth above you which pulls upward on you. This effect reduces your weight, just as your weight is reduced if someone pulls upward on you while you're weighing yourself. Or more accurately, we see that you are effectively within a spherical shell in which the gravitational field contribution is zero; and

that you are being pulled only by the spherical portion below you. You are lighter the deeper you go, and if the mine shaft were to theoretically continue to the Earth's center, your weight moves closer to zero.

86. The increase in weight indicates that the Earth is more compressed—more compact—more dense—toward the center. The weight that normally would be lost when in the deepest mine shafts from the upward force of the surrounding "shell" is more than compensated by the added weight gained due to the closeness to the more dense center of the Earth. (Referring to our analysis of Exercise 49, if the mine shaft were deep enough, reaching halfway to the center of the Earth, you would, in fact, weigh less at the bottom of the shaft than on the surface, but more than half your surface weight.)

87. Open-ended.

Think and Discuss

88. Your friend's misconception is a popular one. But investigation of the gravitational equation shows that no matter how big the distance, force never gets to zero. If it were zero, any space shuttle would fly off in a straight-line path!

89. The force of gravity on Moon rocks at the Moon's surface is considerably stronger than the force of gravity between Moon distant Earth. Rocks dropped on the Moon fall onto the Moon's surface. (The force of the Moon's gravity is about $^1/_6$ of the weight the rock would have on Earth; but the force of the Earth's gravity at that distance is only about $^1/_{3600}$ of the rock's Earth-weight.)

90. If gravity between the Moon and its rocks vanished, the rocks, like the Moon, would continue in their orbital path around the Earth. The assumption ignores the law of inertia.

91. Nearer the Moon, because of its smaller mass and lesser pull at equal distances.

92. The Earth and Moon equally pull on each other in a single interaction. In accord with Newton's 3rd law, the pull of the Earth on the Moon is equal and opposite to the pull of the Moon on the Earth. An elastic band pulls equally on the fingers that stretch it.

93.Earth and Moon *do* rotate around a common point, but it's not midway between them (which would require both Earth and Moon to have the same mass). The point around which Earth and Moon rotate (called the *barycenter*) is within the Earth about 4600 km from the Earth's center.

94. For the planet half as far from the Sun, light would be four times as intense. For the planet ten times as far, light would be $^1/_{100}$th as intense.

95. By the geometry of Figure 9.4, tripling the distance from the small source spreads the light over 9 times the area, or 9 m^2. Five times the distance spreads the light over 25 times the area or 25 m^2, and for 10 times as far, 100 m^2.

96. The gravitational force on a body, its weight, depends not only on mass but distance. On Jupiter, this is the distance between the body being weighed and Jupiter's center—the radius of Jupiter. If the radius of Jupiter were the same as that of the Earth, then a body would weigh 300 times as much because Jupiter is 300 times more massive than Earth. But the radius of Jupiter is about 10 times that of Earth, weakening gravity by a factor of 100, resulting in 3 times its Earth weight. (The radius of Jupiter is actually about 11 times that of Earth).

97.If Earth gained mass you'd gain weight. Since Earth is in free fall around the Sun, the Sun contributes nothing to your weight. Earth gravitation presses you to Earth; solar gravitation doesn't press you to Earth.

98. First of all, it would be incorrect to say that the gravitational force of the distant Sun on you is too small to be measured. It's small, but not immeasurably small. If, for example, the Earth's axis were supported such that the Earth could continue turning but not otherwise move, an 85-kg person would see a gain of 1/2 newton on a bathroom scale at midnight and a loss of 1/2 newton at noon. The key idea is *support*. There is no "Sun support" because the Earth and all objects on the Earth—you, your bathroom scale, and everything else—are continually falling around the Sun. Just as you wouldn't be pulled against the seat of your car if it drives off a cliff, and just as a pencil is not pressed against the floor of an elevator in free fall, we are not pressed against or pulled from the Earth by our gravitational

interaction with the Sun. That interaction keeps us and the Earth circling the Sun, but does not press us to the Earth's surface. Our interaction with the Earth does that.

99. The gravitational force varies with distance. At noon you are closer to the Sun. At midnight you are an extra Earth diameter farther away. Therefore the gravitational force of the Sun on you is greater at noon.

100. As stated in question 98, our "Earth weight" is due to the gravitational interaction between our mass and that of the Earth. The Earth and its inhabitants are freely falling around the Sun, the rate of which does not affect our local weights. (If a car drives off a cliff, the Earth's gravity, however strong, plays no role in pressing the occupant against the car while both are falling. Similarly, as the Earth and its inhabitants fall around the Sun, the Sun plays no role in pressing us to the Earth.)

101. The Moon does rotate like a top as it circles Earth. It rotates once per revolution, which is why we see only the same face. If it didn't rotate, we'd see the back side every half month.

102. Tides would be greater if the Earth's diameter were greater because the difference in pulls would be greater. Tides on Earth would be no different if the Moon's diameter were larger. The gravitational influence of the Moon is just as if all the Moon's mass were at its CG. Tidal bulges on the solid surface of the Moon, however, would be greater if the Moon's diameter were larger—but not on the Earth.

103. Earth would produce the largest microtides in your body. Microtides are greatest where the difference between your head and feet is greatest compared with the distance to the tide-pulling body, Earth.

104. Tides occur in Earth's crust and Earth's atmosphere for the same reason they occur in Earth's oceans. Both the crust and atmosphere are large enough so there are appreciable differences in distances to the Moon and Sun. The corresponding gravitational differences account for tides in the crust and atmosphere.

105. More fuel is required for a rocket that leaves the Earth to go to the Moon than the other way around. This is because a rocket must move against the greater gravitational field of the Earth most of the way. (If launched from the Moon to the Earth, then it would be traveling with the Earth's field most of the way.)

106. On a shrinking star, all the mass of the star pulls in a noncanceling direction (beneath your feet)—you get closer to the overall mass concentration and the force increases. If you tunnel into a star, however, there is a cancellation of gravitational pulls; the matter above you pulls counter to the matter below you, resulting in a decrease in the net gravitational force. (Also, the amount of matter "above" you decreases.)

107. $F \sim m_1 m_2/d^2$, where m_2 is the mass of the Sun (which doesn't change when forming a black hole), m_1 is the mass of the orbiting Earth, and d is the distance between the center of mass of Earth and the Sun. None of these terms change, so the force F that holds Earth in orbit does not change.

108. Letting the gravitational force equation be a guide to thinking, we see that gravitational force and hence one's weight does not change if the mass and radius of the Earth do not change. (Although one's weight would be zero inside a hollow uniform shell, on the outside one's weight would be no different than if the same-mass Earth were solid.)

109. Astronauts are weightless because they lack a support force, but they are well in the grips of Earth gravity, which accounts for them circling the Earth rather than going off in a straight line in outer space.

110. The misunderstanding here is not distinguishing between a theory and a hypothesis or conjecture. A theory, such as the theory of universal gravitation, is a synthesis of a large body of information that encompasses well-tested and verified hypotheses about nature. Any doubts about the theory have to do with its applications to yet untested situations, not with the theory itself. One of the features of scientific theories is that they undergo refinement with new knowledge. (Einstein's general theory of relativity has taught us that in fact there are limits to the validity of Newton's theory of universal gravitation.)

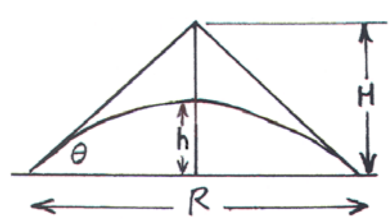
10 Projectile and Satellite Motion

My granddaughter Emily shares good information in opening photo 1. Photos 2 and 3 are of Tenny Lim. As teachers we are rewarded by the success that some of our students achieve after leaving our tutelage. In my career, Tenny Lim is the most outstanding of these. It is with great pride that she is featured in the photo opener to this chapter and the personal profile as well. Photo 3 is of CCSF physics instructor Shruti Kumar projecting a ball after students have made predictions of the landing point. Photo 5 is Peter Rea, whose company Arbor Scientific supplies teaching materials to schools. Arbor is the primary supplier of materials that complement Conceptual Physics. He is also the main supplier of my classroom videos, both on DVDs and more recently via streaming from the Arbor Scientific website.

In editions previous to the ninth edition, projectile motion was treated with linear motion. Kinematics began the sequence of mechanics chapters. Since then I've postponed projectile motion until after Newton's laws and energy, and just before satellite motion. When projectiles move fast enough for the Earth's curvature to make a difference in range, you're at the doorstep to satellite motion.

Regarding 45° as the maximum range for projectiles, keep in mind that this is only true when air resistance can be neglected, and most important and often overlooked, when the launching speed is the same at all angles concerned. Tilt a water hose up 45° and sure enough, for short distances where air resistance is nil, it attains maximum range. The same is true for a slowly-bunted baseball. But for a high-speed ball, air resistance is a factor and maximum range occurs for angles between 39° and 42°. For very high speeds where the lesser air resistance of high altitudes is a consideration, angles greater than 45° produce maximum range. During World War I, for example, the German cannon "Big Bertha" fired shells 11.5 km high and attained maximum range at 52°. Air resistance is one factor; launching speed is another. When one throws a heavy object, like a shot put, its launching speed is less for higher angles simply because some of the launching force must be used to overcome the force due to gravity. (You can throw a heavy boulder a lot faster horizontally than you can straight up.) Shot puts are usually launched at angles slightly less than 40°. The fact that they are launched higher than ground level decreases the angle as well. Screencast *Ball Toss* covers much of this.

Interestingly, the maximum height of a projectile following a parabolic path is nicely given by sketching an isosceles triangle with the base equal to the range of the projectile. Let the two side angles be equal to the launch angle θ, as shown in the figure. The maximum height h reached by the projectile is equal to one-half H, the altitude of the triangle. This goodie from Jon Lamoreux and Luis Phillipe Tosi, of Culver Academies, Culver, IN.



The interesting fact that projectiles launched at a particular angle have the small range if launched at the complementary angle is stated without proof in the chapter, and is shown in Figure 10.11. This fact is shown by the range formula, $R = (2v \sin\theta \cos\theta)/g$. Because the sine of an angle is the cosine of the complement of that angle, replacing the angle with its complement results in the same range. So the range is the same whether aiming at θ or at $(90° - \theta)$. As said, maximum range occurs at a projection angle of 45°, where sine and cosine are equal.

The spin of the Earth is helpful in launching satellites, which gives advantage to launching cities closest to the equator. The launch site closest to the equator is Kaurou, French Guiana, in South America, 5° 08', used by the European Space Agency. The U.S. launches from Cape Canaveral, 28° 22', and Vandenberg, 34° 38'. Russia used to launch at Kapustin Yar, 48° 31', Plesetsk, 62° 42', and Tyuratam (Baikonur) 45° 38'. Is Hawaii, less than 20° in our space launching future?

If you haven't shown the 15-minute oldie but goodie NASA film, "Zero *g*," be sure to show it now. It is of footage taken aboard Skylab in 1978, narrated by astronaut Owen Garriott. Newton's laws of motion are reviewed with excellent and entertaining examples. (It would be a shame for this stimulating movie to fall through the cracks due to being "dated.")

Ask your students this question: An Earth satellite remains in orbit because it's above Earth's A. atmosphere. B. gravitational field. C. Both of these. D. Neither of these. Be prepared for most to answer C. That's because of the common misconception that no gravitational field exists in satellite territory. Of course it's the gravitational field that keeps a satellite from flying off in space, but this isn't immediately apparent to many students. Strictly speaking, there IS *some* atmosphere in satellite territory. That's why boosters on the ISS have to periodically fire to overcome the slight drag that exists. So perhaps in your discussion, qualify your question to "it's above <u>most</u> of Earth's".

Solar Photon Force: To a small extent, sunlight affects satellites, particularly the large disco-ball-like satellite LAGEOS, which wobbles slightly in its orbit because of unequal heating by sunlight. The side in the Sun radiates infrared photons, the energy of which provides a small, but persistent, rocket effect as the photons eject from the surface. So a net force some 100 billion times weaker than gravity pushes on the satellite in a direction away from its hot end. LAGEOS has 426 prism-shaped mirrors. By reflecting laser beams off its mirrored surface, geophysicists can make precise measurements of tiny displacements in the Earth's surface.

Asteroids: Of particular interest are asteroids that threaten Planet Earth. Asteroid 2004 MN4 is big enough to flatten Texas and a couple of European countries with an impact equivalent to 10,000 megatons of dynamite—more than the world's nuclear weapons. The asteroid is predicted to have a close encounter with Earth in 2029, which likely won't be the last of its close encounters. Space missions in the future may employ "tugboat" spacecraft to near-Earth objects, dock with them and gently alter their speeds to more favorable orbits.

Space Debris: More than 20,000 pieces of space trash larger than 10 cm are in low-Earth orbit, along with a half million bits of 1-to-2 cm bits of junk in between. Yuk!

Tunnel through Earth: Neil de Grasse Tyson does a nice job on NOVA describing what would happen if you fell into a tunnel that goes from one side of Earth, through its center, to the other side. I attempt the same in the screencast *Tunnel Through Earth*.

Practicing Physics Book:
- Independence of Horizontal and Vertical Components of Motion
- Tossed Ball
- Satellites in Circular Orbit
- Satellites in Elliptical Orbit
- Mechanics Overview

Problem Solving Book:
Many problems involve projectile motion and satellite motion

Laboratory Manual:
- The BB Race *Horizontal and Vertical Motion* (Demonstration)
- Bull's Eye *A Puzzle You CAN Solve* (Experiment)
- Blast Off! *Rockets Real and Virtual* (Experiment and Tech Lab)
- Worlds of Wonder *Orbital Mechanics Simulation* (Tech Lab)

Next-Time Questions:
- Ball Toss from Tower
- Monkey and Banana
- Elliptical Orbit
- Escape Velocity
- Satellite Speed
- Satellite Mass
- Earth Satellites
- Orbital Speed
- Escape Fuel
- Moon Face
- Dart Gun
- Bull's-Eye
- Projectile Speeds

Hewitt-Drew-It! Screencasts: •*Sideways Drop* •*Ball Toss* •*Tennis-Ball Problem* •*Satellite Speed* •*Circular/Eliptical Orbits*

SUGGESTED LECTURE PRESENTATION

Independence of Horizontal and Vertical Motion

Roll a ball off the edge of your lecture table and call attention to the curve it follows. The ball is a projectile. Discuss the idea of the "downwardness" of gravity, and how there is no "horizontalness" to it, and therefore no horizontal influence on the projectile. Draw a rendition of Figure 10.2 on the board, with vectors. You're going an extra step beyond the textbook treatment.

Pose the situation of the horizontally-held gun and the shooter who drops a bullet at the same time he pulls the trigger, and ask which bullet hits the ground first. (This is treated in screencast *Sideways Drop* and also in a video.)

> DEMONSTRATION: Show the independence of horizontal and vertical motion with a spring-gun apparatus that will shoot a ball horizontally while at the same time dropping another that falls vertically. Follow this up with the popular "monkey and hunter" demonstration.

> CHECK QUESTIONS: Point to some target at the far side of your classroom and ask your class to imagine you are going to project a rock to the target via a slingshot. Ask if you should aim at the target, above it, or below it. Easy stuff. Then ask your class to suppose it takes 1 second for the rock to reach the target. If you aim directly at the target, it will fall beneath and miss. How far beneath the target would the rock hit (if the floor weren't in the way)? Have your students check with their neighbors. Then ask how far above should you aim to hit the target. Do a neighbor check. Now you're ready to discuss Figure 10.6 (nicely developed in Practicing Physics Book pages 55 and 56).

My screencast *Tennis-Ball Problem* features an interesting case involving the independence of horizontal and vertical motion, highlighting a method for solving problems in general—which is to begin *with what is asked for*. This method is as simple and direct as can be, answering the student question, "How do I begin a problem solution?"

Air Resistance

Acknowledge the large effect of air resistance on fast-moving objects such as bullets and cannonballs. A batted baseball, for example, travels only about 60 percent as far in air as it would in a vacuum. Its curved path is no longer a parabola, as Figure 10.13 indicates. What makes its decent steeper than its ascent is the horizontal slowing due to air resistance. What makes it not as high is air resistance vertically, which diminishes with height. This is covered in the screencast *Ball Toss*.

Hang Time Again

Ask if one could jump higher if on a moving skateboard or in a moving bus. It should be clear that the answer is no to both. But one can usually jump higher from a running jump. It is a mistake to assume that the horizontal motion is responsible for the higher jump and longer hang time. The action of running likely enables a greater force between the foot and floor, which gives a greater vertical lift-off component of velocity. This greater bound against the floor, and not any holiday by gravity on a horizontally moving body, is the explanation. Stress that the vertical component of velocity alone determines vertical height and hang time.

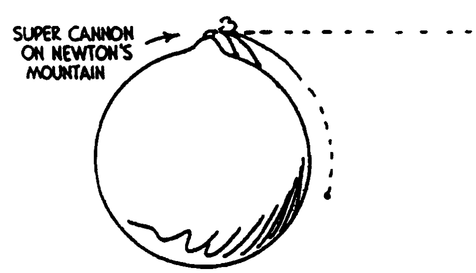
Projectiles

There are several ways to horizontally launch a projectile and have your class predict where it will strike the floor. Chuck Stone nicely shows one method in Figure 10.5. If this isn't a lab activity, consider it a classroom demonstration. If students know the speed at which the projectile is horizontally launched, and the height of launch, they can predict where the projectile will hit. It's a fun experience.

This is supported by the relationship of the curved path of Figure 10.6 and the vertical distance fallen, $d = 5t^2$, of Chapter 3. Stress that the projectile is falling beneath the straight line it would otherwise follow. This idea is important for later understanding of satellite motion. Continue with an explanation of Figure 10.7, and how the dangling beads of page 187 nicely summarizes projectile motion. A worthwhile class project can be fashioning such beads from points on a meterstick.

Discuss Figure 10.15 and ask for the pitching speed if the ball traveled 30 m instead of 20 m. Note the vertical height is 5 m. If you use any height that does not correspond to an integral number of seconds, you're diverting your focus from physics to algebra. This leads to what the screencast *Tennis-Ball Problem* that asks for the maximum speed of a tennis ball clearing the net. More interesting is considering greater horizontal distances—great enough for the curvature of the Earth to make a difference in arriving at the answer. It's easy to see that the time the projectile is in the air increases where the Earth curves beneath the trajectory.

Satellite Motion

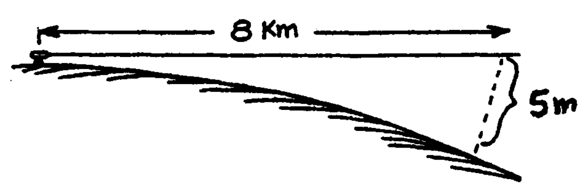


Sketch "Newton's Mountain" and consider the longer time intervals for greater and greater horizontal speeds. Ask if there is a "pitching speed" or cannonball velocity large enough so the time in the air is forever. Not literally "in the air," which is why the cannon is atop a mountain that extends above the atmosphere. The answer of course is yes. Fired fast enough the cannonball will fall around the world rather than into it. You're into satellite motion.

> CHECK QUESTION: Why is it confusing to ask why a satellite doesn't fall? [All satellites are continuously falling, in the sense that they fall below the straight line they would travel if they weren't. Why they don't crash to Earth is a different question.]

Calculating Satellite Speed

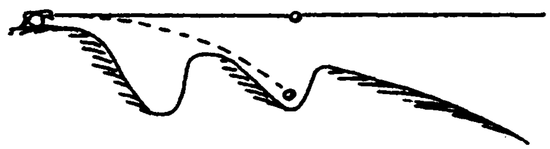
An effective skit (covered in the screencast *Satellite Speed*) that can have your class calculating the speed necessary for close Earth orbit is as follows: Call attention to the curvature of the Earth, Figure 10.17. Consider a horizontal laser standing about a meter above the ground with its beam shining over a level desert. The beam is straight but the desert floor curves 5 m over an 8000 m or 8 km tangent, which you sketch on your chalkboard. Stress this is not to scale.



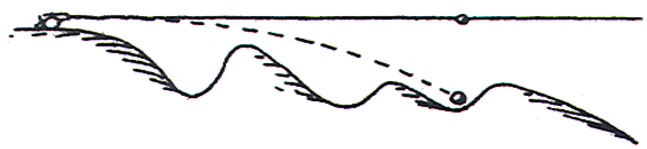
Now erase the laser and sketch in a super cannon positioned so it points along the laser line. Consider a cannonball fired at say, 2 km/s, and ask how far downrange will it be at the end of one second. A neighbor

check should yield an answer of 2 km, which you indicate with an "X." But it doesn't really get to the "X," you say, for it falls beneath the "X" because of gravity. How far? 5 m if the sand weren't in the way. Ask if 2 km/s is sufficient for orbiting the Earth. Clearly not, for the cannonball strikes the ground. If the cannonball is not to hit the ground, we'd have to dig a trench first, as you show on your sketch, which now looks like this:

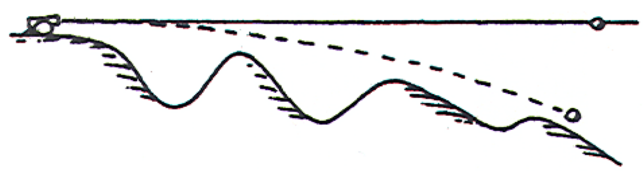
Continue by considering a greater muzzle velocity, say 4 km/s, so the cannonball travels 4 km in one second. Ask if this is fast enough to attain an Earth orbit. Student response should indicate that they realize that the cannonball will hit the ground before 1 second is up. Then repeat the previous line of reasoning, again having to dig a trench, and your sketch looks like this:



Continue by considering a greater muzzle velocity—great enough so the cannonball travels 6 km in 1 second. This is 6 km/s. Ask if this is fast enough not to hit the ground (or equivalently, if it is fast enough for Earth orbit). Then repeat the previous line of reasoning, again having to dig a trench. Now your sketch looks like this:



You're almost there. Continue by considering a muzzle velocity great enough so the cannonball travels 8 km in one second. (Don't state the velocity is 8 km/s here as you'll diminish your punch line.) Repeat your previous reasoning and note that this time you don't have to dig a trench! After a pause, and with a tone of importance, ask the class with what speed must the cannonball have to orbit the Earth. Done properly, you have led your class into a "derivation" of orbital speed about the Earth with no equations or algebra.



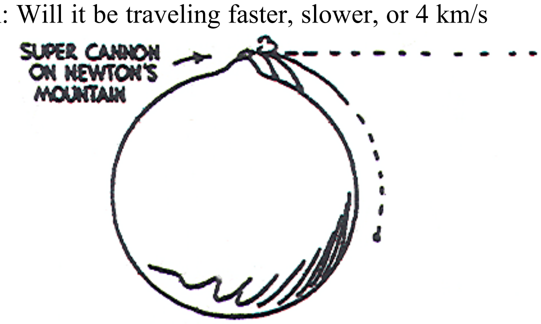
Acknowledge that the gravitational force is less on satellites in higher orbits so they do not need to go so fast. This is acknowledged later in the chapter in a footnote. (Since $v = \sqrt{GM/d}$, a satellite at 4 times the Earth's radius needs to travel only half as fast, 4 km/s.)

You can wind up your brief treatment of satellite motion and catch its essence via the following skit: Ask your students to pretend they are encountered by a bright youngster, too young to have much knowledge of physics and mathematics, but who nevertheless asks why satellites seem to defy gravity and stay in orbit. You ask what answer could correctly satisfy the curiosity of the kid, then pose the following dialogue between the kid and the students in your class (you're effectively suggesting how the student might interact with the bright kid). Ask the kid to observe and then describe what you do, as you hold a rock at arm's length and then simply drop it. The kid replies, "You dropped the rock and it fell to the ground below," to which you respond, "Very good—now what happens this time?", as you move your hand horizontally and again drop the rock. The kid observes and then says, "The rock dropped again, but because your hand was

moving it followed a curved path and fell farther away." You continue, "Very good—now again—" as you throw the rock still farther. The kid replies, "I note that as your hand moves faster, the path follows a wider curve." You're elated at this response, and you ask the kid, "How far away will the rock hit the ground if its curved path matches the curved surface of the Earth?" The kid at first appears very puzzled, but then beams, "Oh—I get it! The stone doesn't hit at all—it's in Earth orbit." Then you interrupt your dialogue and ask the class, "Do YOU get it?" Then back to the kid who asks, "But isn't it really more complicated than that?", to which the answer is NO. The essential idea of satellite motion IS that simple.

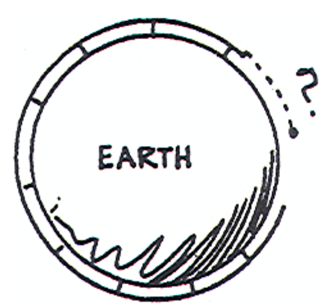
Moving Perpendicular vs Moving Nonperpendicular to Gravity
Pose the case of rolling a ball along a bowling alley. Does gravity pull on the ball? [Yes.] Does gravity speed up or slow down the ball? [No.] Why? [Because all along the horizontal surface, gravity pulls in a direction downward, perpendicular to the surface. There is no component of gravity pulling horizontally, not forward and not backward.] This is the topic of Figure 10.22. Then ask if this fact relates to why a satellite in circular orbit similarly doesn't speed up or slow down due to gravity's persistent pull on it. [Aha! In both the ball on the alley and the satellite above, both "criss-cross" gravity, having no component of gravitational force in the direction of motion. No change in speed, no work, no change in KE, no change in PE. Aha! The cannonball and the bowling ball simply coast.]

Discuss the motion of a cannonball fired horizontally from a mountain top. Suppose the cannonball leaves the cannon at a velocity of say 1 km/s. Ask your class whether the speed when it strikes the ground will be 1 km/s, more than 1 km/s, or less than 1 km/s (neglecting air resistance). The answer is that it strikes at *more* than 1 km/s because gravity speeds it up. (Toss your keys horizontally from a one-story window and catching them would pose no problem. But if you toss them horizontally from the top of a 20-story building, you wouldn't want to catch them!) That's because gravity plays a role on speed. Sketch "Newton's Mountain" on the whole world as shown, and sketch a trajectory that meets Earth's surface. Suppose the firing speed is now 4 km/s. Repeat your question: Will it be traveling faster, slower, or 4 km/s when it hits the ground? Again, faster, because it moves in the direction of gravity. Caution: Do not draw a trajectory that meets the Earth's surface at a point beyond the halfway mark. (Interestingly, the Zero-*g* film and other depictions show a complete orbit when past the half-way point, which is erroneous. Why? Because the parabolic path is actually a segment of a Keplerian ellipse, Figure 10.28. Halfway around puts it all around). Now draw the circular trajectory that occurs when the firing speed is 8 km/s. Ask if the speed increases, decreases, or remains the same after leaving the cannon. This time it remains the same. Why?



Neighbor checking time!

Circular Orbits
Erase the mountain from your sketch of the world and draw a huge elevated bowling alley that completely circles the world (Figure 10.23). You're extending Figure 10.22. Show how a bowling ball on such an alley would gain no speed because of gravity. But now cut part of the alley away, so the ball rolls off the edge and crashes to the ground below. Does it gain speed after falling in the gap? [Yes, because its circular path becomes a parabolic path, no longer moving perpendicular to gravity—having a component of velocity in the downward direction of the Earth's gravity.] Acknowledge that if the ball moves faster it will fall farther before crashing to the ground. Ask what speed would allow it to clear the gap (like a motorcyclist who drives off a ramp and clears a gap to meet a ramp on the other side). [8 km/s, of course.] Can the gap be bigger at this speed? Sketch a gap that nearly circles the world when you ask this question. Then ask, what happens with no alley? And your class sees that at 8 km/s no supporting alley is needed. The ball orbits the Earth.



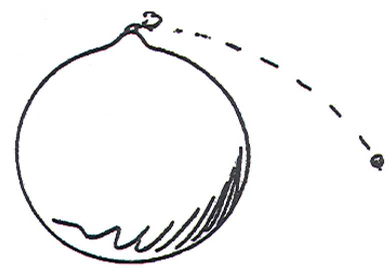
CHECK QUESTION: We say that satellites are falling around the Earth. But communication satellites remain at one place overhead. Isn't this contradictory? [Communication satellites fall in a wider circle than closer satellites. Their periods are 24 hours, which coincides with the period of the spinning Earth. So from Earth they appear to be motionless.]

Ask your class if they are familiar with an Earth satellite that has an average period of one month. There certainly is—it's the Moon, which has been falling around Earth for billions of years! Go further and ask about stars in the sky that appear motionless. Are they motionless, just hovering in space? The answer is NO. Stars in our galaxy, the Milky Way, are falling around the center of the galaxy. How intriguing that *everything is falling*! (This information should elicit interest even in the dullest of your students :-)

CHECK QUESTION: Why is it advantageous to launch rockets close to the equator? [The tangential speed at the equator is 1000 miles per hour, which can be subtracted from the speed needed to put a satellite in orbit. The closer the launch site to the equator, the closer it is to the 1000 mph free ride.]

Elliptical Orbits

Back to Newton's Mountain. Fire the cannonball at 9 km/s. It overshoots a circular path. Your sketch looks like this. Ask, at the position shown, is the cannonball moving at 9 km/s, more than 9 km/s, or less than 9 km/s. And why? After a neighbor check, toss a piece of chalk upward and say you toss it upward with an initial speed of 9 m/s. When it's halfway to the top of its path, is it moving 9 m/s, more than 9 m/s, or less than 9 m/s? Equate the two situations. [In both cases the projectile slows because it is going against gravity.]



Continue your sketch and show a closed path—an ellipse. As you draw the elliptical path, show with a sweeping motion of your arm how the satellite slows in receding from the Earth, moving slowest at its farthermost point, then how it speeds in falling towards the Earth, whipping around the Earth and repeating the cycle over and over again. Move to a fresh part of the chalkboard and redraw with the mountain at the bottom, so your sketch is more like Figure 10.27. (It is more comfortable seeing your chalk moving slowest when farthest coincides with the direction "up" in the classroom. I quip that Australians have no trouble seeing it the first way.)

Sketch in larger ellipses for still greater cannon speeds, with the limit being 11.2 km/s, beyond which the path does not close—escape speed.

State that Newton's equation was deducted from Kepler's laws.

Kepler's Laws

Briefly discuss Kepler's laws. Sketch an elliptical path of a planet about the Sun as in Figure 10.29. Show how the equal areas law means that the planet travels slowest when farthest from the Sun, and fastest when closest. State that Kepler had no idea why this was so. Walk to the side of your room and toss a piece of chalk upward at a slight angle so the class can see the parabolic path it traces. Ask where the chalk is moving slowest? Fastest? Why is it moving slowest at the top? [Because it has been traveling against gravity all the way up!] Why is it moving fastest when it is thrown and when it is caught? [It's moving fastest when it is caught because it has been traveling in the direction of gravity all the way down!] Speculate how amazed Kepler would have been if the same questions were asked of him, and relate this to the speeds of the planets around the Sun—slowest where they have been traveling against the gravity of the Sun, and fastest where they have been falling back toward the Sun. Kepler would have been amazed to see the physics of a body tossed upward is essentially the physics of satellite motion! Kepler lacked this simple model to guide his thinking. What simple models of tomorrow do we lack today, that finds us presently blind to the common sense of tomorrow?

Work-Energy Relationship for Satellites

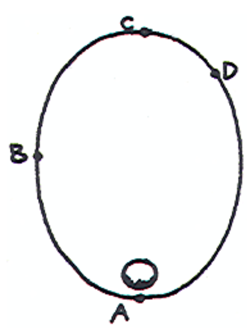
You already have sketches on the board of circular and elliptical orbits. Draw sample satellites and then sketch in force vectors. Ask the class to do likewise, and then draw component vectors parallel and perpendicular to instantaneous directions of motion. Then show how the changes in speed are consistent with the work-energy relationship.

Draw a large ellipse on the board with a planet in various positions and ask your class for a comparison of the relative magnitudes of KE and PE along the orbit. You can do this with different size symbols for KE and PE. Stress that the two add up to be the same. (This is treated in the screencast *Circular/Elliptical* Orbit.)

Escape Speed
Distinguish between ballistic speed and sustained speed, and that the value 11.2 km/s refers to ballistic speed. (One could go to the Moon at 1 km/s, given a means of sustaining that speed and enough time to make the trip!) Compare the escape speeds from different bodies via Table 10-1.

Maximum Falling Speed
The idea of maximum falling speed, footnoted on page 199, is sufficiently interesting for elaboration. Pretend you throw your car keys from ground level to your friend at the top of a building. Throw them too fast and they pass beyond your friend; throw them too slow and they never reach your friend. But if you throw them just right, say 11 m/s, they just barely reach her so she has only to grab them at their point of zero speed. Question: It took a speed of 11 m/s to get the keys up to her—if she simply drops them, how fast will they fall into your hands? Aha! If it takes a speed of 11.2 km/s to throw them to her if she is somewhat beyond Pluto, and she similarly drops them, how fast will they fall into your hands? Now your students understand maximum falling speed.

CHECK QUESTIONS: This reviews several chapters of mechanics; draw an elliptical orbit about a planet as shown on the board. Pose the following questions (from the *Practicing Physics Book*): At which position does the satellite experience the maximum



(a) gravitational force on it?
(b) speed?
(c) momentum?
(d) kinetic energy?
(e) gravitational potential energy?
(f) total energy (KE + PE)?
(g) acceleration?
(h) angular momentum?

Don't be surprised to find many of your students miss (g), acceleration, even though they answer the first about force correctly. If they use either equation for acceleration as their "guide," the answer is at hand; that is, from a - F/m, the acceleration is seen to be maximum where the force is maximum—at A. Or from a = (change in v)/t, acceleration is seen to be greatest where most of the change occurs—where the satellite whips around A. This Check Question summarizes important ideas in four chapters. Go over the answers carefully.

Answers and Solutions for Chapter 10

Reading Check Questions

1. A projectile is any object that is projected by some means and continues in motion by its own inertia.
2. The vertical component moves with or against gravity, while the horizontal component moves with no horizontal force acting.
3. With no air resistance the horizontal component of velocity remains constant, both in rising and falling.
4. Neglecting air resistance, the vertical component of velocity decreases as the stone rises, and increases as it descends, the same as with any freely-falling object.
5. In 1 second it falls 5 m beneath the line; For 2 seconds, 20 m beneath.
6. No, the falling distance beneath the line makes no difference whether or not the line is at an angle.
7. An angle of 15° would produce the same range, in accord with Figure 4.19.
8. The projectile would return at the same speed of 100 m/s, as indicated in Figure 4.22.
9. A projectile can fall around the Earth if it has sufficient tangential speed so that its curve downward is no sharper than that of Earth's curvature.
10. The speed must be enough so that the path of the projectile matches Earth's curvature.
11. A satellite must remain above the atmosphere because air resistance would not only slow it down, but incinerate it at its high speed. A satellite must not have to contend with either of these.
12. Speed doesn't change because there is no component of gravitational force along the ball's direction of motion when the bowling ball is moving horizontally.
13. As with the previous question, speed doesn't change when there's no component of gravitational force in the direction of its motion.
14. The time for a complete close orbit is about 90 minutes.
15. The period for satellites at higher altitudes is more than 90 minutes.
16. In an elliptical orbit there *is* a component of force in the direction of motion.
17. A satellite has the greatest speed when nearest Earth, and least when farthest away.
18. Tycho Brahe gathered the data, Kepler discovered elliptical orbits, and Newton explained them.
19. Kepler discovered the period squared was proportional to the radial distance cubed.
20. Kepler thought the planets were being pulled along their orbits. Newton realized they were being pulled toward the Sun.
21. KE is constant because no work is done by gravity on the satellite.
22. The sum of KE and PE is constant for all orbits.
23. Yes, escape speed can be at speeds less than 11.2 km/s if that speed is *sustained*.

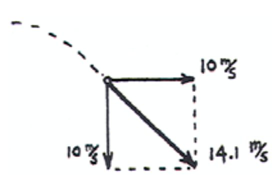
Think and Do

24. A worthwhile activity, and holding the stick at different angles nicely illustrates that distance of "fall" doesn't depend on angle of launch. If using a meterstick, at the 25 cm mark a 5-cm string can be attached; at the 50-cm mark, a 20 cm string; at the 75-cm mark, a 45 cm string; and at the end of the stick, the 100-cm mark, an 80 cm string. (Consider this as a classroom activity.)

25. Physics is about connections in nature. Discovering the connection between falling water in a swung bucket and falling satellites was an "aha" moment for PGH while whirling a water-filled bucket during a rotational-motion classroom demonstration—on a day when a much-publicized satellite launch was being discussed. How exhilarating to discover connections in nature!)

Think and Solve

26. One second after being thrown, its horizontal component of velocity is 10 m/s, and its vertical component is also 10 m/s. By the Pythagorean theorem, V = $\sqrt{(10^2 + 10^2)}$ = 14.1 m/s. (It is moving at a 45° angle.)



27. (a) From $y = 5t^2 = 5(30)^2$ = 4,500 m, or 4.5 km high (4.4 km if we use $g = 9.8\ m/s^2$).
(b) In 30 seconds; $d = vt$ = 280 m/s × 30 s = 8400 m.

(c) The engine is directly below the airplane. (In a more practical case, air resistance is overcome for the plane by its engines, but not for the falling engine. The engine's speed is reduced by air resistance, covering less than 8400 horizontal m, landing behind the plane.)

28. Time during which the bullet travels is 200 m/400 m/s = 0.5 s. (a) So distance fallen is = ½ gt^2 = ½ (10 m/s^2)(0.5 s)^2 = 1.25 m. (b) The barrel must be aimed 1.25 m above the bullseye to match the falling distance.

29. At the top of its trajectory, the vertical component of velocity is zero, leaving only the horizontal component. The horizontal component at the top or anywhere along the path is the same as the initial horizontal component, **100 m/s** (the side of a square where the diagonal is 141).

30. The distance wanted is horizontal velocity $\times$ time. We find the time from the vertical distance the ball falls to the top of the can. This distance y is 1.0 m – 0.2 m = 0.8 m. The time is found using g = 10 m/s^2 and y = 0.8 m = ½ gt^2. Solving for t we get $t = \sqrt{2y/g} = \sqrt{[2(0.8\text{m})/10\text{ m/s}^2]}$ =0.4 s. Horizontal travel is then $d = vt$ = (8.0 m/s)(0.4 s) = 3.2 m. (If the height of the can is *not* subtracted from the 1.0-m vertical distance between floor and tabletop, the calculated d will equal 3.6 m, the can will be too far away, and the ball will miss!)

31. Total energy = 5000 MJ + 4500 MJ = 9500 MJ. Subtract 6000 MJ and KE = 3500 MJ.

32. In accord with the work-energy theorem (Chapter 7) W = ΔKE the work done equals energy gained. The KE gain is 8 - 5 billion joules = 3 billion joules. The potential energy decreases by the same amount that the kinetic energy increases, 3 billion joules.

33. Hang time depends only on the vertical component of initial velocity and the corresponding vertical distance attained. From $d = 5t^2$ a vertical 1.25 m drop corresponds to 0.5 s ($t = \sqrt{2d/g} = \sqrt{2(1.25)/10}$ = 0.5 s). Double this (time up and time down) for a hang time of 1 s. Hang time is the same whatever the horizontal distance traveled.

34. (a) We're asked for horizontal speed, so we write, $v_x = \frac{d}{t}$, where d is horizontal distance traveled in time t. The time t of the ball in flight is as if we drop it from rest a vertical distance y from the top of the net. At highest point in its path, its vertical component of velocity is zero.

From $y = 1/2gt^2 \Rightarrow t^2 = \frac{2y}{g} \Rightarrow t = \sqrt{\frac{2y}{g}}$. So $v = \frac{d}{\sqrt{\frac{2y}{g}}}$.

(b) $v = \frac{d}{\sqrt{\frac{2y}{g}}} = \frac{12.0\text{m}}{\sqrt{\frac{2(1.00\text{ m})}{10\text{m}/\text{s}^2}}} = 26.8\text{ m}/\text{s} \approx 27\text{ m}/\text{s}.$

(c) Note mass of the ball doesn't show in the equation, so mass is irrelevant.

Think and Rank

35. a. B, C, A, D b. B, D, A, C c. A=B=C=D (10 m/s^2)
36. a. A=B=C b. A=B=C c. A=B=C d. B, A, C
37. a. A, B, C b. C, B, A
38. a. A, B, C, D b. A, B, C, D c. A, B, C, D d. A, B, C, D e. D, C, B, A f. A=B=C=D g. A, B, C, D

Think and Explain

39. Divers can orient their bodies to change the force of air resistance so that the ratio of *net* force to mass is nearly the same for each.

40. In accord with the principle of horizontal and vertical projectile motion, the time to hit the floor is independent of the ball's speed.

41. Yes, it will hit with a higher speed in the same time because the horizontal (not the vertical) component of motion is greater.

42. No, because while the ball is in the air its horizontal speed doesn't change, but the train's speed does.

43. The crate will not hit the Porsche, but will crash a distance beyond it determined by the height and speed of the plane.

44. The path of the falling object will be a parabola as seen by an observer off to the side on the ground. You, however, will see the object fall straight down along a vertical path beneath you. You'll be directly above the point of impact. In the case of air resistance, where the airplane maintains constant velocity via its engines while air resistance decreases the horizontal component of velocity for the falling object, impact will be somewhere behind the airplane.

45. (a) The paths are parabolas. (b) The paths would be straight lines.

46. There are no forces horizontally (neglecting air resistance) so there is no horizontal acceleration, hence the horizontal component of velocity doesn't change. Gravitation acts vertically, which is why the vertical component of velocity changes.

47. Minimum speed occurs at the top, which is the same as the horizontal component of velocity anywhere along the path.

48. The bullet falls beneath the projected line of the barrel. To compensate for the bullet's fall, the barrel is elevated. How much elevation depends on the velocity and distance to the target. Correspondingly, the gunsight is raised so the line of sight from the gunsight to the end of the barrel extends to the target. If a scope is used, it is tilted downward to accomplish the same line of sight.

49. Both balls have the same range (see Figure 10.9). The ball with the initial projection angle of 30°, however, is in the air for a shorter time and hits the ground first.

50. The monkey is hit as the dart and monkey meet in midair. For a fast-moving dart, their meeting place is closer to the monkey's starting point than for a slower-moving dart. The dart and monkey fall equal vertical distances—the monkey below the tree, and the dart below the line of sight—because they both fall with equal accelerations for equal times.

51. Any vertically projected object has zero speed at the top of its trajectory. But if it is fired at an angle, only its vertical component of velocity is zero and the velocity of the projectile at the top is equal to its horizontal component of velocity. This would be 100 m/s when the 141-m/s projectile is fired at 45°.

52. Hang time depends only on the vertical component of your lift-off velocity. If you can increase this vertical component from a running position rather than from a dead stop, perhaps by bounding harder against the ground, then hang time is also increased. In any case, hang time depends *only* on the vertical component of your lift-off velocity.

53. The hang time will be the same, in accord with the answer to the preceding exercise. Hang time is related to the vertical height attained in a jump, not on horizontal distance moved across a level floor.

54. The Moon's tangential velocity is what keeps the Moon coasting around the Earth rather than crashing into it. If its tangential velocity were reduced to zero, then it would fall straight into the Earth!

55. From Kepler's third law, $T^2 \sim R^3$, the period is greater when the distance is greater. So the periods of planets farther from the Sun are longer than our year.

56. Yes, the satellite is accelerating, as evidenced by its continual change of direction. It accelerates due to the gravitational force between it and the Earth. The acceleration is toward the Earth's center.

57. Speed does not depend on the mass of the satellite (just as free-fall speed doesn't).

58. Neither the speed of a falling object (without air resistance) nor the speed of a satellite in orbit depends on its mass. In both cases, a greater mass (greater inertia) is balanced by a correspondingly greater gravitational force, so the acceleration remains the same ($a = F/m$, Newton's 2nd law).

59. Gravitation supplies the centripetal force on satellites.

60. The initial vertical climb lets the rocket get through the denser, retarding part of the atmosphere most quickly, and is also the best direction at low initial speed, when a large part of the rocket's thrust is needed just to support the rocket's weight. But eventually the rocket must acquire enough tangential speed to remain in orbit without thrust, so it must tilt until finally its path is horizontal.

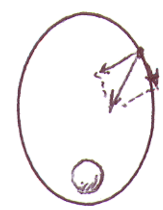
61. Gravity changes the speed of a cannonball when the cannonball moves in the direction of Earth gravity. At low speeds, the cannonball curves downward and gains speed because there is a component of the force of gravity along its direction of motion. Fired fast enough, however, the curvature matches the curvature of the Earth so the cannonball moves at right angles to the force of gravity. With no component of force along its direction of motion, its speed remains constant.

62. Upon slowing it spirals in toward the Earth and in so doing has a component of gravitational force in its direction of motion which causes it to gain speed. Or put another way, in circular orbit the perpendicular component of force does no work on the satellite and it maintains constant speed. But when it slows and spirals toward Earth there is a component of gravitational force that does work to increase the KE of the satellite.

63. A satellite travels faster when closest to the body it orbits. Therefore Earth travels faster about the Sun in December than in June.

64. Yes, a satellite needn't be above the surface of the orbiting body. It could orbit at any distance from the Earth's center of mass. Its orbital speed would be less because the effective mass of the Earth would be that of the mass below the tunnel radius. So interestingly, a satellite in circular orbit has its greatest speed near the surface of the Earth, and decreases with both decreasing and increasing distances.

65. The component along the direction of motion does work on the satellite to change its speed. The component perpendicular to the direction of motion changes its direction of motion.



66. In circular orbit there is no component of force along the direction of the satellite's motion so no work is done. In elliptical orbit, there is always a component of force along the direction of the satellite's motion (except at the apogee and perigee) so work is done on the satellite.

67. When the velocity of a satellite is everywhere perpendicular to the force of gravity, the orbital path is a circle (see Figure 10.20).

68. The period of any satellite at the same distance from Earth as the Moon would be the same as the Moon's, 27.3 days.

69. No way, for the Earth's center is a focus of the elliptical path (including the special case of a circle), so an Earth satellite orbits the center of the Earth. The plane of a satellite coasting in orbit always intersects the Earth's center.

70. Period is greater for satellites farther from Earth.

71. If a box of tools or anything else is "dropped" from an orbiting space vehicle, it has the same tangential speed as the vehicle and remains in orbit. If a box of tools is dropped from a high-flying jumbo jet, it too has the tangential speed of the jet. But this speed is insufficient for the box to fall around and around the Earth. Instead it soon falls into the Earth.

72. It could be dropped by firing it straight backward at the same speed of the satellite. Then its speed relative to Earth would be zero, and it would fall straight downward.

73. When a capsule is projected rearward at 7 km/s with respect to the spaceship, which is itself moving forward at 7 km/s with respect to the Earth, the speed of the capsule with respect to the Earth will be zero. It will have no tangential speed for orbit. What will happen? It will simply drop vertically to Earth and crash.

74. If the speed of the probe relative to the satellite is the same as the speed of the satellite relative to the Moon, then, like the projected capsule that fell to Earth in the previous question, it will drop vertically to the Moon. If fired at twice the speed, it and the satellite would have the same speed relative to the Moon, but in the opposite direction, and might collide with the satellite after half an orbit.

75. The tangential velocity of the Earth about the Sun is 30 km/s. If a rocket carrying the radioactive wastes were fired at 30 km/s from the Earth in the direction opposite to the Earth's orbital motion about the Sun, the wastes would have no tangential velocity with respect to the Sun. They would simply fall into the Sun.

76. Communication satellites only appear motionless because their orbital period coincides with the daily rotation of the Earth.

77. There are several potential advantages. A principal one is bypassing expensive first-stage rockets. Also, the plane, by flying eastward, can impart added initial speed to the spacecraft. And the spacecraft has less air resistance to overcome and somewhat less PE to surmount.

78. Since Moon's surface gravity is much less than Earth's, less thrust and less fuel is required to launch it to escape speed from the Moon.

79. Maximum falling speed by virtue only of the Earth's gravity is 11.2 km/s (see the Table 10.1 or the footnote on page 199).

80. Gravitation may "seem" to cancel, but it doesn't. The airplane is simply in a state of free fall and occupants inside experience no support force. No support force means no sensation of weight.

81. The satellite experiences the greatest gravitational force at A, where it is closest to the Earth, the perigee; and the greatest speed and the greatest velocity at A, and by the same token the greatest momentum and greatest kinetic energy at A, and the greatest gravitational potential energy at the farthest point C. It would have the same total energy (KE + PE) at all parts of its orbit, likewise the same angular momentum because it's conserved. It would have the greatest acceleration at A, where F/m is greatest.

82. Acceleration is maximum where gravitational force is maximum, and that's when Earth is closest to the Sun, at the perigee. At the apogee, force and acceleration are minimum.

Think and Discuss

83. Kicking the ball at angles greater than 45° sacrifices some distance to gain extra time. A kick greater than 45° doesn't go as far, but stays in the air longer, giving players on the kicker's team a chance to run down field and be close to the player on the other team who catches the ball.

84. For very slow-moving bullets, the dropping distance is comparable to the horizontal range, and the resulting parabola is easily noticed (the curved path of a bullet tossed sideways by hand, for example). For high speed bullets, the same drop occurs in the same time, but the horizontal distance traveled is so large that the trajectory is "stretched out" and hardly seems to curve at all. But it does curve. All bullets will drop equal distances in equal times, whatever their speed. (It is interesting to note that air resistance plays only a small role, since the air resistance acting *downward* is practically the same for a slow-moving or fast-moving bullet.)

85. Mars or any body in Earth's orbit would take the same time to orbit. The motion of a satellite, like that of a freely-falling object, does not depend on mass.

86. Consider "Newton's cannon" fired from a tall mountain on Jupiter. To match the wider curvature of much larger Jupiter, and to contend with Jupiter's greater gravitational pull, the cannonball would have to be fired significantly faster. (Orbital speed about Jupiter is about 5 times that for Earth.)

87. Rockets for launching satellites into orbit are fired easterly to take advantage of the spin of the Earth. Any point on the equator of the Earth moves at nearly 0.5 km/s with respect to the center of the Earth or the Earth's polar axis. This extra speed does not have to be provided by the rocket engines. At higher latitudes, this "extra free ride" is less.

88. Hawaii is closer to the equator, and therefore has a greater tangential speed about the polar axis. This speed could be added to the launch speed of a satellite and thereby save fuel. As seen from the North Star, Hawaii is closer to the edge of "turntable Earth" than other locations in the United States.

89. The Moon has no atmosphere (because escape velocity at the Moon's surface is less than the speeds of any atmospheric gases). A satellite 5 km above the Earth's surface is still in considerable atmosphere, as well as in range of some mountain peaks. Atmospheric drag is the factor that most determines orbiting altitude.

90. The satellite circles at the same rate as Earth rotates, which is why it appears motionless to Earth observers. But to remain above a certain location, both the location and satellite need to be in the same line between Earth's center and the satellite. This can only occur above Earth's equator. Above any other location, the "ring" of satellite motion would be out of synch.

91. Singapore lies on the Earth's equator. The plane of the satellite's equatorial orbit includes Singapore, so a satellite can be located directly above Singapore. But in San Francisco, a geosynchronous satellite over the equator is seen at an angle with the vertical—not directly overhead.

92. Considerably less than 8 km/s. To see why, think of "Newton's cannon" fired from a hilltop on tiny Eros, with its small gravity. If the speed of the cannonball were 8 km/s, it would fall far less than 5 m in its first second of travel (as it would on Earth), and would not curve enough to follow the round surface of the asteroid. It would shoot off into space. To follow the curvature of the asteroid, it must be launched with a much smaller speed.

93. At midnight you face away from the Sun, and therefore cannot see the planets closest to the Sun—Mercury and Venus (which lie inside the Earth's orbit).

94. When descending, a satellite meets the atmosphere at almost orbital speed. When ascending, its speed through the air is considerably less and it attains orbital speed well above air drag.

95. No, for an orbit in the plane of the Arctic Circle does not intersect the Earth's center. All Earth satellites orbit in a plane that intersects the center of the Earth. A satellite may pass over the Arctic Circle, but cannot remain above it indefinitely, as a satellite can over the equator.

96. The inverse-square law of gravity finds gravity a mere 62 miles high very nearly as strong as it is on Earth's surface. Gravity is an inverse-square law phenomenon that has nothing to do with being above the atmosphere. Also, there is still some atmosphere, although very thin, above 62 miles in altitude.

97. The GPS system "triangulates" to show locations. One satellite can tell distance between the satellite and the receiver, and two perhaps longitude, but three are needed for altitude, longitude, and latitude. Four confirms the results of three.

98. The half brought to rest will fall vertically to Earth. The other half, in accord with the conservation of linear momentum will have twice the satellite's original velocity, and will move farther from Earth (actually, it will have enough speed to escape Earth and fly into space).

99. The design is a good one. Rotation would provide a centripetal force on the occupants. Watch for this design in future space habitats.

100. In accord with the work-energy relationship, $Fd = \Delta\text{KE}$, for a constant thrust F, the maximum change in KE will occur when d is maximum. The rocket will travel the greatest distance d during the brief firing time when it is traveling fastest—at the perigee.

11 The Atomic Nature of Matter

The photo of the delightful little girl that opens Part Two is Andrea Wu, of Honolulu. This was taken years ago by Mei Tuck Hu. Andrea now has all her teeth and is quite grown up. Mei Tuck went on to become a phyician. I hope all readers will agree that the message related by Andrea is profound, both physics-wise and otherwise.

It is with great pleasure that I begin this chapter with a photo and profile of Richard Feynman, whose books were a great influence on my own writing. Feynman's books were inspirational to me in writing this book. Tucker Haitt is one of the many inspirational physics teachers in the San Francisco Bay Area.

This chapter is the most important chapter in Part two, and should not be skipped.

Practicing Physics Book:
• Atoms and Atomic Nuclei • Subatomic Particles

Laboratory Manual:
• Thickness of a BB Pancake *The Size of an Atom* (Experiment)
• *Oleic Acid Pancake The Size of an Atom* (Experiment)
The first nicely leads into the second, and both may be combined.

Next-Time Questions:
• Germanium Capsules • Adding or Subtracting Protons

Hewitt-Drew-It! Screencasts: •*Atoms* •*Periodic Table*

Although only one neighbor Check Question is identified in the suggested lecture here, please make your own as your lecture unfolds.

SUGGESTED LECTURE PRESENTATION

Begin by posing the situation of breaking a boulder into rocks, rocks into stones, stones into pebbles, pebbles into gravel, gravel into sand, sand into powder, and so forth until you get to the fundamental building block—the atom. Relate how from the earliest days of science people wondered how far the idea of breaking boulders into stones, pebbles, sand, powder, and so on, would go. Does it ever end? Hundreds of years ago, people had no way of finding out, and they instead carried on with philosophical speculation. Not until "modern" chemistry in the late 1700s did people begin to get indirect evidence of some basic order in the combinations of things. The first real "proof" that there were atoms was given by Einstein in 1905, the same year he published his paper on relativity. He calculated what kind of motion is necessary for the observed Brownian motion, based on ideas we've considered already, like energy and momentum

conservation, and the role of atomic motion in heat. Many of the "heavies" in physics at that time didn't believe in atoms until Einstein's work. (The photo of individual atoms taken by Crewe and associates in Figure 11.4 on page 212 is historically significant. It was the first of many to follow.)

Smallness of Atoms

Give examples to convey the idea of the smallness of the atom, i.e., an atom is as many orders of magnitude smaller than a person as an average star is larger than a person—so we stand between the atoms and the stars. The size of an atom is to the size of an apple as the size of an apple is to the size of the Earth. So if you want to imagine an apple full of atoms, think of the Earth, solid-packed with apples.

> CHECK QUESTION: Ask what an atom would "look like" if viewed through a vertical bank of about 40 high-powered optical microscopes stacked one atop the other. [It turns out they wouldn't have an appearance, at least not in the range of frequencies we call light. The atom is smaller than the wavelength of light.]

You might allude to the later study of Chapter 32 and state that the electron beam in the electron microscope has the properties of high-frequency light. Acknowledge the wave nature of matter—the fuzziness in the distinction between particles and waves at the atomic level—that "solid" particles can be seen to be congealed standing waves of energy.

Recycling of Atoms

Lead into the idea of more molecules in your lungs than there are breaths of air in the world with the following: Say that if you put a drop of ink in a bathtub full of water, one sees in a short time that any part of the water has ink in it. The atoms of ink spread out. We can get an idea of how small atoms are from this fact: There are more atoms in a thimbleful of ink than there are thimblefuls of water in the Atlantic Ocean. That means if you throw a thimbleful of ink into the Atlantic Ocean and give it enough years to mix uniformly, and then dip anywhere in the ocean with a thimble, you'll have some atoms of ink in your sample. By now your class is ready for the more interesting bit about breaths of air in the atmosphere, as stated by little Andrea in the photo of the Part 2 opener. As an aside, we've known for many years that methane in the atmosphere originates with cattle, sheep, and termites. Recent findings suggest that green plants are also a source of methane! We all breathe from the same atmosphere.

Empty Space

Discuss the Bohr model of the atom and the electrical role of the nucleus and surrounding electrons. Stress the emptiness of the atom and lead into the idea of solid matter being mostly empty space. State how our bodies are 99.999% empty space, and how a particle, if tiny enough and not affected by electrical forces, could be shot straight through us without even making a hole! Making a direct hit with an atomic nucleus or an electron is as improbable as making a direct hit with a planet or the Sun if you throw a gravity-free dart from outer space at the solar system. Both are mostly empty space. Walk through a beam of neutrons and very few if any will interact with your body. Still smaller neutral particles called neutrinos, the most elusive yet most numerous and fastest of all particles, pass through us every moment. But they do so without consequence, for only very rarely, perhaps once or so per year, do any make a bull's-eye collision with any of our atomic nuclei. They freely pass through the entire Earth with rare interactions. (University of Hawaii at Manoa professor John Learned tells me that the neutrino flux from the 1987 supernova was so enormous that about 1 out of every 240 people on Earth absorbed one of its neutrinos.

Molecules

Distinguish between atoms and molecules. There are a limited number of different atoms, but there are innumerable different molecules—and more are being discovered and constructed.

> CHECK QUESTIONS: What is the number of elements in a water molecule? What is the number of atoms in a water molecule? [Two elements (hydrogen and oxygen), and three atoms (two of hydrogen and one of water).]

Interestingly, whereas an individual atom cannot be seen by the naked eye, some molecules can. One such molecule, called a macro-molecule, is a diamond. A diamond is actually one big carbon molecule! (And

by the way, the lovely girl in Figure 11.8 is my daughter Leslie at the age of 16, who retains that loveliness today.)

Electrical Forces
Discuss the role of electrical forces in preventing us from oozing into our chairs and so forth. Ask the class to imagine that the lecture table is a large magnet, and that you wear magnetic shoes that are repelled by the table you "stand" on. Ask them to imagine whether or not a sheet of paper could be passed between your shoes and the table. For there is a space there. Then state that on the submicroscopic scale that this is indeed what happens when you walk on any solid surface. Only the repelling force isn't magnetic, it's electric! Acknowledge that under very special circumstances the nucleus of one atom can physically touch the nucleus of another atom—that this is what happens in a thermonuclear reaction.

Discuss the relative distances between positive and negative charges in neighboring atoms and the role of the electric forces in molecular structure. (You're discussing the implications of Coulomb's law at short distances—combined with the ideas you previously discussed in your treatment of tides and tidal forces, namely the importance of relative distances.)

Atomic Number and Periodic Table: Schematically show the hydrogen atom, and add a proton and neutrons to build a helium atom, and then a lithium atom, and so on. Discuss atomic number, and the role that the number of protons play in the nucleus in dictating the surrounding electron configuration. Call attention to and briefly discuss the periodic table. Point out that the atomic configurations depicted in Figure 11.6 are simply models not be taken seriously. For example, if the nuclei were drawn to scale they would be scarcely visible specks. And the electrons don't really "orbit," as the drawings suggest—such terms don't seem to have much meaning at the atomic level. It would be more precise to say they "swarm," or are "smeared," around the central nuclei. You might state that the configuration of electrons and their interactions with each other is basically what the field of chemistry is about.

Antimatter
Discuss antimatter, and the speculations that other galaxies may be composed of antimatter. There are even antiquarks. Until recent times the fundamental building blocks of matter were thought to be only protons, neutrons, and electrons. Now we know that the proton and neutron are not the fundamental particles, but are composed of quarks. This change of view or advancement in our knowledge, like others, is often cited as a weakness by people who do not understand what science is about. Science is not a bag of answers to all the questions of the world, but is a process for finding answers to many questions about the world. We continue to refine our models and add new layers to our understanding—sometimes building onto layers and other times replacing layers. This is a strength, not a weakness of science. Recall that Bertrand Russell, publicly changed his mind about certain ideas in the course of his life—changes that were part of his growth, but were looked upon by some as a sign of weakness (as discussed in Chapter 1).

Dark Matter
Dark matter is today's major physics mystery. Whatever it is, there is very little chance it will occupy any place on the periodic table of the elements. How intriguing—most of the stuff of the universe isn't on the periodic table. And it is "out there?" Bear in mind, that *we* are "out there." Dark matter is likely infused in matter as we know it. Interesting point: There is likely dark matter in the platinum cylinder that defines the kilogram, locked in a glass case in France. (What does this say about our knowledge of the number of platinum atoms in the standard mass?) And there's perhaps traces of dark matter in you and me, not to mention in the core of the Earth, which is thought to be all iron. Interesting speculations!

Phases of Matter
Briefly discuss the phases of matter, and how changes in molecular motion (temperature) are responsible for changes from the solid to liquid to gaseous to plasma phases. In earlier editions of Conceptual Physics, "states" of matter were discusssed. Either may be used. One ambiguity is that states also refers to the energy states of atoms—a confusion to avoid.

Answers and Solutions for Chapter 11

Reading Check Questions
1. John Dalton revived the idea of atoms.
2. These small particles are “bombarded” by still smaller particles—atoms or molecules.
3. Albert Einstein explained Brownian motion.
4. The numbers are about equal.
5. Most atoms around us are older than the Sun.
6. Atoms are smaller than the wavelength of visible light and therefore can’t be seen by the naked eye.
7. Atoms are larger than the wavelength of an electron beam.
8. A model in science is a stepping stone to further understanding and more accurate models.
9. Nearly all the mass of an atom is concentrated in its nucleus.
10. A nucleon is the term for either a proton or a neutron.
11. The charge is the same on each, with the proton’s positive and the electron’s negative.
12. Electric repulsion between our atoms and those in a floor prevents our falling through a floor.
13. Hydrogen is lightest.
14. Hydrogen is the most abundant element in the universe.
15. Heavier atoms are formed by fusion in star interiors.
16. Heaviest elements originated in supernovas.
17. Oxygen, carbon, hydrogen, nitrogen, and calcium.
18. The atomic number of an element tells you the number of protons in atoms of this element.
19. The maximum number of shells in atoms is seven.
20. Electrical attraction pulls electrons toward protons.
21. Heavier atoms aren’t much larger due to greater electrical attraction by greater charge in the nucleus.
22. Isotopes differ in their numbers of neutrons.
23. Mass number is the number of protons and neutrons, an integer; atomic mass is the total mass of an atom, in grams, kilograms, or atomic mass units.
24. A compound is a material in which different atoms bond together, for example, (NaCl) and (H_2O).
25. A mixture is a substance mixed together without chemical bonding, for example, sand and salt, or air.
26. A molecule is two or more atoms bonded together.
27. The same, energy of separation equals energy of recombination.
28. Matter is composed of positive protons and negative electrons; antimatter is composed of negative protons and positive electrons.
29. When matter meets antimatter, equal masses of each annihilate.
30. Stars and galaxies move as if more than just visible matter is gravitationally pulling on them.

Think and Do
31. Yes, the candle will burn twice as long because there is twice as much oxygen in the twice-as-large jar.

32. Tell your grandparents that atoms making up their bodies have been around longer than the Sun formed, and will be around after the Sun dies.

Think and Rank
33. a. A, D, B, C. b. A, D, B, C. c. A, D, B, C.
34. B, A, D, C
35. A, B, D, C

Think and Explain
36. One (although perhaps more than one isotope).

37. In a water molecule, H_2O, there are three atoms, two hydrogen and one oxygen.

38. The average speed of molecules increases.

39. The speed at which the scent of a fragrance travels is much less than the speed of the individual molecules that make it up because of the many collisions among molecules. Although the molecular speed between collisions is great, the rate of migration in a particular direction through obstructing molecules is very much less.

40. Water is not an element. It is a compound. Its molecules are made of the atoms of elements hydrogen and oxygen.

41. Of the substances listed, H_2, He, Na, and U are pure elements. H_2O and NaCl are compounds made of two elements, and three different elements contribute to H_2SO_4.

42. Agree partially. It's better to say an element is defined by the number of protons in the nucleus. The number of protons and electrons are equal only when the element is not ionized.

43. Brownian motion is caused by more atoms or molecules bumping against one side of a tiny particle than the other. This produces a net force on the particle, which alters its motion. Such Brownian motion is not observed for larger particles because the numbers of bumps on opposite sides is more nearly equal, and the inertia of the larger particle is greater. Any Brownian motion of a baseball would be imperceptible. The number of bumps on a baseball is practically the same on all sides, with no net force and no change in the baseball's motion.

44. There are seven atoms in the sulfuric acid molecule.

45. (a) In both there are 27 protons (see periodic table). There are 32 neutrons in Co-59 and 33 neutrons in Co-60. (b) The number of orbiting electrons matches the atomic number, 27.

46. The element is copper, atomic number 29. Any atom having 29 protons is by definition copper.

47. Carbon.

48. Lead.

49. Radon.

50. To become negative, gain an electron.

51. To become positive, lose an electron.

52. Germanium would become arsenic.

53. The other inert gases are neon, argon, krypton, xenon, and radon.

54. Germanium, which is in the same column directly below silicon in the periodic table.

55. Protons contribute more to an atom's mass, and electrons more to an atom's size.
56. Letting the formula KE = $^1/_2\, mv^2$ guide your thinking, for the same speed the atom with greater mass has greater KE. Greater-mass carbon therefore has greater KE than hydrogen for the same speed.

57. The hydrogen molecules, having less mass, move faster than the heavier oxygen molecules.

58. Electrical repulsion. Electrons speeding around within an atom create an electrified cloud that repels the similar clouds of other electrons, preventing the atoms from coalescing and keeping us from falling through our chairs. (For the record, quantum effects play a large role as well.)

59. Open-ended.

Think and Discuss

60. The cat leaves a trail of molecules and atoms on the grass. These in turn leave the grass and mix with the air, where they enter the dog's nose, activating its sense of smell.

61. A body would have no odor if all its molecules remained within it. A body has odor only if some of its molecules enter a nose.

62. The atoms that make up a newborn baby or anything else in this world originated in the explosions of ancient stars. The *molecules* that make up the baby, however, were formed from atoms ingested by the mother and transferred to her womb.

63. Individual Ping-Pong balls are less massive than individual golf balls, so equal masses of each means more Ping-Pong balls than golf balls.

64. Individual carbon atoms have less mass than individual oxygen atoms, so equal masses of each means more carbons than oxygens.

65. Since aluminum atoms are less massive than lead atoms, more aluminum atoms than lead atoms compose a 1-kg sample.

66. Silicon and germanium, which are in the same column, which means have similar properties.

67. You really are a part of every person around you in the sense that you are composed of atoms not only from every person around you, but from every person who ever lived on Earth! Little Andrea Wu’s statement in the Part 2 photo opener is indisputable. And the atoms that now compose you will make up the atomic pool that others will draw upon.

68. With every breath of air you take, it is highly likely that you inhale one of the atoms exhaled during your very first breath. This is because the number of atoms of air in your lungs is about the same as the number of breaths of air in the atmosphere of the world.

69. They assumed that a water molecule is made of one hydrogen atom and one oxygen atom, HO.

70. The amount of matter that a given amount of antimatter would annihilate is the same as the amount of antimatter, a pair of particles at a time. The whole world could not be annihilated by antimatter unless the mass of antimatter were at least equal to the mass of the world.

12 Solids

This chapter opens with a depiction of carbon nanotubes that have the greatest tensile strength of any material known, able to resist 100 times more strain than typical structural steel. The second photo is of John Hubisz, among the first friends I made attending AAPT meetings. John's profile begins this chapter. For the third photo I knew I had one for this book when I snapped the one of the stone arches. For the fourth photo, my physics-teaching nephew, Garth Orr, I'm happy to say is following in his Great Uncle Paul's footsteps. He's loving his conceptual physics teaching duties big time. One reason he loves his teaching is because his students love him. Why? Because they know that he loves them. A love of physics, plus a love of sharing it, makes for a successful teaching career!

The treatment of the crystalline nature of solids and bonding are very brief in this chapter. More emphasis is on elasticity, tension and compression, and the application to arches. Students should find the section on "Scaling" of particular interest. A fascinating source of additional scaling examples is George Barnes' fascinating oldie-but-goodie article, "Physics and Size in Biological Systems"—April 1989 issue of *The Physics Teacher*.

Scaling is becoming enormously important as more devices are being miniaturized. Researchers are finding that when something shrinks enough, whether it is an electronic circuit, motor, film of lubricant, or an individual metal or ceramic crystal, it stops acting like a miniature version of its larger self and starts behaving in new and different ways. Palladium metal, for example, which is normally composed of grains about 1000 nanometers in size, is found to be five times as strong when formed from 5 nanometer grains.

Take note of beverage containers that are partially spherical in shape. Some are like two spheres, one atop the other. Compared with a cylinder, any of these shapes that bulge have less surface area for a given volume. That's less waste.

Chromium has long been used to show off a shiny metal surface. But working with chromium has been environmentally harmful. New research suggests a greener alternative: a nano-crystalline nickel-tungsten alloy that tops chrome's features.

Practicing Physics:
• Scaling • Scaling Circles

Problem Solving Book:
Problems, yes

Laboratory Manual:
• Totally Stressed Out *Hooke's Law (Experiment*)
• Spring to Another World *Spring-Mass Simulation* (Tech Lab)

Next-Time Questions:
• Infant Growth • Material Strength • Wet Gravel

Hewitt-Drew-It! Screencasts: •*Solids* •*Quartz-Gold Problem* •*Scaling 1* •*Scaling 2* •*Scaling 3*

This chapter may be skipped with no particular consequence to following chapters. If this chapter is skipped and Chapter 13 is assigned, density should be introduced at that time.

SUGGESTED LECTURE PRESENTATION

Crystal Structure

Begin by calling attention to the micrograph held by John Hubisz in the chapter opener photo. The micrograph is evidence not only for the crystalline nature of the platinum needle, but also evidence for the wave nature of atoms is seen in the resulting diffraction pattern. It is easy to imagine the micrograph as a ripple tank photo made by grains of sand sprinkled in an orderly mosaic pattern upon the surface of water.

Density

Measure the dimensions of a large wooden cube in cm and find its mass with a pan balance. Define density = mass/volume. (Use the same cube when you discuss flotation in the next chapter.) Some of your students will unfortunately conceptualize density as massiveness or bulkiness rather than massiveness *per* bulkiness, even when they give a verbal definition properly. This can be helped with the following:

> CHECK QUESTIONS: Which has the greater density, a cupful of water or a lakeful of water? A kilogram of lead or a kilogram of feathers? A single uranium atom or the world?

I jokingly relate breaking a candy bar in two and giving the smaller piece to my friend who looks disturbed. “I gave you the same density of candy bar as I have.”

Contrast the density of matter and density of atomic nuclei that comprise so tiny a fraction of space within matter. From about 2 gm/cm^3 to 2×10^{14} gm/cm^3. And in a further crushed state, the interior of neutron stars, about 10^{16} gm/cm^3.

Elasticity:

> DEMONSTRATION: Drop glass, steel, rubber, and spheres of various materials onto an anvil and compare the elasticities.

> DEMONSTRATION: Hang weights from a spring and illustrate Hooke’s law. Set a pair of identical springs up as in Think and Solve 33, and ask the class to predict the elongation before suspending the load.

Tension, Compression, and Arches

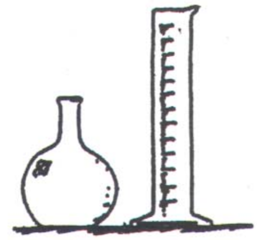
Bend a meterstick held at both ends and ask which side is being stretched and which side is being compressed. Stretching is tension, and compressing is compression. If one side is being stretched and the other compressed, there must be a “crossover” place—where neither stretching nor compression occurs. This is the neutral layer.

Compare a cantilever and a simple beam. Then discuss the shape of an I-beam and Think and Explain 56 at the end of the chapter.

Discuss the strength of arches. Before the time of concrete, stone bridges and the like were self-supporting by virtue of the way they pressed against one another—in an arch shape. Wooden scaffolding allowed their construction, and when the keystone was inserted, the structures stood when the scaffolding was removed. The same practice is used today.

Discuss the **catenary**, as shown by my grandson Manuel in Figure 12.14. From my understanding, the catenary idea likely originated with Robert Hooke, who discussed it with the famed architect, Christopher Wren. Wren wisely used this idea when he designed the dome to St. Paul’s Cathedral in London. Unlike former structures, the dome needs no buttressing. Indeed, a free standing catenary could be made of blocks of slippery ice! How many earlier successful domes approximated the shapes of catenaries? Think and Explains 60 and 61 at the end of the chapter involve catenaries.

Area-Volume



Introduce the relationship between area and volume as Chelcie Liu does by showing the following: Have a 500-ml spherical flask filled with colored water sitting on your lecture table. Produce a tall cylindrical flask, also of 500 ml (unknown to your students), and ask for speculations as to how high the water level will be when water is poured into it from the spherical flask. You can ask for a show of hands for those who think that the water will reach more than half the height, and those who think it will fill to less than half the height, and for those who guess it will fill to exactly half the height. Your students will be amazed when they see that the seemingly smaller spherical flask has the same volume as the tall cylinder. To explain, call attention to the fact that the *area* of the spherical flask is considerably smaller than the surface area of the cylinder. We see a greater area and we unconsciously think that the volume should be greater as well. Be sure to do this. It is more impressive than it may first seem.

Scaling

Now for the most interesting part of your lecture. Have at least 8 large cubes on your lecture table as you explain Figures 12.16 and 12.17. For more about the relationships among the size, area, and volume of objects, read the essays cited in the first footnote of this chapter.

> CHECK QUESTIONS: Which has more surface area, an elephant or a mouse? 2000 kilograms of elephant or 2000 kilograms of mice? (Distinguish carefully between these different questions.)
>
> CHECK QUESTION: Cite two reasons why small cars are more affected by wind.
>
> CHECK QUESTION: Why do cooks preparing Chinese food chop food in such small pieces to stir-fry quickly in a wok?
>
> CHECK QUESTION: In terms of surface area to volume, why should parents take extra care that a baby is warm enough in a cold environment? [Baby has proportionally more radiating surface.]
>
> CHECK QUESTION: Why are elevated reservoirs usually spherical in shape? [Minimum building material for the same volume.]
>
> CHECK QUESTION: What does the somewhat spherical shape in beverage containers have to do with ecology? [Less material, less waste.]

Your lecture can continue by posing exercises from the chapter end material and having your class volunteer answers. The examples posed in the chapter backmatter will perk class interest. (The answer to Think and Solve 34 may need more explanation. How much more surface area is there for a body with twice the volume? Consider a cube; twice the volume means each side is the cube root of two, 1.26 times the side of the smaller cube. Its area is then $1.26 \times 1.26 = 1.588$ times greater than the smaller cube.

Interestingly, this means that a twice-as-heavy person at the beach, say 200 lbs, needs about 1.6 times as much suntan lotion as a 100-lb person.

Regarding Figure 12.18, note that the eartip-to-eartip span is almost the height of the elephant. The dense packing of veins and arteries in the elephant’s ears finds a difference in five degrees in blood entering and leaving the ears. A second type of African elephant that resides in cooler forested regions has smaller ears. Perhaps Indian elephants evolved in cooler climates. Anther consequence of scaling: elephants can’t jump!

Answers and Solutions for Chapter 12

Reading Check Questions

1. Atoms are orderly in a crystalline substance, and random in non-crystalline substances.
2. Micrographs (chapter-opener photo) and X-ray diffraction patterns show the crystal nature of certain solids. Macroscopic evidence of crystals are the 3-dimensional shape of materials such as quartz, and even brass doorknobs that have been etched by the perspiration of hands.
3. A squeezed loaf of bread has reduced volume, the same mass, and increased density.
4. Both densites are one and the same.
5. Close packing of atoms in iridium accounts for its great density.
6. Water has a mass density of 1 g/cm^3, and a weight density of 9.8 N/cm^3.
7. A spring when deformed returns to its initial shape when the deforming force is removed.
8. Putty when deformed, remains deformed when the deforming force is removed.
9. Hooke's law: $F \sim \Delta x$; applies to elastic materials.
10. The elastic limit is the point at which deformation remains after the deforming force is removed.
11. Stretch will be 3 times as much, 6 cm.
12. Tension is "stretching" of a substance when force is applied; compression is squeezing a substance when force is applied.
13. The neutral layer in a beam is the region of neither tension nor compression when supporting a load, and is in the middle portion of the beam.
14. I beams have material removed where strength is not needed, which makes the beam lighter for nearly the same strength.
15. Long horizontal slabs of stone fracture when carrying a load, so vertical columns reduce the lengths of the slabs.
16. For an arch, compression strengthens it.
17. Cement is not needed because compressive forces hold the arch together.
18. Vertical columns are not needed because the shape of the arched parts form an inverted catenary.
19. Strength depends on the cross-sectional area.
20. For the cube, volume is 1 cm^3; cross section is 1 cm^2; total surface area is 6 cm^2.
21. Surface area increases by four; volume increases by eight.
22. An elephant has more skin than a mouse, but less skin *per bodyweight* than a mouse.
23. A mouse daily requires more food per bodyweight than an elephant.
24. The saying is a consequence of a small ratio of surface to volume.
25. Small creatures have more surface area per bodyweight, and encounter greater air resistance per bodyweight, resulting in a slower fall than that of larger creatures.

Think and Do

26. Snowflakes melt quickly, so be alert!
27. Note the smaller area with close packing.
28. You should find you're slightly taller lying down. When standing compression of your spine occurs.
29. The chain will have the shape of the egg. This must be tried!

Think and Solve

30. Density = $\frac{\text{mass}}{\text{volume}} = \frac{5\text{ kg}}{V}$. Now the volume of a cylinder is its (round area) $\times$ (its height), ($\pi r^2 h$).

    So density = $\frac{5\text{ kg}}{\pi r^2 h} = \frac{5000\text{ g}}{(3.14)(3^2)(10)\text{cm}^3}$ = 17.7 g/cm^3.
31. A cubic meter of cork has a mass of 400 kg and a weight of about 4,000 N. Its weight in pounds is 400 kg $\times$ 2.2 lb/kg = 880 lb, much too heavy to lift.

32. 50 N is 5/3 times 30 N, so the spring will stretch 5/3 times as far, **10 cm**. Or from Hooke's law; $F = kx$, $x = F/k$ = 50 N/(30 N/6 cm) = 10 cm. (The spring constant k = 5 N/cm.)

33. When the springs are arranged as in (a), each spring supports half the weight, stretches half as far (2 cm), and reads 5 N. In position (b) each spring supports the full weight, each stretches 4 cm, and each reads 10 N. Both springs stretch 4 cm so the weight pulls the combination down a total distance of 8 cm.

34. (a) **Eight** smaller cubes (see Figure 12.16).

(b) Each face of the original cube has an area of 4 cm^2 and there are 6 faces, so the total area is 24 cm^2. Each of the smaller cubes has an area of 6 cm^2 and there are eight of them, so their total surface area is 48 cm^2, twice as great.
(c) The surface-to-volume ratio for the original cube is (24 cm^2)/(8 cm^3) = 3 cm^{-1}. For the set of smaller cubes, it is (48 cm^2)/(8 cm^3) = 6 cm^{-1}, twice as great. (Notice that the surface-to-volume ratio has the unit inverse cm.)

35. Twice the mass of gold has twice the volume = 2cm^3=L^3 $\Rightarrow L = \sqrt[3]{2}$ cm = 1.26 cm.

36. $\$700 \times 10^9 \times \frac{1\text{gram}}{\$28.40} = 2.46 \times 10^{10}\text{ gram} \times \frac{1\text{cm}^3}{19.3\text{ g}} = 1.28 \times 10^9\text{ cm}^3 \times \left(\frac{1\text{ m}}{100\text{ cm}}\right)^3 =$
$1.28 \times 10^3\text{ m}^3$.

Since this is a cube of volume $V = L^3$, each side $L = \sqrt[3]{V} = \sqrt[3]{1.28 \times 10^3\text{ m}^3} = \mathbf{10.8\ m}$. (This turns out to be more than five times the total stored in Fort Knox, and about 10 times the world's annual gold production.)

Think and Rank

37. C, A, B.
38. a. C, B, A. b. C, B, A. c. C, B, A. d. C, B, A. e. A, B, C.

Think and Explain

39. Both the same, for 1000 mg = 1 g.

40. Disagree, for it is the arrangement of atoms and molecules that distinguishes a solid from a liquid.

41. The carbon and part of the oxygen that comprises much of the mass of a tree originates from CO_2 in the air.

42. Physical properties involve the order, bonding, and structure of atoms that make up a material, and on the presence of other atoms and their interactions in the material. The silicon in glass is amorphous, whereas in semiconductors it is crystalline. Silicon in sand, from which glass is made, is bound to oxygen as silicon dioxide, while that in semiconductor devices are elemental and extremely pure. Hence their physical properties differ.

43. Evidence for crystalline structure include the symmetric diffraction patterns given off by various materials, micrographs such as the one shown by Professor Hubisz in the chapter-opener photo, the 3-dimensional shape of materials such as quartz, and even brass doorknobs that have been etched by the perspiration of hands.
44. Density decreases as the volume of the balloon increases.

45. The densities are the same, for they are both samples of iron.

46. Density of water decreases when it becomes ice.

47. Its density increases.

48. Aluminum has more volume because it is less dense.

49. Water is denser, so a liter of water has more mass than a liter of ice. (Once a liter of water freezes, its volume is greater than 1 liter.)

50. For one thing, drop a steel ball on a steel anvil. It will bounce!

51. The top part of the spring supports the entire weight of the spring and stretches more than, say the middle, which only supports half the weight and stretches half as far. Parts of the spring toward the bottom support very little of the spring's weight and hardly stretch at all.

52. All parts of the spring would stretch more nearly the same because the lower part of the spring would be supporting nearly as much weight as the upper part is supporting.

53. The concave side is under compression; the convex side is under tension.

54. Case 1: Tension at the top and compression at the bottom. Case 2: Compression at the top and tension at the bottom.

55. Concrete undergoes compression well, but not tension. So the steel rods should be in the part of the slab that is under tension, the top part.

56. A horizontal I-beam is stronger when the web is vertical because most of the material is where it is needed for the most strength, in the top and bottom flanges. When supporting a load, one flange will be under tension and the other flange under compression. But when the web is horizontal, only the edges of the flanges, much smaller than the flanges themselves, play these important roles.

57. The design to the left is better because the weight of water against the dam puts compression on the dam. Compression tends to jam the parts of the dam together, with added strength like the compression on an arch. The weight of water puts tension on the dam at the right, which tends to separate the parts of the dam.

58. Like the dams in the preceding exercise, the ends should be concave as on the left. Then the pressure due to the wine inside produces compression on the ends that strengthens rather than weakens the barrel. If the ends are convex as on the right, the pressure due to the wine inside produces tension, which tends to separate the boards that make up the ends.

59. Scale a beam up to twice its linear dimensions, I-beam or otherwise, and it will be four times as thick. Along its cross-section then, it will be four times as strong. But it will be eight times as heavy. Four times the strength supporting eight times the weight results in a beam only half as strong as the original beam. The same holds true for a bridge that is scaled up by two. The larger bridge will be only half as strong as the smaller one. (Larger bridges have different designs than smaller bridges. How they differ is what architects and engineers get paid for!) Interestingly, how strength depends on size was one of Galileo's "two new sciences," published in 1638.

60. Catenaries make up the arches of the ends of an egg. Pressing them together strengthens the egg. Not so when pressing the sides, which do not constitute catenary shapes, and easily splay outward under pressure.

61. Since each link in a chain is pulled by its neighboring links, tension in the hanging chain is exactly along the chain—parallel to the chain at every point. If the arch takes the same shape, then compression all along the arch will similarly be exactly along the arch—parallel to the arch at every point. There will be no internal forces tending to bend the arch. This shape is a catenary, and is the shape of modern-day arches such as the one that graces the city of St. Louis.

62. No, the rods would not be necessary if the shape of the arch were an upside down version of a hanging chain. Why? Because compression of the stones in the semi-circular design press outward. Compression in the hanging chain design (catenary) is everywhere parallel to the arch, with no net sideways components.

63. The candymaker needs less taffy for the larger apples because the surface area is less per kilogram. (This is easily noticed by comparing the peelings of the same number of kilograms of small and large apples.)

64. Kindling will heat to a higher temperature in a shorter time than large sticks and logs. Its greater surface area per mass results in most of its mass being very near the surface, which quickly heats from all sides to its ignition temperature. The heat supplied to a log, on the other hand, is not so

concentrated as it conducts into the greater mass. Large sticks and logs are slower to reach the ignition temperature.

65. The answer to this question uses the same principle as the answer to the previous exercise. The greater surface area of the coal in the form of dust insures an enormously greater proportion of carbon atoms in the coal having exposure to the oxygen in the air. The result is very rapid combustion.

66. More heat is lost from the rambling house due to its greater surface area.

67. An apartment building has less area per dwelling unit exposed to the weather than a single-family unit of the same volume. The smaller area means less heat loss per unit. (It is interesting to see the nearly cubical shapes of apartment buildings in northern climates—a cube has the least surface area for a solid with rectangular sides.)

68. For a given volume, a sphere has less surface area than any other geometrical figure. A dome-shaped structure similarly has less surface area per volume than conventional block designs. Less surface exposed to the climate = less heat loss.

69. The ratio of area (square meters) to volume (cubic meters) decreases.

70. The surface area of crushed ice is greater which provides more melting surface to the surroundings.
71. Curling up presents less surface area to the surroundings.

72. Rusting is a surface phenomenon. For a given mass, iron rods present more surface area to the air than thicker piles.

73. More potato is exposed to the cooking oil when sliced thinly than in larger pieces. Thin fries will therefore cook faster than larger fries.

74. The wider, thinner burger has more surface area for the same volume. The greater the surface area, the greater will be the heat transfer from the stove to the meat.

75. Mittens have less surface than gloves. Anyone who has made mittens and gloves will tell you that much more material is required to make gloves. Hands in gloves will cool faster than hands in mittens. Fingers, toes, and ears have a disproportionately large surface area relative to other parts of the body and are therefore more prone to frostbite.

76. The greater amount of radiating area of a mouse means that it radiates a greater amount of energy, which in turn means the small creature needs a greater proportion of food daily.

77. The mouse has more surface area per bodyweight, which means greater air resistance per bodyweight, which means its terminal speed of fall is slower than the gorillas.

78. Small animals radiate more energy per bodyweight, so the flow of blood is correspondingly greater, and the heartbeat faster.

79. The inner surface of the lungs is not smooth, but is sponge-like. As a result, there is an enormous surface exposed to the air that is breathed. This is nature’s way of compensating for the proportional decrease in surface area for large bodies. In this way, an adequate amount of oxygen vital to life is taken in.

80. Cells of all creatures have essentially the same upper limit in size dictated by the surface area per volume relationship. The nourishment of all cells takes place through the surface by the process called osmosis. As cells grow they require more nourishment, but the proportional increase in surface area falls behind the increase in mass. The cell overcomes this liability by dividing into two cells. The process is repeated and there is life that takes the form of whales, mice, and us.

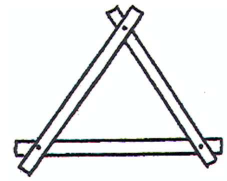
81. Large raindrops fall faster than smaller raindrops for the same reason that heavier parachutists fall faster than lighter parachutists. Both larger things have less surface area and therefore less air resistance relative to their weights.

Think and Discuss

82. Iron is denser than cork, but not necessarily heavier. A common cork from a wine bottle, for example, is heavier than an iron thumbtack—but it wouldn't be heavier if the volumes of each were the same.

83. Density has not only to do with the mass of the atoms that make up a material, but with the size of those atoms and their stacking arrangement. Iridium atoms are both smaller and they stack more closely than uranium atoms, which is why iridium metal is denser than uranium metal even though uranium's atoms are heavier.

84. A triangle is the most rigid of geometrical structures. Consider nailing four sticks together to form a rectangle, for example. It doesn't take much effort to distort the rectangle so that it collapses to form a parallelogram. But a triangle made by nailing three sticks together cannot collapse to form a tighter shape. When strength is important, triangles are used. That's why you see them in the construction of so many things.



85. A twice-as-thick rope has four times the cross-section and is therefore four times as strong. The length of the rope does not contribute to its strength. (Remember the old adage, a chain is only as strong as its weakest link—the strength of the chain has to do with the thickness of the links, not the length of the chain.)

86. Cupcakes have more surface area per amount of material than a cake, which means there is more area exposed to the heat that the oven will provide, which means cooking will be facilitated. This also means the cupcakes will be overcooked if they are cooked for the time specified for a cake. (Now you see why recipes call for a "shallow pan" or a "deep dish" when baking times are given.)

87. As an organism increases in size, surface area decreases relative to the increasing size. Therefore, a large organism such as a human being must have a many-folded intestinal tract so that the area will be large enough to digest the needed food.

88. Strength varies in approximate proportion to the cross-sectional area of arms and legs (proportional to the square of the linear dimensions). Weight varies in proportion to the volume of the body (proportional to the cube of the linear dimension). So—other things being equal—the ratio of strength to weight is greater for smaller persons.

89. A child, for a child has more surface area per volume, and therefore loses disproportionately more water to the air.

90. Scaling plays a significant role in the design of the hummingbird and the eagle. The wings of a hummingbird are smaller than those of the eagle relative to the size of the bird, but are larger relative to the mass of the bird. The hummingbird's swift maneuvers are possible because the small rotational inertia of the short wings permits rapid flapping that would be impossible for wings as large as those of an eagle. If a hummingbird were scaled up to the size of an eagle, its wings would be much shorter than those of an eagle, so it couldn't soar. Its customary rate of flapping would be insufficient to provide lift for its disproportionately greater weight. Such a giant hummingbird couldn't fly, and unless its legs were disproportionately thicker, it would have great difficulty walking. The great difference in the design of hummingbirds and eagles is a natural consequence of the area to volume ratio of scaling. Interesting!

91. The idea of scaling, that one quantity, such as area, changes in a different way than another quantity, such as volume, goes beyond geometry. Rules that work well for a system of one size may be disastrous when applied to a system of a different size. The rules for managing a small town well may not work at all for a large city. Other examples are left to you. This is an open-ended question that may provoke thought—or better, discussion.

13 Liquids

Photo 1 of the water tower was taken by my best friend, Paul Ryan. The tower provides pressure to the faucets of his neighborhood. Photo 2 is Tsing Bardin, who after retiring from doing nuclear physics and material science research in Lockheed and IBM, and teaching at San Jose State and City College of San Francisco, now devotes herself to upgrading math and science education in elementary and secondary schools. Photo 3 shows the impressive Falkirk Wheel, a most fascinating illustration of physics applied to liquids. The wheel turns independent of the weight of ships it carries, for their weight is the same as the volume of water they displace. This is treated in the chapter. Photo 4 is of my friend and neighbor Ray Serway, known to many physics students as the author of algebra and calculus-based physics textbooks.

The profile for this chapter is Blaise Pascal, for whom the unit of pressure is named.

The lovely young woman on the bed of nails in Figure 13.2 is Swedish physicist Sara Blomberg.

The depths of the ocean as well as the expanse of outer space are of current interest, yet liquids are seldom studied in introductory physics classes anymore. Perhaps this is because Archimedes' Principle and the like are too far from the frontiers of present research. Because much of the physics in this chapter is more than 2000 years old is no reason that it should not be in your physics course. Liquids are a very real part of your students' everyday world.

It is well known that falling from great heights into water has much the same effect as falling to solid ground. Less well known are the new "water saws," with pressures of about 5500 lb/in^2 used for cutting through armor-plate steel.

Regarding Figure 13.3, you may point out that the average mass of a giraffe's heart is about 40 kg. That's quite a pump.

The dedicated teacher walking on broken glass with bare feet in his classroom in Think and Discuss 99 is Marshall Ellenstein, profiled in Chapter 29. Marshall has been a contributor to this book for years and is the editor of the video and DVD series of my lectures in both San Francisco and Hawaii. He also posts my screencasts on YouTube.

Think and Discuss 112 is Bruce Novak's mom, Greta Novak. Bruce wonderfully tweaked the manuscript and all back matter for this edition. His photo is Figure 26.4. Bruce's knowledge of physics with his many suggestions makes the 12th a proud edition for me. And I hope you too!

In student laboratory exercises, it is more common to work with mass density than with weight density, and floating or submerged materials are more often described in units of mass rather than weight. Displaced liquid is also described in units of mass rather than weight. This is why buoyant force in this chapter is treated as "the weight of so many kilograms," rather than "so many newtons." The expression of buoyancy in terms of mass units should be compatible with what goes on in lab.

DEMONSTRATION, an impressive one on buoyancy: Place about 8 grams of dry ice in a large (several cm) uninflated balloon. Tie the balloon. Immediately set it on a digital balance reading to the nearest milligram. As the balloon inflates (over a few minutes) the balance readout plummets at a rate of about 2 mg/sec. The scale will finally read about 2.4 grams less, assuming the balloon inflates to about 2 liters (density of air is about 1.2 g/L). I learned of this demo from my nephew John Suchocki.

Oceans tidbit: The Atlantic is getting wider, the Pacific narrower.

Practicing Physics Book:
• Archimedes' Principle I
• Archimedes' Principle II

Problem Solving Book: There is a good selection of problems for this chapter.

Laboratory Manual:
• Pool Cubes: *Density Simulations of density and flotation* (Tech Lab)
• Pool Cubes: *Buoyancy Simulations of buoyancy and flotation* (Tech Lab)
• Eureka! *Archimedes' Principle* (Activity)
• Sink or Swim: *What Makes an Object Sink or Float* (Activity)
• Boat Float: *Flotation* (Activity)

Next-Time Questions:
• Styrofoam Cargo
• Water's Own Level
• Fire Truck
• Boat with Scrap Iron
• Wood and Rock Float
• Floating Block
• Ice Cube on the Moon
• Deuterium Ice Cube
• Balance Stand
• Submerged Cube and Sphere
• Submerged Teabag

Hewitt-Drew-it! Screencasts: •*Liquid Pressure* •*Buoyancy* •*Archimedes* •*Buoyancy on a Submarine* •*More on Buoyancy* •*Buoyancy Problems* •*Pascal's Principle*

Prerequisite to this chapter is understanding of density, covered in the previous chapter. So if you skipped Chapter 12, discuss *density* here. This chapter is prerequisite to Chapter 14, but is not prerequisite to the remaining chapters of the textbook.

SUGGESTED LECTURE PRESENTATION

Force versus Pressure
Begin by distinguishing between force and pressure. Illustrate with examples: Somebody pushing on your back with a force of only 1 N—with a pin! Or as you're lying on the floor, a 400-N lady stands on your stomach—perched atop spike heels! Indian master lying on a bed of 1000 nails—apprentice being advised to start with one nail! The rounded corners on tables, sharp blades on cutting knives, and the absurdity of standing tall while pointing your toes downward when caught in quicksand.

Have students compare in their hands the weights of a small steel ball and a large Styrofoam ball, and after agreeing that the little ball is heavier (since density was treated in the previous chapter), weigh them and show the Styrofoam ball is heavier! Another example of pressure (on the nerve endings).

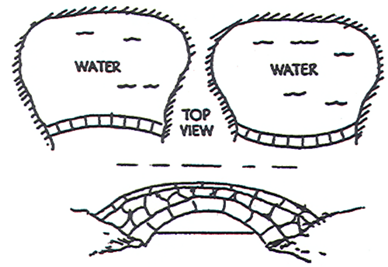
Liquid Pressure
Liquid pressure = density × depth. After a few words about density, you may want to derive or call attention to the derivation of this relationship in the second footnote in the chapter.

DEMONSTRATION: Pascal's Vases (similar to Figure 13.5) are shown by Tsing Bardin in the chapter opener photo. Rationalize your results in terms of the supporting forces exerted by the

sloping sides of the vases. [That is, in the wide sloping vase, the water pushes against the glass, and the glass reacts by pushing against the water. So the glass supports the extra water without the pressure below increasing. For the narrow vase that slopes outward near the bottom, the water pushes up against the sloping glass. By reaction, the glass pushes down on the water, so the pressure at the bottom is the same as if water were present all the way up to the surface.]

Discuss Figure 13.3 of the giraffes and why your heart gets more rest if you sleep in a prone position versus sitting up. Call attention to the fact that when swimming, the pressure one feels against one's eardrums is a function of only depth—that swimming 3 meters deep in a small pool has the same effect as swimming 3 meters deep in the middle of a huge lake.

CHECK QUESTION: Would the pressure be greater swimming 3 m deep in the middle of the ocean? (Then compare the densities of fresh and salt water.)



Ask why dams are built thicker at the bottom, and after discussing Figure 13.4 sketch the top view of a couple of dams on the board and ask which design is best (Think and Explain 57, previous chapter). Then relate this to the shape of stone bridges (which actually need no mortar), and the arched shape of doorways in old stone structure (photo opener, previous chapter), and the aqueducts shown in Figure 13.6. Another illustration is the concave ends of large wine barrels (Think and Explain 58, previous chapter).

Buoyant Force
Show that the consequence of pressure being depth-dependent is the phenomenon of buoyancy. Sketch Figure 13.9 on the board. Follow up with a sketch and explanation of Figure 13.14.

DEMONSTRATION: Show how an overflow can enables the measure of an object's volume. Ask how one could measure a quarter cup of butter in a liquid measuring cup using this method.

DEMONSTRATION: Archimedes' Principle, as shown in Figure 13.13.

You may find that many students who have trouble with conceptualizing buoyant force are confused about the distinction between area and volume. Be sure to make this distinction clear, (as elementary as it seems). (If you didn't pour the contents of the spherical flask into the tall cylindrical flask of the same volume as described in the suggested lecture of the previous chapter, be sure to do so here.) Also, point out that because a liquid is incompressible (practically incompressible, as the volume of water decreases by only 50 one-millionths of its original volume for each atmosphere increase in pressure, or equivalently, for each addition 10.3 m in depth) its density is not depth-dependent. The density of water near the surface is practically the same as the density far beneath the surface. You may wish to acknowledge that some variation occurs due to temperature differences. Usually a student will inquire about waterlogged objects which lie submerged yet off the bottom of the body of water. Such objects are slightly denser than the warmer surface water and not quite as dense as the cooler water at the bottom. Stress that this is unusual and that objects appreciably denser than water always sink to the bottom, regardless of the depth of the water. Scuba divers do not encounter "floating" rocks near the bottoms of deep bodies of water!

CHECK QUESTION: Two solid blocks of identical size are submerged in water. One block is lead and the other is aluminum. Upon which is the buoyant force greater? [Same, since volumes of water displaced are the same.]

After discussion, try this one:
CHECK QUESTION: Two solid blocks of identical size, one of lead and the other of wood, are put in the same water. Upon which is the buoyant force greater? [This time the buoyant force is greater on the lead because it displaces more water than the wood that floats!]

> CHECK QUESTIONS: What is the buoyant force on a ten-ton ship floating in fresh water? In salt water? In a lake of mercury? [Same BF, but different *volumes* displaced.]

The unit "ton" is used in several places in this text. It may be taken to mean a metric tonne, the weight of 1000 kg, or the British ton, 2000 pounds. Either interpretation is sufficient in treating the concept involved.

Flotation
Discuss boats and rafts and the change of water lines when loaded.

> CHECK QUESTIONS: What is the approximate density of a fish? Of a person? What can you say of people who can't float?

> DEMONSTRATION: Cartesian diver (inverted partially filled small bottle submerged in a larger flexible plastic bottle that you squeeze to increase and decrease the weight of water in the small bottle to make it rise and fall).

Discuss the same weight of the flasks in Figure 13.18 carefully. This leads to the Falkirk Wheel, Figure 13.19, and how the water-filled caissons always weigh the same whether or not they carry boats, and that the weight of such boats makes no difference. To see the wheel in action, check Falkirk Wheel on the Internet! Most impressive, and some great physics!

Discuss the compressibility of the human body in swimming—how the density of most people a meter or two below the surface of the water is still less than the density of water, and that one need only relax and be buoyed to the surface. But that at greater depths, the greater pressure compresses one to densities greater than the density of water, and one must swim to the surface. Simply relaxing, one would sink to the bottom! Relate this to the Cartesian diver demonstration. Also state why one cannot snorkel with a tube that goes deeper than a half-meter or so.

Side point: Contrary to those old Tarzan movies, you cannot sink in quicksand. Quicksand is the name given to a mass of sand particles that are supported by circulating water rather than by each other. Its density is greater than the density of human bodies, so you can float on it. If you struggle, you'll unfortunately succeed in digging yourself deeper in. So if you're ever stuck in it, keep yourself still until you stop sinking (you will), and then use slow swimming motions to get yourself into a horizontal position and then roll onto the ground.

Pascal's Principle
Begin by pushing against the wall with a meterstick and state that the stick affords a means of applying pressure to the wall—then state that the same can be done with a confined fluid. Explain how any external pressure applied to a liquid that tightly fills a volume is transmitted to all parts of the liquid equally. Discuss Figures 13.21 and 13.22. If a hydraulic press is available, crush a block of wood with it. Point out that the pressure transmitted throughout a confined liquid is pressure over and above that already in the liquid. For example, the pressure in a hydraulic system at any point is equal to the applied pressure plus the density × depth. See the screencast *Pascal's Principle*.

Surface Tension
In the next chapter on gases we'll think of atoms as rigid balls that ricochet off one another. Here we think of atoms as sticky balls—capillarity. An interesting example of capillarity (not in the text) involves the tallness of trees. The cohesive forces of water explains the transport of water from roots to the top of tall trees. When a single water molecule evaporates from the cell membrane inside a leaf, it is replaced by the one immediately next to it due to the cohesive forces between water molecules. A pull is created on the column of water that is continuous from leaves to roots. Water can be lifted far higher than the 10.2-m height that atmospheric pressure would serve—even to 100 m in this way, the height of the largest trees.

Answers and Solutions to Chapter 13

Reading Check Questions

1. Pressure is force per area.
2. Pressure is due to the weight of water above (and total pressure, plus the weight of the atmosphere).
3. Liquid pressure is proportional to depth, and to weight density.
4. Greater pressure in salt water due to its greater density.
5. Pressures will be the same at the same depth.
6. Direction of water flow is at right angles to the container surface.
7. Buoyant force acts upward because there is more force beneath an object due to more pressure at greater depth.
8. Forces on opposite sides are equal and opposite and cancel.
9. Both volumes are the same.
10. Buoyant force equals the weight of water displaced.
11. A submerged body is completely immersed, completely beneath the surface.
12. 1 L of water has a mass of 1 kg, and a weight of 10 N (more precisely, 9.8 N).
13. Volume of displace water will be ½ L. Buoyant force will be 5 N.
14. Buoyant force equals the weight of fluid displaced.
15. Yes. When an object floats, buoyant force equals its weight.
16. Buoyant force depends on the volume of the submerged object.
17. Sink; float; neither sink nor float.
18. Density is controlled in a fish by expansion or contraction of an air sac; in a submarine by the weight of water blown in or out of ballast tanks.
19. Not a coincidence because in the case of floating the buoyant force equals both weight of the object as well as the weight of water displaced.
20. They have the same weight because when carrying a boat, the weight of the boat is the same as the weight of water that overflows (as in Figure 13.18).
21. If pressure in one part is increased, the same increase in pressure is transmitted to all parts.
22. 500 N will be supported by the output piston (10 N/cm^2 x 50 cm^2 = 500 N).
23. A sphere has the least surface area for a given volume.
24. Surface tension is caused by molecular attractions.
25. Adhesion is the attraction between unlike substances; cohesion is the attraction between like substances.
26. Height of water occurs when adhesive forces balance the weight of water lifted.

Think and Do

27. An egg is denser than fresh water, but less dense than salted water. Therefore an egg will float in salt water, but sink in fresh water.

28. When the can is held still, pressure due to the weight of water in the can accounts for the spurt. But when dropped, the weight of water and the water pressure are nil, and no spurt occurs.

29. The wetted ball is pulled by surface tension beneath the surface when the system is weightless (dropping). When the can makes impact the submerged ball, much lighter than the water it displaces, is popped with great force out of the water.

30. Share this information about why soap cleans well with your friends.

31. The pepper grains float due to surface tension. When the surface tension is diminished by the addition of soap, the grains sink. Intriguing!

Plug and Chug

32. Pressure = 10 N/50 cm^2 = 0.2 N/cm^2.
33. Pressure = weight density $\times$ depth = 10,000 N/m^3 $\times$ 1 m = 10,000 N/m^2 = 10 kPa.
34. Pressure = weight density $\times$ depth = 10,000 N/m^3 $\times$ 50 m = 500,000 N/m^2 = 500,000 Pa = 500 kPa.
35. Pressure = weight density $\times$ depth = 10,000 N/m^3 $\times$ 220 m = 2,200,000 N/m^2 = 2,200 kPa.
36. Pressure = weight density $\times$ depth = 10,000 N/m^3 $\times$ 20 m = 200,000 N/m^2 = 200 kPa.

Think and Solve

37. Force per nail is 120 pounds/600 nails = 0.2 pounds per nail, which is quite tolerable.

38. A 5-kg ball weighs 50 N, so the pressure is 50 N/cm^2 = 500 kPa.

39. Density $= \frac{m}{V} = \frac{12\text{ kg}}{2\text{ L}}$ = 6 kg/L **.** (Since there are 1000 liters in 1 cubic meter, density may be expressed in units kg/m^3). Density $= \frac{6\text{ kg}}{1\text{ L}} \times \frac{1000\text{ L}}{\text{m}^3} = 6000\text{ kg/m}^3$. That's six times the density of water.

40. Pressure = weight density $\times$ depth = 10,000 N/m^3 $\times$ (5 + 1)m = 10,000 N/m^3 $\times$ 6 m = 60,000 N/m^2 = 60 kPa.

41. Yes. First find the pressure. It is weight density $\times$ depth = (10,000 N/m^3)(2 m) = 20,000 N/m^2, or 20,000 Pa. Force is pressure $\times$ area, and 1 cm^2 = 10^{-4} m^2, so F = (20,000 N/m^2)(10^{-4} m^2) = 2 N. It would be easy for the boy to exert this force. It is about the weight of a notebook or a small box of cereal. (Note: Air pressure is not figured into this calculation because its effect in pushing down on the water from above is canceled by its effect in pushing from outside the hole against the leaking water.)

42. a. BF is 10 N – 8 N = 2 N.
b. The gain in scale reading is 2 N; total weight = 12 N.
c. Weight of the rock is 10 N, so total weight is 20 N.

43. From Table 12.1 the density of gold is 19.3 g/cm^3. Your gold has a mass of 1000 grams, so $\frac{1000\text{ g}}{V}$ = 19.3 g/cm^3. Solving for V,

$$V = \frac{1000\text{ g}}{19.3\text{ g/cm}^3} = 51.8\text{ cm}^3.$$

44. The relative areas are as the squares of the diameters; $6^2/2^2$ = 36/4 = 9. The large piston can lift 9 times the input force to the smaller piston.

45. Human density is about water's, 1000 kg/m^3. From density = m/V, $V = m$/density = (100 kg)/(1000 kg/m^3) = 0.1 m^3.

Think and Rank

46. C, A, B
47. C, B, A
48. A, B, C

Think and Explain

49. Water covers most of Earth and is essential to human life.

50. A sharp knife cuts better than a dull knife because it has a thinner cutting area which results in more cutting pressure for a given force.

51. Pressure would be appreciably greater by the woman because of the relatively small area of contact at the heel, which would hurt you more.

52. A woman with spike heels exerts considerably more pressure on the ground than an elephant! A 500-N lady with 1-cm^2 spike heels puts half her weight on each foot, distributed (let's say) half on her heel and half on her sole. So the pressure exerted by each heel will be (125 N/1 cm^2) = 125 N/cm^2. A 50,000-N elephant with 1000 cm^2 feet exerting $^1/4$ its weight on each foot produces (12,500N/1000 cm^2) = 12.5N/cm^2; about 10 times less pressure. (So a woman with spike heels will make greater dents in a new linoleum floor than an elephant will.)

53. There is less pressure with a waterbed due to the greater contact area.

54. Your upper arm is at the same level as your heart, so the blood pressure in your upper arms will be the same as the blood pressure in your heart.

55. Your body gets more rest when lying than when sitting or standing because when lying, the heart does not have to pump blood to the heights that correspond to standing or sitting.

56. No, in orbit where support is absent there are no pressure differences due to gravity.

57. More water will flow from open faucets downstairs because of the greater pressure. Since pressure depends on depth, a downstairs faucet is effectively “deeper” than an upstairs faucet. The pressure downstairs is greater by an amount = weight density $\times$ depth, where the depth is the vertical distance between faucets.

58. Both are the same, for pressure depends on depth.

59. (a) The reservoir is elevated so as to produce suitable water pressure in the faucets that it serves. (b) The hoops are closer together at the bottom because the water pressure is greater at the bottom. Closer to the top, the water pressure is not as great, so less reinforcement is needed there.

60. Both blocks have the same volume and therefore displace the same amount of water.

61. A one-kilogram block of aluminum is larger than a one-kilogram block of lead. The aluminum therefore displaces more water.

62. A 10-N block of aluminum is larger than a 10-N block of lead. The aluminum therefore displaces more water. Only in Question 60 were the block volumes equal. In this and the preceding exercise, the aluminum block is larger. (These questions serve only to emphasize the distinctions between volume, mass, and weight.)

63. The smaller the window area, the smaller the crushing force of water on it.

64. A typical plumbing design involves short sections of pipe bent at 45-degree angles between vertical sections two-stories long. The sewage therefore undergoes a succession of two-story falls which results in a moderate momentum upon reaching the basement level.

65. Water seeking its own level is a consequence of pressure depending on depth. In a bent U-tube full of water, for example, the water in one side of the tube tends to push water up the other side until the pressures at the same depth in each tube are equal. If the water levels were not the same, there would be more pressure at a given level in the fuller tube, which would move the water until the levels were equal.

66. In deep water, you are buoyed up by the water displaced and as a result, you don’t exert as much pressure against the stones on the bottom. When you are up to your neck in water, you hardly feel the bottom at all.

67. Buoyant force is the result of differences in pressure; if there are no pressure differences, there is no buoyant force. This can be illustrated by the following example, Think and Do 29: A Ping-Pong ball pushed beneath the surface of water will normally float back to the surface when released. If the container of water is in free fall, however, a submerged Ping-Pong ball will fall with the container and make no attempt to reach the surface. In this case there is no buoyant force acting on the ball because there are no pressure differences—the local effects of gravity are absent.

68. Saltwater is denser than freshwater, which means you don’t “sink” as far when displacing your weight. You’d float even higher in mercury (density 13.6 g/cm^3), and you’d sink completely in alcohol (density 0.8 g/cm^3).

69. A body floats higher in denser fluid because it does not have to sink as far to displace a weight of fluid equal to its own weight. A smaller volume of the displaced denser fluid is able to match the weight of the floating body.

70. The can of diet drink is less dense than water, whereas the can of regular drink is denser than water. (Water with dissolved sugar is denser than pure water.) Also, the weight of the can of diet drink is less than the buoyant force that would act on it if totally submerged. So it floats, where buoyant force equals the weight of the can.

71. Mercury is more dense (13.6 g/cm^3) than iron. A block of iron will displace its weight and still be partially above the mercury surface. Hence it floats in mercury. In water it sinks because it cannot displace its weight.

72. Mountain ranges are very similar to icebergs: Both float in a denser medium, and extend farther down into that medium than they extend above it. Mountains, like icebergs, are bigger than they appear to be. The concept of floating mountains is *isostacy*—Archimedes' principle for rocks.

73. A mostly-lead mountain would be more dense than the mantle and would sink in it. Guess where most of the iron in the world is. In the Earth's center!

74. The force needed will be the weight of 1 L of water, which is 9.8 N. If the weight of the carton is not negligible, then the force needed would be 9.8 N minus the carton's weight, for then the carton would be "helping" to push itself down.

75. When the ball is held beneath the surface, it displaces a greater weight of water.

76. The buoyant force on the ball beneath the surface is much greater than the force of gravity on the ball, producing a large net upward force and large acceleration.

77. Heavy objects may or may not sink, depending on their densities (a heavy log floats while a small rock sinks, or an ocean liner floats while a paper clip sinks, for example). People who say that heavy objects sink really mean that dense objects sink. Be careful to distinguish between how heavy an object is and how dense it is.

78. While floating, BF equals the weight of the submarine. When submerged, BF equals the submarine's weight *plus* the weight of water taken into its ballast tanks. Looked at another way, the submerged submarine displaces a greater weight of water than the same submarine floating.

79. Buoyant force will remain unchanged on the sinking rock because it displaces the same volume and weight of water at any depth.

80. Buoyant force on a sinking swimmer will decrease as she sinks. This is because her body, unlike the rock in the previous exercise, will be compressed by the greater pressure of greater depths.

81. You are compressible, whereas a rock is not, so when you are submerged, the water pressure tends to squeeze in on you and reduce your volume. This increases your density. (Be careful when swimming—at shallow depths you may still be less dense than water and be buoyed to the surface without effort, but at greater depths you may be pressed to a density greater than water and you'll have to swim to the surface.)

82. No, there does not have to actually be 14.5 N of fluid in the skull to supply a buoyant force of 14.5 N on the brain. To say that the buoyant force is 14.5 N is to say that the brain is taking up the space that 14.5 N of fluid would occupy if fluid instead of the brain were there. The amount of fluid in excess of the fluid that immediately surrounds the brain does not contribute to the buoyancy on the brain. (A ship floats the same in the middle of the ocean as it would if it were floating in a small lock just barely larger than the ship itself. As long as there is enough water to press against the hull of the ship, it will float. It is not important that the amount of water in this tight-fitting lock weigh as much as the ship—think about that, and don't let a literal word explanation "a floating object displaces a weight of fluid equal to its own weight" and the idea it represents confuse you.)

83. The buoyant force does not change. The buoyant force on a floating object is always equal to that object's weight, no matter what the fluid.

84. Ice cubes will float lower in a mixed drink because the mixture of alcohol and water is less dense than water. In a less dense liquid a greater volume of liquid must be displaced to equal the weight of the floating ice. In pure alcohol, the volume of alcohol equal to that of the ice cubes weighs less than the ice cubes, and buoyancy is less than weight and ice cubes will sink. Submerged ice cubes in a cocktail indicate that it contains a high percentage of alcohol.

85. When the ice cube melts the water level at the side of the glass is unchanged (neglecting temperature effects). To see this, suppose the ice cube is a 5-gram ice cube; then while floating it will displace 5

grams of water. But when melted it becomes the same 5 grams of water. Hence the water level is unchanged. The same occurs when the ice cube that contains air bubbles melts. Whether the ice cube is hollow or solid, it displaces as much water floating as when melted. If the ice cube contains grains of heavy sand, however, upon melting, the water level at the edge of the glass will drop (see Think and Discuss 107).

86. The total weight on the scale is the same either way, so the scale reading will be the same whether or not the wooden block is outside or floating in the beaker. Likewise for an iron block, where the scale reading shows the total weight of the system.

87. The gondolas weigh the same because they're brim full, and whatever the weight of a floating boat, that same weight of water was displaced when the boat entered the gondola.

88. The gondolas weigh the same because the floating boats have displaced a weight of water equal to their own weights, equaling the weight of the brim filled gondola with no boat.

89. If water doesn't overflow, the reading on the scale will increase by the ordinary weight of the fish. However, if the aquarium is brim filled so a volume of water equal to the volume of the fish overflows, then the reading will not change. We correctly assume that the fish and water have the same density.

90. Both you and the water would have the same weight density as on Earth, and you would float with the same proportion of your body above the water as on Earth.

91. Because of surface tension, which tends to minimize the surface of a blob of water, its shape without gravity and other distorting forces will be a *sphere*—the shape with the least surface area for a given volume.

92. A Ping-Pong ball in water in a zero-*g* environment would experience no buoyant force. This is because buoyancy depends on a pressure difference on different sides of a submerged body. In this weightless state, no pressure difference would exist because no water pressure exists.

93. Part of whatever pressure you add to the water is transmitted to the hungry crocodiles, via Pascal's principle. If the water were confined, that is, not open to the atmosphere, the crocs would receive every bit of pressure you exert. But even if you were able to slip into the pool to quietly float without exerting pressure via swimming strokes, your displacement of water raises the water level in the pool. This ever-so-slight rise, and accompanying ever-so-slight increase in pressure at the bottom of the pool, is an ever-so-welcome signal to the hungry crocodiles.

94. The strong man will be unsuccessful. He will have to push with 50 times the weight of the 10 kilograms. The hydraulic arrangement is arranged to his disadvantage. Ordinarily, the input force is applied against the smaller piston and the output force is exerted by the large piston—this arrangement is just the opposite.

95. In Figure 13.23, the increased pressure in the reservoir is a result of the applied force distributed over the input piston area. This increase in pressure is transmitted to the output piston. In Figure 13.22, however, the pressure increase is supplied by the mechanical pump, which has nothing to do with the area of fluid interface between the compressed air and the liquid. Many hydraulic devices have a single piston upon which pressure is exerted.

96. When water is hot, the molecules are moving more rapidly and do not cling to one another as well as when they are slower moving, so the surface tension is less. The lesser surface tension of hot water allows it to pass more readily through small openings.

97. A heavier clip would push deeper into the water surface, overcoming the small force of surface tension, whereupon it sinks.

98. Surface tension accounts for the "floating" of the razor blade. The weight of the blade is less than the restoring forces of the water surface that tends to resist stretching.

Think and Discuss

99. The concept of pressure is being demonstrated. Marshall is careful that the pieces are small and numerous so that his weight is applied over a large area of contact. Then the sharp glass provides insufficient pressure to cut the feet.

100. The water can be no deeper than the spouts, which are at the same height, so both teapots hold the same amount of liquid.

101. From a physics point of view, the event was quite reasonable, for the force of the ocean on his finger would have been quite small. This is because the pressure on his finger has only to do with the depth of the water, specifically the distance of the leak below the sea level—not the weight of the ocean. For a numerical example, see Think and Solve 41.

102. This dramatically illustrates that water pressure depends on depth, which directly relates to Think and Solve 40.

103. The use of a water-filled garden hose as an elevation indicator is a practical example of water seeking its own level. The water surface at one end of the hose will be at the same elevation above sea level as the water surface at the other end of the hose.

104. The block of wood would float higher if the piece of iron is suspended below it rather than on top of it. By the law of flotation: The iron-and-wood unit displaces its combined weight and the same volume of water whether the iron is on top or the bottom. When the iron is on the top, more wood is in the water; when the iron is on the bottom, less wood is in the water. Or another explanation is that when the iron is below—submerged—buoyancy on it reduces its weight and less of the wood is pulled beneath the water line.

105. When a ship is empty its weight is least and it displaces the least water and floats highest. Carrying a load of anything increases its weight and makes it float lower. It will float as low carrying a few tons of Styrofoam as it will carrying the same number of tons of iron ore. So the ship floats lower in the water when loaded with Styrofoam than when empty. If the Styrofoam were outside the ship, below water line, then the ship would float higher as a person would with a life preserver.

106. A sinking submarine will continue to sink to the bottom so long as the density of the submarine is greater than the density of the surrounding water. If nothing is done to change the density of the submarine, it will continue to sink because the density of water is practically constant. In practice, water is sucked into or blown out of a submarine's tanks to adjust its density to match the density of the surrounding water.

107. The water level will fall. This is because the iron will displace a greater amount of water while being supported than when submerged. A floating object displaces its weight of water, which is more than its own volume, while a submerged object displaces only its volume. (This may be illustrated in the kitchen sink with a dish floating in a dishpan full of water. Silverware in the dish takes the place of the scrap iron. Note the level of water at the side of the dishpan, and then throw the silverware overboard. The floating dish will float higher and the water level at the side of the dishpan will fall. Will the volume of the silverware displace enough water to bring the level to its starting point? No, not as long as it is denser than water.)

108. For the same reason as in the previous exercise, the water level will fall. (Try this one in your kitchen sink also. Note the water level at the side of the dishpan when a bowl floats in it. Tip the bowl so it fills and submerges, and you'll see the water level at the side of the dishpan fall.)

109. The balloon will sink to the bottom because its density increases with depth. The balloon is compressible, so the increase in water pressure beneath the surface compresses it, squeezes and reduces its volume, thereby increasing its density. Density further increases as it sinks lower to regions of greater pressure and compression. Think buoyant force: As its volume is reduced by increasing pressure as it descends, the amount of water it displaces becomes less. So buoyant force decreases as it descends.

110. Since both preservers are the same size, they will displace the same amount of water when submerged and be buoyed up with equal forces. Effectiveness is another story. The amount of buoyant force exerted on the heavy gravel-filled preserver is much less than its weight. If you wear it, you'll sink. The same amount of buoyant force exerted on the lighter Styrofoam preserver is greater

than its weight and it will keep you afloat. The *amount* of the force and the *effectiveness* of the force are two different things.

111. He's truthful. But what he doesn't tell you is that you'll drown! Your life preserver will submerge and displace more water than those of your friends who float at the surface. Although the buoyant force on you will be greater, your increased weight is greater still! Whether you float or sink depends on whether or not the buoyant force equals your weight.

112. A floating body displaces its own weight of water, any water! So the buoyant force on Greta is the same as when she floats in fresh water. What is different is the volume of water displaced in the two cases. In the very dense salt water less of her volume is needed to displace her weight, which is why she floats so high in the Dead Sea.

113. Buoyancy would not occur in the absence of weight. Buoyancy depends on pressure differences due to different weights of water beneath different depths of water. No pressure differences, no buoyancy. In the ISS, surface tension rather than buoyancy dictates the behavior of immersed objects.

114. When the ball is submerged (but not touching the bottom of the container), it is supported partly by the buoyant force on the left and partly by the string connected to the right side. So the left pan must increase its upward force to provide the buoyant force in addition to whatever force it provided before, and the right pan's upward force decreases by the same amount, since it now supports a ball lighter by the amount of the buoyant force. To bring the scale back to balance, the additional weight that must be put on the right side will equal twice the weight of water displaced by the submerged ball. Why twice? Half of the added weight makes up for the loss of upward force on the right, and the other half for the equal gain in upward force on the left. (If each side initially weighs 10 N and the left side gains 2 N to become 12 N, the right side loses 2 N to become 8 N. So an additional weight of 4 N, not 2 N, is required on the right side to restore balance.) Because the density of water is less than half the density of the iron ball, the restoring weight, equal to twice the buoyant force, will still be less than the weight of the ball.

115. If the gravitational field of the Earth increased, both water and fish would increase in weight and weight density by the same factor, so the fish would stay at its prior level in water.

14 Gases

Photo openers begin with the father-and-son team of physics professors, P.O. and Johan Zetterberg, pulling on a classroom model of the Magdeburg hemispheres. Photo 2 is a depiction of the original experiment by Otto von Guericke. Photos 3 and 4 are physics friend Evan Jones, demonstrating his favorite physics activity, the Bernoulli Principle. Norwegian physics friend Ole Anton Haugland conducts atmospheric research in photo 5.

The personal profile is of dear Swedish friends, the Zetterbergs and Sara Blomberg.

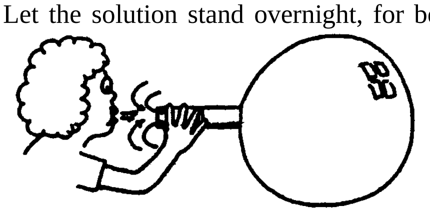
The concepts of fluid pressure, buoyancy, and flotation introduced in the previous chapter are applied to the atmosphere in this chapter. The chief difference between common fluid water and common fluid air has to do with the variability of density. Unlike a body of water, the density of the atmosphere is depth-dependent. The section on Boyle's Law avoids distinguishing between absolute pressure and gauge pressure. Charles' Law is not covered, and reference is made to temperature effects only in a footnote.

The ideal gas law in the form $PV = nRT$, especially in chemistry classes, where n is the number of moles of gas (one mole is equal to 6.02×10^{23} particles). The quantity R is a number called the *molar* (universal) *gas constant* and has a value of 8.31 J/(mol·K). Treatment of Boyle's law in this chapter is much simpler.

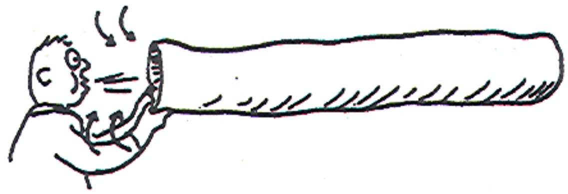
The first three phases of matter, solids, liquids, and gases, are well known. The fourth phase, plasma, is less well known. It is widely known in its role in TV sets and nuclear fusion research.

If you're into lecture demonstrations, this is the chapter material for a show. There are two good sources I have found useful: *A Demonstration Handbook for Physics*, by G.D. Frier and F.J. Anderson, published by AAPT, and *Invitations to Science Inquiry*, by the late Tik L. Liem, at St. Francis Xavier University, in Antigonish, Nova Scotia.

Blowing bubbles is always fun, and here's one from the Exploratorium that nicely illustrates Bernoulli's Principle. Question: Can you blow a 1-breath bubble bigger than your lungs? Answer: Yes, depending on how you do it. Here's how: Tape together two or three small juice cans that have had both ends removed. (You can use the cardboard core of a roll of paper towels, but this tube will not last through repeated uses.) Make up a soap solution that consists of concentrated Joy or Dawn dish liquid, glycerin, and water [recipe: 1 gallon of water, $^2/_3$ cup of dishwashing soap, 3 tablespoonfuls glycerin (available from any drugstore)]. Let the solution stand overnight, for better bubbles are produced by an "aged" mixture. Dip the tube to form a soap film over the end. To make a lung-sized bubble, take a deep breath and, with your mouth near but not touching the nonsoapy end of the tube, exhale and blow a bubble. Don't blow too hard or else the bubble film will break. You'll note the size of this bubble is nearly the volume of your lungs (you can't exhale *all* the air from your lungs).



You can do the same with a long plastic bag. Invite students to blow up the bag, counting their breaths. After two or three students have demonstrated that many breaths of air are required, announce that you can do it with one breath. Then hold the bag a few centimeters in front of your mouth, not on it as your students likely did, and then blow. Air pressure in the airstream you produce is reduced, entrapping surrounding air to join in filling up the bag! (Available from Arbor Scientific. P6-7350.)



The text credits Bernoulli's principle and the airfoil shape of wings to explain wing lift, but wings would work without the airfoil. Remember those model planes you flew as a kid, that were constructed of flat wings? And do you remember that the slot to hold the wing was cut with an "angle of attack"? In this way, oncoming air is forced downward. Newton's 3rd law states the rest: If the wing forces air downward, the air simultaneously forces the wing upward. So birds were able to fly before the time of Daniel Bernoulli. The question is sometimes raised; could birds fly before the time of Isaac Newton?

I've found only futility in trying to explain Bernoulli's principle in terms of differences in molecular impacts on the top and bottom surfaces of wings. Especially when experiments show that molecules don't make impact upon the top surface anyway. A thin boundary layer of air is carried in this low-pressure region as evidenced by the dust found on the surface of fan blades!

In distinguishing between laminar and turbulent flow: Blood flow in the arteries is normally laminar, but when arteries are clogged, blood flow becomes turbulent and the heart has to work harder, resulting in higher blood pressure and a variety of other medical complications. Laminar airflow from hand dryers in public restrooms takes a longer drying time. Turbulent airflow does a better job of drying in a shorter time. Interestingly, you approximate turbulent airflow when you shake your hand in the airflow.

In discussing the global atmosphere, if you get into the abuses that the atmosphere is undergoing, acid rain, and so on, please do not end on a sour note. Also get into what can be done to better the situation. Our students have no shortage of inputs telling them about the abuses of technology, and they hear less often about how technology can be used to improve the quality of life in the world.

Practicing Physics Book:
• Gas Pressure

Problem Solving Book:
There are many problems on gases and atmospheric pressure

Laboratory Manual:
• Tire Pressure and 18-Wheelers Force, Area, and Pressure (Experiment)

Next-Time Questions include:
• Empty Refrigerator
• Flexible Bottle
• Bell Jar
• Floating Ping-Pong Ball
• Weighted Balloon
• Balloon in Falling Elevator
• Balsa Wood and Iron
• Inverted Glass
• Whirling Candle
• Space Shuttle Candle
• Bernoulli Top
• Two Balloons

Hewitt-Drew-It! Screencasts: •*Atmospheric Pressure* •*Boyle's Law* •*Buoyancy of Balloons* •*Air-Buoyancy Problems* •*Bernoulli Principle* •*Bernoulli Applications*

This chapter is not prerequisite to the following chapters.

SUGGESTED LECTURE PRESENTATION

Weight of Air

Hold out an empty drinking glass and ask what's in it. It's not really empty, for it's filled with air, and has weight. It is common to think of air as having very little mass, when the truth is air has a fairly large mass—about $1\frac{1}{4}$ kilogram for a cube one meter on a side (at sea level). The air that fills your bathtub has a mass of about $\frac{1}{2}$ kilogram. We don't feel the weight of this mass only because we are immersed in an ocean of air. A plastic bag full of water, for example, has a significant weight, but if the bag is taken into a swimming pool it weighs nothing (Figure 14.3). Likewise for the surrounding air. A bag of air may have a fairly large mass, but as long as the bag is surrounded by air, its weight is not felt. We are as unconscious of the weight of air that surrounds us as a fish is unconscious of the weight of water that surrounds it.

> CHECK QUESTION: Open the door of a refrigerator and inside is a large lonely grapefruit. Which weighs more, the air in the fridge or the grapefruit? [The inside volume of a common refrigerator is between $\frac{1}{2}$ and $\frac{3}{4}$ m^3, which corresponds to nearly a kilogram of cold air (about 2 pounds). So unless the grapefruit is more than a 2-pounder, the air weighs more.]

The Atmosphere

Draw a circle as large as possible on the chalkboard, and then announce that it represents the Earth. State that if you were to draw another circle, indicating the thickness of the atmosphere surrounding the Earth to scale, you would be drawing the same line—for over 99% of the atmosphere lies within the thickness of the chalk line! Then go on to discuss the ocean of air in which we live.

> DEMONSTRATION: While discussing the preceding, have a gallon metal can with a bit of water in it heating on a burner. When steam issues, cap it tightly and remove from the heat source. Continue your discussion and the collapsing can will interrupt you as it crunches. If you really want to impress your class, do the same with a 50-gallon drum! [The explanation is that pressure inside the can or drum decreases as cooling occurs and the steam condenses. Atmospheric pressure on the outside produces the crunching net force on the can or drum.] (These demos are featured in the photo openers of Chapter 18.)

> DEMONSTRATION: You may or may not want to get into the dramatic demo of crunching soda-pop cans by atmospheric pressure. This is featured in the thermodynamics chapter, page 348. Since it features condensation, perhaps better to treat it later. But for an impressive demo of atmospheric pressure, it complements the collapsing 50-gallon drum!

Atmospheric Pressure

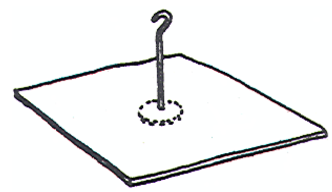
While this is going on, state that if you had a 30-km tall bamboo pole of cross section 1 square cm, the mass of the air from the atmosphere in it would amount to about 1 kg. The weight of this air is the source of atmospheric pressure. The atmosphere bears down on the Earth's surface at sea level with a pressure that corresponds to the weight of 1 kg per square cm. (Some of you may remember the old days when we could talk about plain old 14.7 $1b/in^2$. Since the unit of force is now the newton and the unit of area is the square meter, conceptualizing atmospheric pressure is less simple than before. Nevertheless, continue with the following description.) To understand the pressure of the atmosphere in terms of newton per square meter, ask your class to imagine a 30-km tall sewer pipe of cross section 1 square m, filled with the air of the atmosphere. How much would the enclosed air weigh? The answer is about 10^5 N. So if you draw a circle of one square meter on the lecture table, and ask what the weight is for all the air in the atmosphere above, you should elicit a chorus, silent or otherwise of "10^5 N!" If your table is above sea level, then the weight of air is correspondingly less. Then estimate the force of the air pressure that collapsed the metal can—both of a perfect vacuum and for a case where the pressure difference is about half an atmosphere.

Paul Doherty at the Exploratorium has a steel bar 1.31 m long that has a cross-sectional area of one square inch. It weighs 14.7 pounds. When balanced vertically it produces 14.7-lb/in^2 pressure—that of the

atmosphere. Problems with this approach for the atmospheres of other planets are nicely featured in the Problem Solving Book.

Estimate the force of the atmosphere on a person. You can estimate the surface area by approximating different parts of the body on the board—leg by leg, arm by arm, etc. (This can be quite funny, if you want it to be!)

DEMONSTRATION: This great one from John McDonald of Boise State University in Idaho that consists of a square sheet of soft rubber with some sort of handle at its center. A 50-gram mass hanger poked through its center works well. Toss the rubber sheet on any perfectly flat surface—best on the top of a lab stool. Picking the rubber up by a corner is an easy task because the air gets under it as it is lifted. But lifting it by the middle is another story. As the middle is raised, a low-pressure region is formed because air cannot get in. The rubber sheet behaves as a suction cup, and the entire stool is lifted when the handle is raised. (A version of this is available from Arbor Scientific. P1-2010.)



DEMONSTRATION: Whap a toilet plunger or other suction cup on the wall. (Instruct your class to inquire with their neighbors to see if there is a consensus as to the reason.)

DEMONSTRATION: Place a wooden shingle on the lecture table so that it overhangs the edge a bit. Cover the shingle with a flattened sheet of newspaper, and strike the overhanging part of the shingle with a stick or your hand (be careful of splinters). Promote more "discuss with your neighbor" activity.

Discuss the cushion of air provided by the wonderful air puck demonstrated by Ann Brandon in Figure 14.6. The puck she demonstrates was made by her students as a class project. Can you do the same?

Barometer
State that a better vacuum source than sucking would remove much more air, and if all the air were removed, a very large column of water would be needed to balance the atmosphere on the other side. This would be about 10.3 m, but depends a little on today's atmospheric pressure. Such devices made up the first barometers. They are impractically large, so mercury is instead commonly used. Since mercury is 13.6 times as dense as water, the height of water needed to balance the atmosphere is $^{1}/_{13.6}$ of 10.3 m = 76 cm. If you have the opportunity, construct a mercury barometer before the class.

CHECK QUESTION: How would the barometer level vary while ascending and descending in the elevator of a tall building? [You might quip about the student who was asked to find the height of a building with a sensitive barometer who simply dropped it from the top and measured the seconds of fall—or who exchanged it with the builder of the building for the correct information.]

Discuss ear popping in aircraft, and why cabin pressure is lower than atmospheric pressure at high altitudes.

DEMONSTRATION: As the sketch shows, try sucking a drink through a straw with two straws; one in the liquid and the other outside. It can't be done because the pressure in your mouth is not reduced because of the second straw (although with some effort a bit of liquid can be drawn). Invite your students to try this, and to share this (and other ideas!) at parties.

DEMONSTRATION: The siphon. Careful! Many instructors have found in front of their classes that they misunderstood the operation of a siphon. The explanation does not have to do with differences in atmospheric pressures at the ends of the tube, but with the end of the tube exceeds 10.3 m, atmospheric pressure acting upwards against the liquid in the tube is greater than the downward pressure of liquid. The situation is analogous to

pushing upward against the bottom ends of a seesaw with unequal pushes. Liquid in the short end of the tube is pushed up with more net force than the liquid in the long end of the tube. (Or it's analogous to a chain hanging over a peg, with one end longer and heavier than the other end.)

Boyle's Law

Discuss Boyle's Law. At the risk of information overload you may or may not want to get into the differences between absolute and gauge pressures. (I avoid it in the text.)

Consider discussion of Think and Do 31, estimating the weight of a car by the pressure in its tires and the amount of tire contact area. Now your students know why trailer trucks commonly have 18 wheels—the air pressure in the tires multiplied by the area of contact of the 18 tires is the weight of the truck and its load. Fewer tires mean greater air pressure in the tires. (In this project we ignore the significant support supplied by the sidewalls of the tires—much more in today's tires.)

Discuss or show Think and Do 32 (dunking a glass mouth downwards in water to show the "empty" glass contains air—and how air is compressed with deeper depths) and relate this to the compressed air breathed by scuba divers. Discuss the reason for the difficulty of snorkeling at a depth of 1 m and why such will not work for greater depths; i.e., air will not of itself move from a region of lesser pressure (the air at the surface) to a region of greater pressure (the compressed air in the submerged person's lungs).

Recall the sinking balloon problem from the previous chapter (Think and Discuss 39 in Chapter 13) and relate this to the smaller volume to which a swimmer is subjected with increasing depth. Hence the need for pressurized air for scuba divers. Without the pressurized air, one's volume and therefore buoyancy is decreased, making it more difficult to return to the surface. Whereas at shallow depths the average swimmer can passively return to the surface, at greater depths a passive swimmer will sink to the bottom.

Buoyancy of Air

Hold your hands out, one a few centimeters above the other, and ask if there really is any difference in air pressure at the two places. The fact that there is can be demonstrated by the rising of a helium-filled balloon of the same size! The balloon rises only because the atmospheric pressure at its bottom is greater than the atmospheric pressure at its top. Pressure in the atmosphere really is depth-dependent!

CHECK QUESTION: Which is greater, the buoyant force on the helium-filled balloon, or the buoyant force on you? [Assuming the balloon has less volume than you, there is more buoyant force on you.] Discuss why.

Interestingly enough, atmospheric pressure halves with every 6 km increase in elevation, so a freely expanding balloon grows by twice its volume with each 6 km rise. Does this increase the buoyant force? No, because the displacement of twice as much half-as-dense air has the same weight!

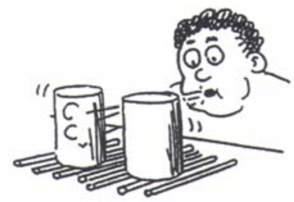
CHECK QUESTION: A large block of Styrofoam and a small block of iron have identical weights on a weighing scale. Which has the greater mass? [Actually the Styrofoam has the greater mass. This is because it has a greater volume, displaces more air, and experiences a great buoyant force. So it's weight on the scale is its "true weight," minus the buoyant force of the air, which is the case for all things weighed in air. The fact that it reads the same on the scale as the iron means it must have more mass than the iron. (A lobster that walks on a bathroom scale on the ocean bottom has more mass than the reading indicates.)]

CHECK QUESTIONS: What would happen to the bubbles in a beer mug if you dropped the mug of beer from the top of a high building? Would the bubbles rise to the top, go to the bottom, or remain motionless with respect to the mug? [First of all, you'd likely be apprehended for irresponsible behavior. As for the bubbles, they'd remain motionless relative to the mug, since the local effects of gravity on the beer would be absent. This is similar to the popular demo of dropping a cup of water with holes in the side. When held at rest the water spurts out, but drop it and the spurting stops.]

Bernoulli's Principle

Introduce Bernoulli's principle by blowing into a spool as Evan Jones does in the opening photos of the chapter. A piece of card at the opposite end isn't blown off! Follow up with a variety of demonstrations as suggested:

DEMONSTRATIONS:
(1) Make a beach ball hover in a stream of air issuing from the reverse end of a vacuum cleaner.
(2) Do the same with a Ping-Pong ball in the airstream of a hairdryer.
(3) Line a cardboard tube with sandpaper and sling the ball sidearm. The sandpaper produces the friction to make the ball roll down the tube and emerge spinning—you'll see that the ball breaks in the correct direction. Point out that paddles have a rough surface like the sandpaper for the same reason—to spin the ball when it is properly struck—that is, to apply "English" to the ball.
(4) Swing a Ping-Pong ball taped to a string into a stream of water as shown. Follow this up with a discussion of the shower curtain in the last paragraph of Bernoulli's Principle.



DEMONSTRATION: Place a pair of upright empty aluminum soft drink cans on a few parallel straws on your lecture table. Blow between the cans and they roll toward each other. Or do the same with the nearby cans suspended by strings. A puff of air between them makes them click against one another, rather than blowing them apart as might be expected. [Some people avoid Bernoulli's principle because in some cases, like plane flight, there are alternate models to account for the forces that occur. These clicking cans, however, are straight Bernoulli!]

DEMONSTRATION: Show the sailboat demo described earlier for Chapter 5 in this manual; first with the flat sail, and then with the curved sail. The difference is appreciable. It's nice if you can show this on an air track.

Plasma
Describe the changes of phase of matter as the rate of molecular motion is increased in a substance, say piece of ice changing to water, and then to steam. State how increased motion results in the molecules shaking apart into their constituent atoms, and how still increased motion results in the freeing of orbital electrons from the atomic nuclei—and you have a plasma. Acknowledge the partial plasmas in the everyday world—advertising signs, fluorescent lamps, street lamps, and the like. Discuss the role of plasma in power production (MHD generators, Chapter 25).

Discuss the role of plasma in TV sets. A search on the web will provide you with detailed explanations.

NEXT-TIME QUESTION: Place a small birthday-type candle in a deep drinking glass. When the glass is whirled around in a circular path, say held at arm's length while one is spinning like an ice skater, which way does the flame point? And most important, why? (Note the similarity of this with Think and Explain 66.)

NEXT-TIME QUESTION: Discuss the role of Bernoulli in increasing the size of wave in the wind. [Air pressure is reduced as air increases speed in moving over the tops of waves, and increased in the troughs. This pressure difference enhances the height of the waves.]

Answers and Solutions to Chapter 14

Reading Check Questions

1. The Sun is the energy source for motion of air molecules. Earth's gravity pulls air molecules down, keeping most from escaping into space.
2. Half the atmosphere is below 5.6 kilometers.
3. The cause of atmospheric pressure is the weight of air.
4. The mass of one cubic meter of air is about 1.25 kg.
5. Approximate mass is 1 kg, with weight 10 N.
6. Pressure is 10 N/cm^2.
7. Both pressures are the same.
8. Both weights are the same.
9. It would have to be taller because it's 1/13.6 as dense.
10. Correct to say pushed up. The pressure of the surrounding air does the pushing.
11. The atmosphere can push water a maximum of 10.3 m via its pressure.
12. The pressure sensed by an aneroid barometer is calibrated in altitude.
13. Density doubles when volume is halved.
14. Pressure doubles when volume is halved.
15. An ideal gas is one in which intermolecular forces and size of molecules can be neglected.
16. BF equals 1 N. If the BF decreases, the balloon descends. If BF increases, the balloon ascends.
17. A BF exists for all objects that displace fluid.
18. The balloons expand and would likely rupture with increased altitude if fully inflated.
19. Streamlines are imaginary lines that show the path of a fluid.
20. Where streamlines are crowded, pressure is less.
21. When speed increases, internal pressure decreases.
22. When speed decreases, internal pressure increases.
23. Bernoulli's principle is about internal pressures.
24. Faster-moving air above the wing has reduced pressure.
25. Faster-moving water between the ships results in reduced pressure.
26. The ships are pushed together by the greater water pressure on their opposite sides.
27. The fluid is pushed up by the pressure of the atmosphere on its surface.
28. Particles in a gas are electrically neutral. In a plasma they're charged.
29. Neon signs, fluorescent lamps, certain TV screens.
30. Low pollution MHD power can be produced when a plasma beam is directed into the field of a magnet

Think and Do

31. The pressures should be approximately the same. The rigid walls of the tire prevent the pressure calculations from being closer. The calculated value should therefore be somewhat greater.

32. This is certainly worth doing!

33. You have a barometer of sorts, but since the medium is water, it would have to reach a column 10.3 m tall to give the same pressure as a column of mercury 76 cm tall.

34. Atmospheric pressure holds the card to the glass, in any direction.

35. The gurgling is due to air entering the jar. No gurgling would occur if this were somehow tried on the Moon where there is no atmosphere.

36. The aluminum can implodes dramatically. What occurs is rapid condensation of the steam, described later in Chapter 18. This is a must-do activity!

37. When your finger closes the top of the water-filled straw, atmospheric pressure no longer acts on the top part of the water, which is easily lifted. When you raise your finger the water spills out the bottom. This is a nice procedure for transferring liquids from one test tube to another.

38. The blown air that spreads between the spool and card is of low pressure, low enough that the greater atmospheric pressure on the outside part of the card presses the card to the spool.

39. Water pressure is lowered in the part flowing over the curved part of the spoon, resulting in that part moving toward the stream instead of away from it.

Think and Solve

40. To find the buoyant force that the air exerts on you, find your volume and multiply by the weight density of air (From Table 14.1 we see that the mass of 1 m^3 of air is about 1.25 kg. Multiply this by 10 N/kg and you get 12.5 N/m^3). You can estimate your volume by your weight and by assuming your density is approximately equal to that of water (a little less if you can float). The weight density of water is 10^4 N/m^3, which we'll assume is your density. By ratio and proportion:

$$= \frac{\text{(your weight in newtons)}}{\text{(your volume in meters}^3\text{)}} .$$

If your weight is a heavy 1000 N, for example (about 220 lb), your volume is 0.1 m^3. So buoyant force = 12.25 $N/m^3 \times$ 0.1 m^3 = about 1.2 N, roughly the weight of an apple. (A useful conversion factor is 4.45 N = 1 pound.) Another way to do this is to say that the ratio of the buoyant force to your weight is the same as the ratio of air density to water density (which is your density). This ratio is 1.25/1000 = 0.00125. Multiply this ratio by your weight to get the buoyant force.

41. To effectively lift (0.25)(80 kg) = 20 kg the mass of displaced air would be 20 kg. Density of air is about 1.2 kg/m^3. From density = mass/volume, the volume of 20 kg of air, also the volume of the balloon (neglecting the mass of the helium) would be volume = mass/density = (20 kg)/(1.2 kg/m^3) = **17 m^3**. (Of course as altitude is reached the helium in the balloon expands, displacing more volume of air – but thinner air as the atmosphere also becomes less dense.)

42. (a) The weight of the displaced air must be the same as the weight supported, since the total force (gravity plus buoyancy) is zero. The displaced air weighs **20,000 N**.
(b) Since weight = *mg*, the mass of the displaced air is $m = W/g$ = (20,000 N)/(10 m/s^2) = 2,000 kg. Since density is mass/volume, the volume of the displaced air is volume = mass/density = (2,000 kg)/(1.2 kg/m^3) = **1,700** m^3 (same answer to two figures if g = 9.8 m/s^2 is used).

43. From $P = \frac{F}{A}$; $F = PA = (0.04)\left(10^5 \frac{N}{m^2}\right)(100\ m^2) = 4 \times 10^5$ N.

44. From $P = F/A$ = (den $\times g \times$ vol)/A = (den $\times g \times A \times h$)/A = den $\times g \times h$; $h = P$/(den $\times g$) = (100,000 N/m^2)/(1.2 $kg/m^3 \times$ 10 N/kg) = 8300 m = 8.3 km.

Think and Rank

45. A, B, C
46. A, C, B
47. C, A, B

Think and Explain

48. Some of the molecules in the Earth's atmosphere *do* go off into outer space—those like helium with speeds greater than escape speed. But the average speeds of most molecules in the atmosphere are well below escape speed, so the atmosphere is held to Earth by Earth's gravity.

49. There is no atmosphere on the Moon because the speed of a sizable fraction of gas molecules at ordinary temperatures exceeds lunar escape velocity (because of the Moon's smaller gravity). Any appreciable amounts of gas have long leaked away, leaving the Moon airless.

50. The tires heat, giving additional motion to the gas molecules within.

51. When the diameter is doubled, the area is four times as much. For the same pressure, this would mean four times as much force.

52. At higher altitude, less atmospheric pressure is exerted on the ball's exterior, making relative pressure within greater, resulting in a firmer ball.

53. The ridges near the base of the funnel allow air to escape from a container it is inserted into. Without the ridges, air in the container would be compressed and would tend to prevent filling as the level of liquid rises.

54. The density of air in a deep mine is greater than at the surface. The air filling up the mine adds weight and pressure at the bottom of the mine, and according to Boyle's law, greater pressure in a gas means greater density.

55. The bubble's mass does not change. Its volume increases because its pressure decreases (Boyle's law), and its density decreases (same mass, more volume).

56. Airplane windows are small because the pressure difference between the inside and outside surfaces result in large net forces that are directly proportional to the window's surface area. (Larger windows would have to be proportionately thicker to withstand the greater net force—windows on underwater research vessels are similarly small.)

57. Unlike water, air is easily compressed. In fact, its density is proportional to its pressure (at a given temperature). So, near the ground, where the pressure is greater, the air's density is greater and corresponds to more squashed bricks; at high altitude, where the pressure is less, the air's density is less, corresponding to less squashed bricks.

58. A vacuum cleaner wouldn't work on the Moon. A vacuum cleaner operates on Earth because the atmospheric pressure pushes dust into the machine's region of reduced pressure. On the Moon there is no atmospheric pressure to push the dust anywhere.

59. A perfect vacuum pump could pump water no higher than 10.3 m. This is because the atmospheric pressure that pushes the water up the tube weighs as much as 10.3 vertical meters of water of the same cross-sectional area.

60. If barometer liquid were half as dense as mercury, then to weigh as much, a column twice as high would be required. A barometer using such liquid would therefore have to be twice the height of a standard mercury barometer, or about 152 cm instead of 76 cm.

61. The height of the column in a mercury barometer is determined by pressure, not force. Fluid pressures depend on density and depth—pressure at the bottom of a wide column of mercury is no different than at the bottom of a narrow column of mercury of the same depth. The weight of fluid *per area* of contact is the same for each. Also with the surrounding air, hence why wide and narrow-tube barometers show the same height.

62. Mercury can be drawn a maximum of 76 cm with a siphon. This is because 76 vertical cm of mercury exert the same pressure as a column of air that extends to the top of the atmosphere. Or looked at another way; water can be lifted 10.3 m by atmospheric pressure. Mercury is 13.6 times denser than water, so it can only be lifted only $^{1}/_{13.6}$ times as high as water.

63. The height would be less. The weight of the column balances the weight of an equal-area column of air. The denser liquid would need less height to have the same weight as the mercury column.

64. Drinking through a straw is slightly more difficult atop a mountain. This is because the reduced atmospheric pressure is less effective in pushing soda up into the straw.

65. One's lungs, like an inflated balloon, are compressed when submerged in water, and the air within is compressed. Air will not of itself flow from a region of low pressure into a region of higher pressure. The diaphragm in one's body reduces lung pressure to permit breathing, but this limit is strained when nearly 1 m below the water surface. This limit is exceeded at more than a depth of 1 m.

66. The air tends to pitch toward the rear (law of inertia), becoming momentarily denser at the rear of the car, less dense in the front. Because the air is a gas obeying Boyle's law, its pressure is greater where its density is greater. Then the air has both a vertical and a horizontal "pressure gradient." The vertical gradient, arising from the weight of the atmosphere, buoys the balloon up. The horizontal gradient, arising from the acceleration, buoys the balloon forward. So the string of the balloon makes an angle. The pitch of the balloon will always be in the direction of the acceleration. Step on the brakes and the balloon pitches backwards. Round a corner and the balloon noticeably leans radially towards the center of the curve. Nice! (Another way to look at this involves the effect of two accelerations, *g* and the acceleration of the car. The string of the balloon will be parallel to the resultant of these two accelerations. Nice again!)

67. The lead and feathers have the same mass. Weight is measured as the force with which something presses on a supporting surface. When the buoyancy of air plays a role, the net force against the supporting surface is less, indicating a smaller weight. Buoyant force is more appreciable for larger volumes, like feathers. So with less buoyancy, the same mass of lead weighs more than the same mass of feathers.

68. Objects that displace air are buoyed upward by a force equal to the weight of air displaced. Objects therefore weigh less in air than in a vacuum. For objects of low densities, like bags of compressed gases, this can be important. For high-density objects like rocks and boulders the difference is usually negligible.

69. Helium is less dense than air, and will weigh less than an equal volume of air. A helium-filled bottle would weigh less than the air bottle (assuming they are filled to the same pressure). However, the helium-filled bottle will weigh more than the empty bottle.

70. The buoyant force does not change, because the volume of the balloon does not change. The buoyant force is the weight of air displaced, and doesn't depend on what is doing the displacing. The net lift, however, is greater because of a smaller weight of gas.

71. An object rises in air only when buoyant force exceeds its weight. A steel tank of anything weighs more than the air it displaces, so won't rise. Also, the helium is compressed in the tank, and wouldn't rise even if the tank's weight were nil. A helium-filled balloon weighs less than the air it displaces and rises.

72. A moving molecule encountering a surface imparts force to the surface. The greater the number of impacts on a given-size surface, the greater the pressure.

73. According to Boyle's law, the pressure will increase to **three times** its original pressure.

74. The volume of gas in the balloon increases.

75. The pressure increases, in accord with Boyle's law.

76. Pressure of the water decreases and the bubbles expand.

77. The shape would be a catenary. It would be akin to Gateway Arch in St. Louis and the hanging chain discussed in Chapter 12.

78. The stretched rubber of an inflated balloon provides an inward pressure. So the pressure inside is balanced by the sum of two pressures; the outside air pressure plus the pressure of the stretched balloon. (The fact that air pressure is greater inside an inflated balloon than outside is evident when it is punctured—the air "explodes" outward.)

79. The force of the atmosphere is on both sides of the window; the net force is zero, so windows don't normally break under the weight of the atmosphere. In a strong wind, however, pressure will be reduced on the windward side (Bernoulli's Principle) and the forces no longer cancel to zero. Many windows are blown *outward* in strong winds.

80. According to Bernoulli's principle, the wind at the top of the chimney lowers the pressure there, producing a better "draw" in the fireplace below.

81. As speed of water increases, internal pressure within the water decreases.

82. Air speed across the wing surfaces, necessary for flight, is greater when facing the wind.

83. Air moves faster over the spinning top of the Frisbee and pressure against the top is reduced. A Frisbee, like a wing, needs an "angle of attack" to ensure that the air flowing over it follows a longer path than the air flowing under it. So there is a difference in pressures against the top and bottom of the Frisbee that produces an upward lift.

84. (a) Speed increases (so that the same quantity of gas can move through the pipe in the same time). (b) Pressure decreases (Bernoulli's principle). (c) The spacing between the streamlines decreases, because the same number of streamlines fit in a smaller area.

85. Spacing of airstreams on opposite sides of a non-spinning ball are the same. For a spinning ball, airstream spacings are less on the side where airspeed is increased by spin action.

86. A tennis ball has about the same size as a baseball, but much less mass. Less mass means less inertia, and more acceleration for the same force. A Ping-Pong ball provides a more obvious curve due to spinning because of its low mass.

87. Greater wing area produces greater lift, important for low speeds where lift otherwise would be less. Flaps are pulled in to reduce area at cruising speed, where a smaller wing area can provide lift equal to the weight of the aircraft.

88. An airplane flies upside down by tilting its fuselage so that there is an angle of attack of the wing with oncoming air. (It does the same when flying right side up, but then, because the wings are designed for right-side-up flight, the tilt of the fuselage may not need to be as great.)

89. The thinner air at high-altitude airports produces less lift for aircraft. This means aircraft need longer runways to achieve greater speed for takeoff.

90. In accord with Bernoulli's principle, the sheets of paper will move together because air pressure between them is reduced, and be less than the air pressure on the outside surfaces.

91. Bernoulli's Principle. For the moving car the pressure will be less on the side of the car where the air is moving fastest—the side nearest the truck, resulting in the car's being pushed by the atmosphere towards the truck. Inside the convertible, atmospheric pressure is greater than outside, and the canvas rooftop is pushed upwards towards the region of less pressure. Similarly for the train windows, where the interior air is at rest relative to the window and the air outside is in motion. Air pressure against the inner surface of the window is greater than the atmospheric pressure outside. When the difference in pressures is great enough, the window is blown out.

92. A solid-walled wharf is disadvantageous to ships pulling alongside because water currents are constrained and speed up between the ship and the wharf. This results in a reduced water pressure, and the normal pressure on the other side of the ship then forces the ship against the wharf. The pilings avoid this mishap by allowing the freer passage of water between the wharf and the ship.

Think and Discuss

93. The weight of a truck is distributed over the part of the tires that make contact with the road. Weight/surface area = pressure, so the greater the surface area, or equivalently, the greater the number of tires, the greater the weight of the truck can be for a given pressure. What pressure? The pressure exerted by the tires on the road, which is determined by (but is somewhat greater than) the air pressure in its tires. Can you see how this relates to Think and Do 31?

94. To begin with, the two teams of horses used in the Magdeburg hemispheres demonstration were for showmanship and effect, for a single team and a strong tree would have provided the same force on the hemispheres. So if two teams of nine horses each could pull the hemispheres apart, a single team of nine horses could also, if a tree or some other strong object were used to hold the other end of the rope.

95. If the item is sealed in an air-tight package at sea level, then the pressure in the package is about 1 atmosphere. Cabin pressure is reduced somewhat for high altitude flying, so the pressure in the package is greater than the surrounding pressure and the package therefore puffs outwards.

96. If an elephant steps on you, the pressure that the elephant exerts is over and above the atmospheric pressure that already is exerted on you. It is the *extra* pressure the elephant's foot produces that crushes you. For example, if atmospheric pressure the size of an elephant's foot were somehow removed from a patch of your body, you would be in serious trouble. You would be soothed, however, if an elephant stepped onto this area!

97. You agree with your friend, for the elephant displaces far more air than a small helium-filled balloon, or small anything. The *effects* of the buoyant forces, however, is a different story. The large buoyant force on the elephant is insignificant relative to its enormous weight. Not so for the tiny buoyant force acting on the balloon of tiny weight.

98. If the air pressure in the inflated balloon were equal to the outside air pressure, the extra weight of the air in the balloon would be canceled by an equal buoyant force and the scale reading would not change. But to keep a rubber balloon inflated, its air pressure inside has to be greater than outside air pressure. Then the extra weight is greater than the buoyant force and the scale will show a greater weight.

99. No, assuming the air is not compressed. The air filled bag is heavier, but buoyancy negates the extra weight and the reading is the same. The buoyant force equals the weight of the displaced air, which is the same as the weight of the air inside the bag (if the pressures are the same).

100. The end supporting the punctured balloon tips upwards as it is lightened by the amount of air that escapes. There is also a loss of buoyant force on the punctured balloon, but that loss of upward force is less than the loss of downward force, since the density of air in the balloon before puncturing was greater than the density of surrounding air.

101. The balloon which is free to expand will displace more air as it rises than the rigid balloon. Hence, the balloon that is free to expand will experience more buoyant force than the balloon that does not expand, and will rise higher. Also, as the rigid balloon rises, its constant volume displaces ever-lighter volumes of air.

102. The buoyant force on each is the same, but is much less effective for the basketball due to its greater weight. Buoyancy is simply more conspicuous on the helium-filled balloon.

103. The rotating habitat is a centrifuge, and denser air is “thrown to” the outer wall. Just as on Earth, the maximum air density is at “ground level,” and becomes less with increasing altitude (distance toward the center). Air density in the rotating habitat is least at the zero-*g* region, the hub.

104. The helium-filled balloon will be buoyed from regions of greater pressure to regions of lesser pressure, and will “rise” in a rotating air-filled habitat.

105. According to Bernoulli’s principle, when a fluid gains speed in flowing through a narrow region, the pressure of the fluid is reduced. The gain in speed, the cause, produces reduced pressure, the effect. But one can argue that a reduced pressure in a fluid, the cause, will produce a flow in the direction of the reduced pressure, the effect. For example, if you decrease the air pressure in a pipe by a pump or by any means, neighboring air will rush into the region of reduced pressure. In this case the increase in air speed is the result, not the cause of, reduced pressure. Cause and effect are open to interpretation. Bernoulli’s principle is a controversial topic with many physics types!

15 Heat, Temperature, and Expansion

The little boy holding the fireworks sparkler in the Part 3 opener is Francesco Ming Giovannuzzi, the grandson of Tsing and Keith Bardin. A photo of Tsing opens Chapter 13.

Lil and I are in the second photo opener to this chapter, sampling the effects of radioactive processes in Earth's interior. Photo 3 is of Anette Zetterberg, wife of P.O. and mother of Johan, whose profile was in the previous chapter. In a visit to Gdansk, Poland, in 2004, physicist Kasia Werel showed Lil and I the birthplace of Daniel Gabriel Fahrenheit, where I snapped this photo. Photo 4 is the result of a visit to Gdansk in Poland while visiting Kasia Werel a few years ago.

The profile for this chapter is Benjamin Thompson, better known as Count Rumford—a distant relative.

Just as the chapters on Properties of Matter placed particular emphasis on water and the atmosphere, the chapters on heat do the same. Note that no attempt is made to familiarize the student with methods of temperature conversion from one scale to another. The effort saved can be better spent on physics.

The concept of heat flow between temperature differences provides some background to the concept of current flow between electric potential differences in Chapter 23. Here we introduce the concept of KE/molecule, *temperature,* which is analogous to the later concept of PE/charge, *voltage*. Both high temperatures and high voltages are ordinarily harmful only when large energies are transferred in a relatively short time (that is, when large power is transferred). The white-hot sparks of a 4th-of-July sparkler have very high temperatures, but their energies are very small. So they are quite harmless. Similarly, a balloon rubbed on your hair may have thousands of volts, but the energy stored is very small. The *ratios* energy per molecule or energy per charge may be high, but if the molecules or charges involved are small in number, the energy content is also small. Aside from the parallels between heat and electricity, the chapter serves as a prerequisite only for the three following chapters dealing with heat transfer, change of phase, and thermodynamics.

In the text, temperature is treated in terms of the kinetic energy per molecule of substances. Although strictly speaking, temperature is directly proportional to the kinetic energy per molecule only in the case of ideal gases, we take the view that temperature is related to molecular translational kinetic energy in most common substances. Rotational kinetic energy, on the other hand is only indirectly related to temperature, as illustrated in a microwave oven. In the oven the H_2O molecules are set oscillating with considerable rotational kinetic energy. But this doesn't cook the food. What does is the translational kinetic energy imparted to neighboring molecules that are bounced from the oscillating H_2Os like marbles that are set flying in all directions when they encounter the spinning blades of fans. If the neighboring atoms did not interact with the oscillating H_2O molecules, the temperature of the food would be no different before and after activation of the microwave oven. Temperature has to do with the translational kinetic energy of molecules. Degrees of freedom, rotational and vibrational states, and the complications of temperature in liquids and solids are not treated. Next course!

Care must be taken when using a microwave oven for boiling water. It can become superheated, and when disturbed, like removing the cup from the oven, it can blow up in your face. If water is heated in a microwave oven, something should be placed in the cup to diffuse energy. It is much safer to boil water in a conventional pan or teakettle.

Quantity of heat is spoken of mainly in terms of the calorie, with acknowledgement of the SI unit, the joule.

The definition of the calorie in the chapter implies that the same amount of heat will be required to change the temperature of water 1°C—whatever the temperature of the water. Although this relation holds true to a fair degree, it is not exactly correct: A calorie is precisely defined as the amount of heat required to raise a gram of water from 14° to 15°C.

The exaggeration of the volume versus temperature scale in Figure 15.21 should be pointed out, for it is easy for a student to erroneously conclude that a great change in the volume of water occurs over a relatively small temperature change. Take care our students don't interpret the volume at 0°C to be that of ice rather than ice water.

Practicing Physics Book:
• Temperature
• Thermal Expansion

Problem Solving Book:
Many problems on heat and temperature

Laboratory Manual:
• Dance of the Molecules *Observing Molecular Motion* (Demonstration)
• Bouncing off the Walls *Kinetic Theory Simulation* (Tech Lab)
• Temperature Mix *Specific Heat Capacity* (Experiment)
• Spiked Water *Specific Heat Capacity* (Experiment)

Next-Time Questions:
• Metal Ring •Sparkler Temperature • Metal Gap

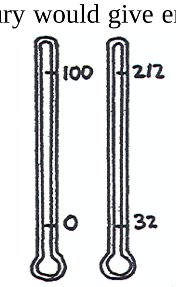
Hewitt-Drew-It! Screencasts: •*Heat and Temperature* •*Specific Heat* •*Thermal Expansion* •*Thermal Expansion of Water*

Check Questions are few in the following suggested lecture. By now it is hoped that this technique is a major part of your lecture method. Take pity on students who sit through lectures where the instructor poses questions that he or she immediately answers without involving the students, who are passive observers rather than participants in the learning process. Pose Check Questions before you move onto new material.

SUGGESTED LECTURE PRESENTATION

Begin by asking what the difference is between a hot cup of coffee and a cold cup of coffee. Think small for the answer: The molecules in the hot cup of coffee are moving faster—they are more energetic. Heat and temperature involves kinetic energies of the molecules in substances. Heat and temperature are different: To begin with, **heat** is energy that is measured in joules, or calories. **Temperature** is measured in degrees. More on this soon.

Temperature Calibration: Describe how the increased jostling of molecules in a substance result in expansion and show how this property underlies the common thermometer. Draw a sketch of an uncalibrated thermometer on the board, with its mercury vessel at the bottom, and describe how the energy of jostling molecules is transferred from the outer environment to the mercury within. If placed in boiling water, energy of the jostling water molecules would transfer to the mercury, which would expand and squeeze its way up the tube. State that one could make a scratch on the glass at this level and label it 100. And then describe how, if placed in a container of ice water, the molecules of mercury would give energy to the cold water and slow down, contract, and fall to a lower level in the tube.



One could again make a scratch and call this point zero. Then, if 100 equally-spaced scratches are made between the two reference points, one would have a centigrade thermometer.

In a vein of humor draw a second uncalibrated thermometer on the board and repeat your discussion (in abbreviated fashion) of placing it in boiling water. State that the upper level needn't be called 100, that any number would do so long as all thermometers were calibrated the same. Ask the class for any random number. Someone will say 212. Casually acknowledge the 212 response and write that on your diagram. Repeat the bit about placing the instrument in ice water and state that the position on the scale needn't be called zero, that any number would do. Ask for a random number. You'll have several students volunteer 32, which you graciously accept. The class should be in a good mood at this point, and you briefly discuss the two scales and lead into the idea of absolute zero and the Kelvin scale. (For humor, named after "Lord Scale"?)

> CHECK QUESTION: Which has the largest degrees, a Celsius thermometer or a Fahrenheit thermometer? [Celsius.]

> CHECK QUESTION: True or false: Cold is the absence of fast-moving molecules. [False; cold refers to very slow-moving molecules, not their absence. If you have no molecules at all, the concept of temperature is inapplicable.]

Absolute Zero: The treatment of the Kelvin scale is very brief in this chapter, and it is not really treated until Chapter 18. So you can gloss over it and explain that it is "nature's scale" beginning at the coldest possible value for its zero point. In case your treatment of heat is brief and you will not be including the Thermodynamics Chapter 18, you may want to develop the idea of absolute zero here, in which case you should consider the following lecture skit (which is repeated in the suggested lecture of Chapter 18).

Begin by supposing you order at your friendly restaurant a piece of hot apple pie. The waitress brings you cold pie, straight from the fridge and at 0°C. You tell her you'd like hotter pie, in fact, twice as hot. Question: What will be the temperature of the pie? Encourage neighbor discussion. Many will say zero degrees. Then ask what the new temperature would be if the pie were initially 10°C, and acknowledge that the answer is *not* 20°C! Now you're ready for the "Celsius, the Village Tailor" story.

> Celsius, the Village Tailor: To answer the pie temperature questions and develop the idea of absolute zero, hold a measuring stick against the wall of the lecture room (so that the bottom of the vertically-oriented stick is about 1 meter above the floor) and state that you are Celsius, the village tailor, and that you measure the heights of your customers against the stick, which is firmly fastened to the wall. You state that the stick need not extend all the way to the floor, nor to the ceiling, for your shortest and tallest customers fall within the extremities of the stick. Mention that all tailors using the same method could communicate meaningfully with each other about the relative heights of their customers providing the measuring sticks in each shop were fastened the same distance above the "absolute zero" of height. It just so happens that the distance to the floor, the "absolute zero," is 273 notches—the same size notches on the stick itself. Then one day, a very short woman enters your shop and stands against the wall, the top of her head coinciding with the zero mark on the measuring stick. As you take her zero reading, she comments that she has a brother who is twice her height. Ask the class for the height of her brother. Then ask for the temperature of the twice-as-hot apple pie. (There is a difficulty with the pie example, for twice the energy involves a phase change—the subject of Chapter 17. So the pie will not *really* be 273°C. Strictly speaking, your example should use helium gas or a metal that doesn't change phase in the temperature range in question. But the pie is more interesting!)

Heat: Distinguish between *heat* and *temperature*. Heat has to do with energy flow while temperature is a ratio of energy per molecules. They are very different. A Fourth-of-July-type sparkler emits sparks with temperature about 2000°C, but the heat one receives when one of these sparks lands on one's face is very small. High temperature means a high ratio of heat per molecule (as cited by the boy with the fireworks sparkler in the Part 3 opening photo). The *ratio* and the *amount* of heat energy transferred are different things. Relatively few molecules comprise the tiny bit of white-hot matter that makes up the sparks of the

sparkler. (Later you'll involve a similar argument when you discuss the small energy associated with the high voltage of a charge Van de Graaff generator or party balloon rubbed on your hair.)

> CHECK QUESTION: How are the sparks from a sparkler that strike your skin akin to tiny droplets of boiling water striking your skin? [Both have high temperatures, but safe levels of internal energy to transfer to your skin.]

Distinguish between *heat* and *internal energy*. (Internal energy is treated in more detail in Chapter 18.) Internal energy is loosely referred to as heat energy, although by definition, heat is the energy that flows from one place to another by virtue of a temperature difference. Heat is energy in transit.

Quantity of Heat: Define the calorie, and distinguish it from the Calorie, the concern of people who watch their diet.

Specific Heat Capacity: Lead into a distinction between the difference between calories and degrees, and the concept of specific heat capacity by asking your class to consider the difference in touching an empty iron frying pan that has been placed on a hot stove for one minute (ouch!) and touching water in a frying pan in the oven for the same time. With the water, you could place your hand in it safely even if it were on the stove for several minutes. Ask which has the higher temperature, the empty pan or the one filled with water. Clearly, it is the empty pan. Ask which absorbed the greater amount of energy. The answer is the water-filled pan because it was on the stove for a longer time. The water has absorbed more energy for a smaller rise in temperature! Physics types have a name for this idea—specific heat *capacity*, or for short, *specific heat*. Cite the different specific heat capacities of cooked foods, of a hot TV dinner and the aluminum foil that can be removed with bare hands while the food is still too hot to touch.

Water's High Specific Heat: Cite examples of water's high specific heat—old fashioned hot water bottles on cold winter nights, cooling systems in cars, and the climate in places where there is much water. With the aid of a large world map, globe, or chalkboard sketch, show the sameness of latitudes for England and the Hudson Bay, and the French and Italian Rivieras with Canada. State how the fact that water requires so long a time to heat and cool, enables the Gulf Stream to hold heat energy long enough to reach the North Atlantic. There it cools off. In accord with the conservation of energy, when the water cools something else warms. What is that something? The air. The cooling water warms the air, and the winds blow westerly at that latitude. So warmed air moves over the continent of Europe. If this weren't the case, Europe would have the same climate as regions of northern Canada. A similar situation occurs in the United States. The Atlantic Ocean off the coast of the eastern states is considerably warmer than the Pacific Ocean off the coast of Washington, Oregon, and California, yet in winter months the east coast is considerably colder. This has to do with the high specific heat of water and the westerly winds. Air that is warmed by cooling water on the west coast moves landward and gives mild winters to Washington, Oregon, and California. But on the east coast, this warmed air moves seaward, leaving the east coast frigid in winter months. In summer months, when the air is warmer than the water, the air cools and the water warms. So summer months on the west coast states are relatively cool, while the east coast is relatively hot. The high specific heat of water serves to moderate climates. The climates on islands, for example, are fairly free of temperature variations. San Francisco, a peninsula that is close to being an island, has the most stable climate of any city in continental America.

4°C Water: To lead into the idea of water's low density at 4°C you can ask if anyone in class happens to know what the temperature at the bottom of Lake Michigan was on a particular date, for example, New Year's eve in 1905. Then for the bottom of Lake Tahoe in California for any other date. And for another, until many are responding "4°C."

> CHECK QUESTION: Ask the same for the bottom of a rain puddle outside the building and be prepared for some to say 4°C.

Then ask why 4°C was the right answer for the deep lakes but the wrong answer for a puddle. Then go into the explanation as given in the book—how the microscopic slush forms as the freezing temperature is approached, yielding a net expansion below 4°C. (I haven't done this, but I have thought of showing a

Galileo-type thermometer in class—a small flask with a narrow glass tube filled with colored water, so changes in temperature would be clearly evident by different levels of water in the narrow tube. Then surround the flask with perhaps dry ice to rapidly chill the water. The water level drops as the temperature of the water decreases, but its rate slows as it nears 4°C, and then the direction reverses as cooling continues. This expansion of the water is due to the formation of "microscopic slush." The level of water observed, as a function of time, yields the graphs of Figures 15.20 and 5.21.)

Ice Formation on Lakes: Discuss the formation of ice, and why it forms at the surface and why it floats. And why deep bodies of water don't freeze over in winter because all the water in the lake has to be cooled to 4°C before colder water will remain at the surface to be cooled to the freezing temperature, 0°C. State that before one can cool a teaspoonful of water to 3°C, let alone 0°C, all the water beneath must be cooled to 4°C and that winters are neither cold or long enough for this to happen in the United States.

> CHECK QUESTION: Will a chunk of lead float on melted lead as ice floats on water? [No, solid lead is more dense than liquid lead. Water is almost unique in that it is less dense in the solid phase.]

Expansion: (Note the order differs from the text—in lecture I stay with the topic of water.) State that steel lengths expand about 1 part 100,000 for each 1°C increase in temperature. Show a steel rod and ask if anybody would be afraid to stand with their stomach between the end of the rigidly held steel rod and a wall while the temperature of the rod is increased a few degrees. This is a safe activity, for the slight expansion of the rod would hardly be noticeable. Now ask for volunteers for a steel rod several kilometers in length. This is much different, for although the rate of change in length is the same, the total change in length could impale you! Then discuss the expansion joints of large structures (Figures 15.12 and 15.13).

The photo in Figure 15.14 is intriguing. Much has been learned about laying railroad tracks, so this photo goes back many years ago.

> DEMONSTRATION: Place the middle of a bimetallic strip in a flame to show the unequal expansions of different metals, and the subsequent bending.

> CHECK QUESTION: When a metal ball is heated in a Bunsen flame, which undergoes a change: Volume, mass, or density? [Only volume and density change. Mass remains the same.]

Point out that different substances expand or contract (length, area, and volume) at their own characteristic rates (coefficients of expansion). Cite examples such as the need for the same expansion rate in teeth and teeth fillings; iron reinforcing rods and concrete; and the metal wires that are encased in glass light bulbs and the glass itself. Provision must be made when materials with different expansion rates interact; like the piston rings when aluminum pistons are enclosed in steel cylinders in a car, and the rockers on bridges (Figure 15.12), and the overflow pipe for gasoline in a steel tank.

A common consequence of expansion with increased temperature occurs with power lines. They expand and sag on hot days and when they carry large currents. Power lines short out when they sag against trees (or when overgrowth of trees touch the lines).

> CHECK QUESTION: How would a thermometer differ if glass expanded with increasing temperature more than mercury? [Answer: The scale would be upside down because the reservoir would enlarge (like the enlarged hole in the heated metal ring), and mercury in the column would rise with increasing temperature.]

> CHECK QUESTION: Why is it advisable to not completely fill the gas tank of a car that may sit in sunlight on a hot day after being filled? [As the fuel warms it expands, likely overflowing and causing a hazard.]

> NEXT-TIME QUESTION: Ask your students to place an ice cube in a glass of ice water at home, and compare the water level at the side of the glass before and after the ice melts. Ask them to

account for the volume of ice that extends above the water line after it melts. [The answer to the original question is, of course, that the level remains unchanged. This can be explained from the principles learned in Chapter 13. The floating ice cube displaces its own weight of water, so if the ice cube weighs say a newton, then when placed in the glass, one newton of water is displaced and the water level rises. If it is first melted and then poured in the glass, again the water line would be higher, but by one newton, the same amount.] More interesting is to account for the volume of floating ice that extends above the water line (Think and Discuss 105). The ice expanded upon freezing because of the hexagonal open structures of the crystals. Ask the class if they have any idea of how much volume all those billions and billions of open spaces constitute. [Their combined volume is essentially that of the part of ice extending above the water line! When the ice melts, the part above the water line fills in the open structures within the ice upon collapse.] Discuss this idea in terms of icebergs, and whether or not the coastline would change if all the *floating* icebergs in the world melted. [The oceans would rise a bit, but only because icebergs are composed of fresh water. (They form above sea level and break off and then fall into sea.) The slight rise is more easily understood by exaggerating the circumstance—think of ice cubes floating in mercury. When they melt, the depth of fluid (water on mercury) is higher than before.]

Distinguish between the melting of floating icebergs and the melting of ice on land—the floating icebergs contribute nil to a rising ocean level upon melting, where the melting ice on land can appreciably raise ocean levels.

Take note that ocean levels also rise due to thermal expansion. If you had a water-filled test tube that was 2 miles high (an average depth in most oceans), even a slight increase in temperature would raise the level of water appreciably. Fortunately, temperature changes occur near the surface, not all the way down. So changes in sea level are smaller due to thermal expansion. (Too often we attribute rising oceans only to ice-cap melting.)

Tidbits on frozen food: Experts say not to refreeze food that has been thawed. If the food spends too much time above refrigeration temperature (40°F) it may be unsafe to eat due to bacteria growth. So you'd be refreezing unsafe food. If the food still contains ice crystals and is as cold as if it were refrigerated, it may be refrozen safely. Ice cream and frozen yogurt are exceptions and should be discarded. For food such as bread that never needs freezing in the first place, refreezing is safe even if fully thawed.

NEXT-TIME QUESTION: Think and Solve 41, the ring around Earth.

Answers and Solutions for Chapter 15

Reading Check Questions

1. Water freezes at 0°C and 32°F, and boils at 100°C and 212°F.
2. Freezing water is 273K and boiling water is 373K.
3. Translational kinetic energy is the energy of to-and-fro molecular motion.
4. Temperature is a measure of the *average* translational KE per molecule.
5. The necessary condition is thermal equilibrium, for only then will the thermometer and thing being measured have the same temperature.
6. They are two terms for the same thing. Physicists prefer the term *internal* energy.
7. Energy transfers from warmer objects to cooler objects.
8. Hot objects contain internal energy, not heat.
9. Heat is internal energy that flows from hot to cold locations. They are not two terms for the same thing.
10. The direction of internal energy flow is from objects at higher temperatures to objects at lower temperatures.
11. Food is burned and the energy release measured.
12. One Calorie is 1000 calories.
13. One calorie is equivalent to 4.19 joules.
14. The energy needed is 4.19 J.
15. Silver heats more quickly and therefore has a lower specific heat capacity.
16. A substance that heats quickly has a low specific heat capacity.
17. A substance that cools quickly has a low specific heat capacity.
18. Water has an appreciably higher specific heat capacity than other common materials.
19. Internal energy is carried in the Gulf Stream from tropical waters to the North Atlantic where it warms the otherwise cold climate.
20. The air above the cooling water warms.
21. Water has a moderating effect, slow to warm and slow to cool.
22. Molecules move faster with increasing temperature and take more space.
23. The strip bends due to its two metals with different rates of thermal expansion.
24. Liquids generally expand more for equal increases in temperature.
25. Ice-cold water contracts with increasing temperature, until it reaches 4°C.
26. Ice is less dense than water due to its ice crystals that have open structures.
27. Microscopic slush makes water less dense.
28. As temperature increases, microscopic slush melts.
29. The smallest volume of water (and the densest) occurs when water is at 4°C.
30. Only when water below is more dense than water above, can water remain at the surface to freeze.

Think and Do

31. If you use a 0.6-gram peanut, your value should be about 1400 calories, assuming all the heat energy transfers to the water.

32. Tell your grandparents that heat is energy in transit, not energy inside something, which you refer as internal energy.

Plug and Chug

33. $Q = cm\Delta T$ = (1 cal/g·°C)(300 g)(30°C - 22°C) = 3000 cal.
34. $Q = cm\Delta T$ = (4,190 J/kg·°C)(0.30 kg)(30°C - 22°C) = 12,570 J.
35. 3000 cal (4.19 J/1 cal) = 12570 J

Think and Solve

36. (a) The amount of heat absorbed by the water is
    $Q = cm\Delta T$ = (1.0 cal/g·°C)(50.0 g)(50°C – 22°C) = 1400 cal. At 40% efficiency only 0.4 the energy from the peanut raises the water temperature, so the calorie content of the peanut is 1400 cal/0.4 = 3500 cal.
    (b) The food value of a peanut is 3500 cal/0.6 g = 5.8 kilocalories/gram = 5.8 Cal/g.

37. Each kg requires 1 kcal for each degree change, so 50 kg needs 50 kcal for each degree change. Twenty degrees means twenty times 50 kcal, which is 1000 kcal.

By formula: $Q = cm\Delta T$ = (1 cal/g·°C)(50,000 g)(20°C) = 1000 kcal. We can convert this to joules knowing that 4.19 J = 1 cal. In joules this quantity of heat is 4190 kJ (about 4200 kJ).

38. Raising the temperature of 10 kg of steel by one degree takes 10kg(450 J/kg·°C) = 4500 J. Raising it through 100 degrees takes 100 times as much, or 450,000 J.
By formula, $Q = cm\Delta T$ = (450 J/kg·°C)(10 kg)(100°C) = 450,000 J.
Heating 10 kg of water through the same temperature difference takes 1,000,000 calories, which is [1,000,000 cal(4.18 J/cal)] = 41,800,000 J, nearly ten times that for the piece of steel—another reminder that water has a large specific heat capacity.

39. If a 1-m long bar expands 0.6 cm when heated, a bar of the same material that is 100 times as long will expand 100 times as much, 0.6 cm for each meter, or 60 cm. (The heated bar will be 100.6 m long.)

40. By equation: $\Delta L = L\alpha\Delta T$ = (1300 m)(11 x 10^{-6}/°C)(20°C) = 0.29 m, nearly 0.3 m.

41. If a snugly fitting steel pipe that girdled the world were heated by 1 C°, it would stand about 70 m off the ground! The most straight-forward way to see this is to consider the radius of the 40,000 long kilometer pipe, which is the radius of Earth, 6370 kilometers. Steel will expand 11 parts in a million for each C° increase in temperature; the radius as well as the circumference will expand by this fraction. So 11 millionths of 6370 km = 70 m. Is this not astounding?

Think and Rank

42. Ans: B, A, C. (1 cal = 4.18 J; so 1 J = 0.23 cal. So 1 J > 1 cal. 1 Calorie = 1,000 cal = 4180 J. So 1 Cal > 1 cal > 1 J.)

43. C, A, B.

44. B, A, C. The wire to mostly sag is the wire that elongates more for equal changes in temperature.

45. C, A, B.

Think and Explain

46. Inanimate things such as chairs and tables have the same temperature as the surrounding air. People and other mammals, however, generate their own heat and have body temperatures that are normally higher than air temperature.

47. Since Celsius degrees are larger than Fahrenheit degrees, an increase of 1 C° is larger. It's 9/5 as large.

48. No, they have the same average speed, but not the same instantaneous speed. At any moment molecules with the same average speed can have enormously different instantaneous speeds.

49. Gas molecules move haphazardly and move at random speeds. They continually run into one another, sometimes giving kinetic energy to neighbors and sometimes receiving kinetic energy. In this continual interaction, it would be statistically impossible for any large number of molecules to have the same speed. Temperature has to do with average speeds.

50. You cannot establish by your own touch to determine whether or not you are running a fever because there would be no temperature difference between your hand and forehead. If your forehead is a couple of degrees higher in temperature than normal, your hand is also a couple of degrees higher.

51. A molecule in a gram of steam has considerably more kinetic energy, as evidenced by its higher temperature.

52. The hot coffee has a higher temperature, but not a greater internal energy. Although the iceberg has less internal energy per mass, its enormously greater mass gives it a greater total energy than that in the small cup of coffee. (For a smaller volume of ice, the fewer number of more energetic molecules in the hot cup of coffee may constitute a greater total amount of internal energy—but not compared to an iceberg.)

53. Mercury must expand more than glass. If the expansion rates were the same there would be no different readings for different temperature. All temperatures would have the same reading.

54. Calorie is largest, which is 1000 calories.

55. The average speed of molecules in both containers is the same. There is greater internal energy in the full glass (twice the matter at the same temperature). More heat will be required to increase the temperature of the full glass by 1°C, twice as much, in fact.

56. Gaseous pressure changes with changes in temperature.

57. Increasing temperature means increasing KE which means increasing momentum of molecules, which means greater impact and greater pressure against the walls of the container. Simply put, as the temperature of a confined gas is increased, the molecules move faster and exert a greater pressure as they rebound from the walls of the container.

58. Different substances have different thermal properties due to differences in the way energy is stored internally in the substances. When the same amount of heat produces different changes in temperatures in two substances of the same mass, we say they have different specific heat capacities. Each substance has its own characteristic specific heat capacity. Temperature measures the average translational kinetic energy of random motion, but not other kinds of energy.

59. The substance with the smaller specific heat capacity, iron, undergoes the greater change in temperature.

60. In the same environment, the slowly cooling object has the greater specific heat capacity.

61. Less specific heat means shorter time for temperature change, and a shorter hot bath.

62. Water in the melon has more "thermal inertia"—a higher specific heat than sandwich ingredients. Be glad water has a high specific heat capacity the next time you're enjoying cool watermelon on a hot day!

63. Alcohol, for less specific heat means less thermal inertia and a greater change in temperature.

64. Both the pan and water undergo the same temperature change. But water, with its greater specific heat capacity, absorbs more heat.

65. The brick will cool off too fast and you'll be cold in the middle of the night. Bring a jug of hot water with its higher specific heat to bed and you'll make it through the night.

66. The climate of Bermuda, like that of all islands, is moderated by the high specific heat of water. What moderates the climates are the large amounts of energy given off and absorbed by water for small changes in temperature. When the air is cooler than the water, the water warms the air; when the air is warmer than the water, the water cools the air. (Warmth due to the Gulf Stream helps as well.)

67. The climate of Iceland, like that of Bermuda in the previous exercise, is moderated by the surrounding water. (Warmth due to the Gulf Stream helps as well.)

68. In winter months when the water is warmer than the air, the air is warmed by the water to produce a seacoast climate warmer than inland. In summer months when the air is warmer than the water, the air is cooled by the water to produce a seacoast climate cooler than inland. This is why seacoast communities and especially islands do not experience the high and low temperature extremes that characterize inland locations.

69. As the ocean off the coast of San Francisco cools in the winter, the heat it loses (transfers) warms the atmosphere it comes in contact with. This warmed air blows over the California coastline to produce a relatively warm climate. If the winds were easterly instead of westerly, the climate of San Francisco would be chilled by winter winds from dry and cold Nevada. The climate would be reversed also in Washington, D.C. because air warmed by the cooling of the Atlantic Ocean would blow over Washington, D.C. and produce a warmer climate in winter there.

70. Sand has a low specific heat capacity, as evidenced by its relatively large temperature changes for small changes in internal energy. A substance with a high specific heat capacity, on the other hand, must absorb or give off large amounts of internal energy for comparable temperature changes.

71. Water between 0°C and 4°C is an exception.

72. No, the different expansions are what bends the strip or coil. Without the different expansions a bimetallic strip would not bend when heated.

73. When the rivets cool they contract. This tightens the plates being attached.

74. When doused, the outer part of the boulders cooled while the insides were still hot. This caused a difference in contraction, which fractured the boulders.

75. The tires heat up, which heats the air within. The molecules in the heated air move faster, which increases air pressure in the tires. (See question 57.)

76. Temperature differences cause differences in expansion and contraction, which produce sounds as structures expand or contract.

77. Cool the inner glass and heat the outer glass. If it's done the other way around, the glasses will stick even tighter (if not break).

78. Higher expansion rate would mean greater difference in shape with different temperature, a liability for a telescope mirror.

79. If they expanded differently, as for different materials, the key and lock wouldn't match.

80. A chimney undergoes more changes in temperature than any other part of the building, and therefore more changes in expansion and contraction. Such changes should be the same for all parts of the building that bear the building's weight. Otherwise, sags and worse occur.

81. The photo was likely taken on a warm day. If it were taken on a cold day there would be more space between the segments.

82. Gas is sold by volume. The gas meter that tallies your gas bill operates by measuring the number of volume units (such as cubic feet) that pass through it. Warm gas is expanded gas and occupies more space, and if it passes through your meter, it will be registered as more gas than if it were cooled and more compact. The gas company gains if gas is warm when it goes through your meter because the same amount of warmer gas has a greater volume.

83. Overflow is the result of liquid gasoline expanding more than the solid tank.

84. When a mercury thermometer is warmed, the outside glass is heated before heat gets to the mercury inside. So the glass is the first to expand, momentarily opening (like the heated ring in the third chapter-opener photo) which allows the mercury to drop from the glass tube into the slightly enlarged reservoir. When the mercury warms to the same temperature of the glass, it is then forced up the glass tube because of its greater expansion rate.

85. The U shape takes up the slack of expansion or contraction, without changing the positions of the end points.

86. Thin glass is used because of the sudden temperature changes. If the glass were thicker, unequal expansions and contractions would break the glass with sudden temperature changes.

87. In the construction of a light bulb, it is important that the metal leads and the glass have the same rate of heat expansion. If the metal leads expand more than glass, the glass may crack. If the metal expands less than glass upon being heated, air will leak in through the resulting gaps.

88. 4°C.

89. Water has the greatest density at 4°C; therefore, either cooling or heating at this temperature will result in an expansion of the water. A small rise in water level would be ambiguous and make a water thermometer impractical in this temperature region.

90. The atoms and molecules of most substances are more closely packed in solids than in liquids. So most substances are denser in the solid phase than in the liquid phase. Such is the case for iron and aluminum and most all other metals. But water is different. In the solid phase the structure is open-spaced and ice is less dense than water. Hence ice floats in water.

91. Volume increases.

92. At 0°C it will contract when warmed a little; at 4°C it will expand, and at 6°C it will expand.

93. It is important to keep water in pipes from freezing because when the temperature drops below freezing, the water expands as it freezes and the pipes (if metal) will fracture if water in them freezes.

94. Ponds would be more likely to freeze if water had a lower specific heat capacity. This is because the temperature would decrease more when water releases energy; water would more readily be cooled to the freezing point.

95. If cooling occurred at the bottom of a pond instead of at the surface, ice would still form at the surface, but it would take much longer for ponds to freeze. This is because all the water in the pond would have to be reduced to a temperature of 0°C rather than 4°C before the first ice would form. Ice that forms at the bottom where the cooling process is occurring would be less dense and would float to the surface (except for ice that may form on materials anchored to the bottom of the pond).

Think and Discuss

96. The hot rock will cool and the cool water will warm, regardless of the relative amounts of each. The amount of temperature change, however, does depend in great part on the relative masses of the materials. For a hot rock dropped into the Atlantic Ocean, the change in the ocean's temperature would be too small to measure. Keep increasing the mass of the rock or keep decreasing the mass of the ocean and the change will be evident.

97. Other effects aside, the temperature should be slightly higher, because the PE of the water above has been transformed to KE below, which in turn is transformed to heat and internal energy when the falling water is stopped. (On his honeymoon, James Prescott Joule could not be long diverted from his preoccupation with heat, and he attempted to measure the temperature of the water above and below a waterfall in Chamonix. The temperature increase he expected, however, was offset by cooling due to evaporation as the water fell.)

98. A high specific heat capacity. The more ways a molecule can move internally, the more energy it can absorb to excite these internal motions, which don't raise the temperature of the substance. This greater capacity for absorbing energy makes a higher specific heat capacity.

99. Every part of a metal ring expands when it is heated—not only the thickness, but the outer and inner circumference as well. Hence the ball that normally passes through the hole when the temperatures are equal will more easily pass through the expanded hole when the ring is heated. (Interestingly enough, the hole will expand as much as a disk of the same metal undergoing the same increase in temperature. Blacksmiths mounted metal rims in wooden wagon wheels by first heating the rims. Upon cooling, the contraction resulted in a snug fit.)

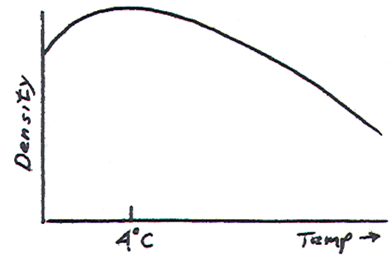
100. The heated balls would have the same diameter.

101. Brass expands and contracts more than iron for the same changes in temperature. Once the iron has cooled and has its "iron grip" on the brass, the two materials, being good conductors and being in contact with each other, are heated or cooled together. If the temperature is increased, the iron expands—but the brass expands even more. Even cooling them won't produce separation.

102. The gap in the ring will become wider when the ring is heated. Try this: Draw a couple of lines on a ring where you pretend a gap to be. When you heat the ring, the lines will be farther apart—the same amount as if a real gap were there. Every part of the ring expands proportionally when heated uniformly—thickness, length, gap and all.

103. On a hot day a steel tape expands more than the ground. You will be measuring land with a "stretched" tape. So your measurements of a plot of land will be smaller than measurements taken on a cold day. Measurements taken on a cold day will show the ground to be larger. (If, on the other hand, you're staking off land not already plotted, then on a hot day you'll get more land.)

104. The curve for density versus temperature is:



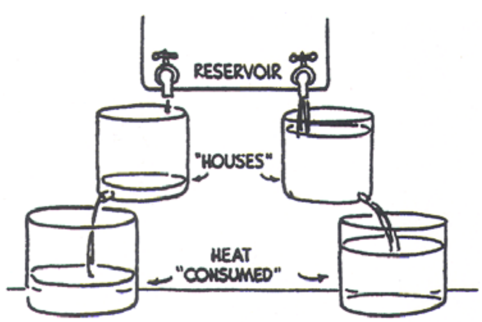
105. The combined volume of all the billions of "open rooms" in the hexagonal ice crystals of a piece of ice is equal to the volume of the part of the ice that extends above water when ice floats. When the ice melts, the open spaces are filled in by the amount of ice that extends above the water level. This is why the water level doesn't rise when ice in a glass of ice water melts—the melting ice "caves in" and nicely fills the open spaces.

16 Heat Transfer

Helen Yan is a merit badge in my teaching career, as she continued from my Conceptual Physics class to a stellar career in space science. It is my pleasure that Helen's personal profile begins this chapter, and a nice touch to be able to show her photos two decades ago with newer ones doing the same demonstration. John Suchocki, my nephew, took the photo of the snow-covered mailboxes along his street. Your students may ask why the snow gathered on the lighter colored metal boxes and not on the black ones. If you answer this right away, you have a way to go before becoming a good teacher. With more teaching experience, you'll give an answer *after* your students have given it more thought. The black boxes, better absorbers, are somewhat warmer in sunlight or even an overcast day than the lighter boxes, so snow is more likely to melt upon the warmer black surfaces than the lighter ones. Hence snow accumulates more on the lighter mailboxes.

This chapter begins with conduction, convection and radiation of heat with emphasis again on bodies of water and the atmosphere. The section on radiation serves as some background to later chapters on light.

To turn your thermostat down or off in order to save energy, Think and Discuss 93, about whether to turn your thermostat down makes an excellent NEXT-TIME QUESTION. To illustrate its answer [turn it off], make up the apparatus shown, which consists of a main reservoir that feeds "heat" into two identical "houses," that leak heat to the environment. The amount of leakage is caught by the bottom jars and can be compared at a glance. Arrange the input flow rates so that equilibrium is established when the "houses" are nearly full: then input = outflow. Turn one input off altogether. After some time, turn it back on until it fills to the level of the other "house." Now compare the differences in leaked water! Make comparisons of turning it down partway instead of off. This roughly approximates Newton's law of cooling. Leak rate is highest when ΔT, or in this case, ΔP, is greatest.



Adiabatic expansion is suggested in this chapter, and a molecular model is described to account for the cooling that expanding air undergoes. This idea continues again in more detail in Chapter 18.

Firewalking: Charlatans still cite firewalking as overcoming nature. James Randi interestingly points out that when a charlatan is exposed, the outrage of his or her victims is most frequently aimed at the one who strips away the mask. And on the matter of nonsense, it seems unlikely that there will never be a claim so whacky that at least one PhD physicist cannot be found to vouch for it. There are fringies in every group—ours include.

Paul Doherty points out that unlike the decrease in temperature with distance about a hot coal or two, above a bed of coals the temperature remains fairly constant, like the constant electric field near a plane of charges.

Heat transfer is becoming more evident with concrete and glass buildings that absorb heat by day and release it by night. More transfer occurs with increases in temperatures, populations, and urbanization.

As more snow disappears, less sunlight is reflected into outer space, and world temperature increases. Hence rooftops should be painted white. Such reflective roofs would cut energy consumption by cooling buildings and reducing the need for air conditioners. Some of the greatest ideas are the simplest!

Cosmic microwave background (CMB), not treated in the chapter but mentioned in footnote 4 on page 311, was discovered in 1965 by Penzias and Wilson. CMB was emitted about 300,000 years after the Big Bang, when the universe was only one-thousandths of its present size. Today, CMB is one of cosmology's most important objects of study.

A discussion of the Earth's seasons is in order with this chapter. It is not covered in the text, but is an exercise in the Practice Book, pages 73 and 74, and relates to the section on Climate Change in this chapter.

Practicing Physics Book:
• Transmission of Heat

Problem Solving Book:
Heat problems, yes indeed!

Laboratory Manual:
• Canned Heat: Heating Up *Thermal Absorption* (Experiment)
• Canned Heat: Cooling Down *Thermal Absorption* (Experiment)
• I'm Melting, I'm Melting *Conduction and Absorption* (Demonstration)

Next-Time Questions:
• Firewalk
• Black or White Coffee
• Radiant Glow
• Winter Night
• Radiator
• Emitter
• Sleep Well
• Thermostat
• White House
• Equinox
• Black-Shiny Cookware
• Black-Shiny space Packaging
• How Warm or Cold

Hewitt-Drew-It! Screencasts: •*Heat Transfer* •*Radiant Energy*

SUGGESTED LECTURE PRESENTATION

Conduction: Begin by asking why pots and pans have wooden or plastic handles. Discuss conduction from an atomic point of view, citing the role of the electrons in both heat and electrical conductors. You might demonstrate the oldie of melting wax on different metal rods equidistance from a hot flame, and illustrate relative conductivities of the rods. Other materials can be compared in their ability to conduct heat, like newspaper when having to sleep out-of-doors. Discuss the poor conductivity of water, which ties to the discussion in the previous lecture of the 4°C temperature at the bottom of deep lakes all year round.

DEMONSTRATION: Do the activity suggested on page 307, of ice wedged at the bottom of a test tube. Some steel wool will hold the ice at the bottom of the tube. It is impressive to see that the water at the top is brought to a boil by the flame of a burner while the ice below barely melts!

DEMONSTRATION: Think and Do 33, at the end of the chapter on page 317 and wrap a piece of paper around a thick metal bar and attempt to burn it in the flame. The paper does not reach its ignition temperature because heat is conducted into the metal.

DEMONSTRATION: Extend the previous demo and lace a paper cup filled with water in the flame. Again, the paper will not reach its ignition temperature and burn because heat from the flame is conducted into the conductor—this time water. Water is not *that* poor a conductor—its high specific heat plays a role here also.

Discuss the poor conductivity of air, and its role in insulating materials—like snow. Discuss thermal underwear, and how the fish-net open spaces actually trap air between the skin and the undergarment. Discuss double-window thermopane. If your lecture was preceded by Chapter 14, cite the case of the manufacturer in the midwest who sent a shipment of thermopane windows by truck over the Rocky Mountains only to find that all the windows broke at the higher altitude. The atmospheric pressure between the panes was not matched by the same pressure outside. Ask if the windows "imploded" or "exploded." [Imploded.]

Convection and Rising Warm Air:

CHECK QUESTION: Why does smoke from a cigar rise and then settle off?

CHECK QUESTIONS: Why does helium rise to the very top of the atmosphere? Why doesn't it settle like the smoke? [Unlike the heated smoke, the helium molecule doesn't "cool off" and slow down when it interacts with the surrounding molecules. Due to its low mass, its average speed is higher than heavier molecules at the same temperature.]

After explaining that for the same temperature, the relatively small mass of helium is compensated for by a greater speed at whatever temperature and altitude, state that helium is not found in the air but must be mined from beneath the ground like natural gas. (The helium nucleus is the alpha particle that emanates from radioactive ores.) This idea of faster-moving helium underscores the relationship of kinetic energy to temperature. Stress it.

Expanding Air Cools: (The rising of warm air and its subsequent cooling is treated thermodynamically in Chapter 18—the treatment here and the later treatment complement each other nicely.) Now you're into the cooling effect of expanding air. Depart from the order of topics in the text and first treat the warming of compressed air. The familiar bicycle pump offers a good example. Why does the air become warm when the handle is depressed? It's easy to see that the air molecules speed up when the piston slams against them. A Ping-Pong ball similarly speeds up when a paddle hits it. Now, consider what happens to the speed of a Ping-Pong ball when it encounters a receding paddle! Can your students see that its rebound speed will be less than its incident speed? Now you're ready to discuss the cooling of expanding air, Figure 16.6, and compare this to the case of the slowing Ping-Pong balls with molecules that are on the average receding from one another.

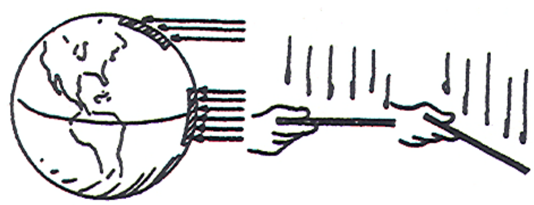
Here's a great one: Have everyone in class blow against their hands with open mouths. Their breaths feel warm. Then repeat with mouth openings very small. Their breaths are remarkably cooler. They **experience** first hand that expanding air *really does* cool! (That's my son Paul in Figure 16.5, and his mom in Figure 16.7.)

DEMONSTRATION: Heat water in a pressure cooker, remove the cap and place your hand in the expanding steam that is ejected to show the cooling of expanding air, as Millie does in Figure 16.7. Mixing of water vapor with the outside air also contributes to this cooling. Cite that the students

don't see steam as such, for the steam is actually not visible. The cloud they see is not steam but condensed water vapor—and considerably cooled!

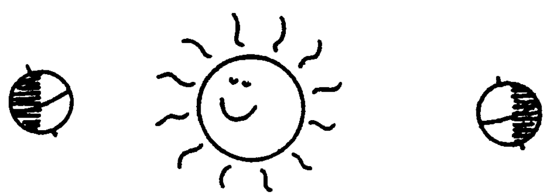
Discuss the role of convection in climates. Begin by calling attention to the shift in winds as shown in Figure 16.8. This leads you into radiation, the heat from the Sun.

Warm at the Equator — Cold at the Poles: You may want to discuss why the Earth is warmer at the equator than at the poles, and get into the idea of solar energy per unit area. A neat way to do this is to first draw a large circle on the board that represents Earth (like the one below, only without the Sun's rays at this point). Ask for a neighbor check and speculate why it is warm near the equator and cold at the poles. To dispel the idea that the farther distance to the poles is the reason, do the following:

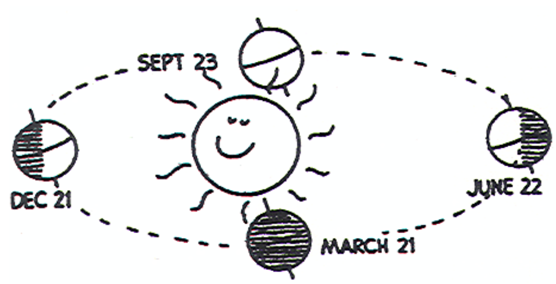


SKIT: Ask the class to pretend there is a vertical rainfall, into which you reach out your window with two sheets of paper—one held horizontally and the other held at an angle as shown. You bring the papers inside as a friend strolls by and inquires what you're doing. You remark that you have been holding the sheets of paper out in the rain. Your friend sees that the horizontally held paper is much wetter and asks why. You repeat with both papers held outward as before, and your friend says, "Oh, I see why. You're holding the tilted sheet farther away from the clouds!" Ask your class if you *are* holding it farther away from the overhead clouds. The answer is yes. Ask if this is the *reason* the paper is not as wet. The answer is no!

Seasons: (This is illustrated on Practice Page 74.) The plane of the Earth's equator is not parallel to the plane of the Earth's orbit. Instead, the polar axis is inclined at $23^1/_2$ degrees (the ecliptic). Draw the sketch below on the board, first with only the two positions of the Earth at the far left and far right. Ask which of these two positions represents winter months and which represents summer months. Encourage neighbor discussion.



Once it is clear that winter is at the left, show the position of the Earth in autumn and in spring. Shift the position of the Sun closer to the Earth in winter, for this is actually the case. From your drawing, your class can see why Northern Hemisphere types enjoy an extra week of spring and summer! Southern Hemisphere types are compensated by a somewhat milder climate year round due to the greater amount of ocean in the Southern Hemisphere (80% as compared to about 60% for the Northern Hemisphere).



Radiation: Discuss the radiation one feels from red hot coals in a fireplace. And how the radiation decreases with distance. Consider the radiation one feels when stepping from the shade to the sunshine. Amazing! The heat is not so much due to the Sun's temperature because like temperatures are to be found in the torches of some welders. One feels hot not because the Sun is hot, but because it is *big*. Comfortably big!

The equation $\bar{f} \sim T$ is nicely illustrated with an infra-red thermometer, Figure 16.15. (Available from Arbor Scientific, 68-6505.)

Everyone knows that the Sun radiates, and most people know the internal energy of the Sun involves nuclear processes—namely thermonuclear fusion. But relatively few people know that the same holds for planet Earth. The Earth's radiation, terrestrial radiation, is less intense and lower in frequency, but is nonetheless the same—electromagnetic radiation. The source of Earth's internal heat is also radioactive processes—mainly radioactive decay of uranium, thorium, and potassium (perhaps some fission, but certainly no thermonuclear fusion). Expand on these ideas—Figure 16.13 and one of the Next-Time Questions.

It should be surprising to your students that terrestrial radiation rather than solar radiation is directly responsible for the warmth of the air around us. Air is primarily warmed by the Earth, which is an important reason we don't freeze at night when we're not in the Sun's light.

Acknowledge that everything emits radiation—everything that has any temperature. But everything does not become progressively cooler because everything simultaneously absorbs radiation. Whether something is a net emitter or net absorber depends on the relative temperatures involved. In Figure 16.16, my buddy Dennis McNelis tastes the difference.

Acknowledge the role of smudge pots in an orchard. They create a cloud close to the ground, which enables terrestrial radiation a means of absorption and re-radiation back to the ground. This results in a longer cooling time for ground cooling, enabling more time to survive the night without freezing until sunlight comes to the rescue the following morning. Three cheers for terrestrial radiation!

We live in a sea of radiation, everything emitting and everything absorbing. When emission rate equals absorption rate, temperature remains constant. Some materials, because of their molecular design, emit better than others. They also absorb better than others. They're easy to spot because they absorb visible radiation as well and appear black.

> DEMONSTRATION: Make up and show the black hole in the white box, as shown by Helen Yan in the photo openers.

> DEMONSTRATION: Pour hot water into a pair of vessels, one black and the other shiny silver. Ask for a neighbor check as to which will cool faster. Have thermometers in each that you ask a student to read aloud at the beginning and a few minutes later. (You can repeat this demo with initially cold water in each vessel.)

Explain the frost in the above-freezing mornings bit described in the chapter on page 311.

> DEMONSTRATION: When a pair of heavy steel balls are smashed together, say by your hands, your class will see a smashing demonstration of energy dissipating to heat. The kinetic energy of the balls transforms into enough heat to burn a hole in a piece of paper. So do this while a student holds a sheet of paper where the balls will collide. A pair of 1 pound, 2-inch diameter chrome steel spheres is available from Arbor Scientific (P6-6070).

Newton's Law of Cooling: If you're into graphical analysis, construct a large plot of the exponential decrease of the temperature of either of the vessels in the previous demonstration. It's easy to see the curve is steep at first (when the water is hotter) and less steep as it cools. The slope of your curve is of changing temperature per time interval—the slope decreases as time increases. But one can as well say the slope decreases as the temperature approaches the ambient temperature. This is Newton's law of cooling.

The rate will be different for the black and silver vessels, so we see the difference between a proportionality sign and an equals sign for the formula here. The actual rate of cooling or warming is not only proportional to the difference in temperatures, but in the "emissivities" of the surfaces.

Relate Newton's law of cooling to Think and Discuss 92 (cream in the coffee), 93 (thermostat on a cold day), and 94 (air conditioner on a hot day). These exercises are excellent for class discussion.

Greenhouse Effect: As the text states, if there were no greenhouse effect, the average temperature of the Earth would be a frigid -18°C. So be glad that prayers are not answered that ask for an end to the greenhouse effect!

Compare the window glass of the florist's greenhouses to the carbon-dioxide window glass of the Earth's atmosphere. CO_2 builds up year by year by increased usage of fossil fuels that spew carbon into the atmosphere. Interestingly enough, the carbon that is spewed by burning is the same carbon that is absorbed by tree growth. So a realistic step in the solution to the greenhouse-effect problem is to simply grow more trees (while decreasing the rate at which they are cut down)! Johnny-Appleseed types—to the task! This would not be an end-all to the problem, however, because the carbon returns to the biosphere when the trees ultimately decay. More general than the term greenhouse effect is *global warming*, or more recently, *climate change*.

Interesting point: The Earth is always "in equilibrium" whether it is overheating or not. At a higher temperature that global warming produces, the Earth simply radiates more terrestrial radiation. Income and outgo match in any case; the important consideration is the temperature at which this income and outgo match.

Climate Change: I pose this question about global warming: How could the billions of tons of CO_2 pumped into the air by human activity *NOT* affect Earth's climate? I embrace the adage: You can't change only one thing.

Solar Power: Solar power has been with humans from the beginning. We see its application whenever we see clothes hung on a line (do you see that much anymore?) and we see it as an energy source on rooftops that provide hot water (Figure 16.25). And Lil's mom is shown utilizing solar power in Figure 16.26. Share up-to-date information on this growing technology with your class.

Excess Terrestrial Heat: Discuss the overheating of the Earth problem, with updates from the Internet.

As an interesting side point that pertains to heating, it has long been known that a frog cannot discern small changes in temperature, and if sitting comfortably in a pan of water that is slowly heated on a stove, it will make no effort to jump out as the water temperature increases. It will just sit there and be cooked. But this is not limited to frogs. According to accounts given by cannibals who cook their victims in large pots of water, the same is true of humans. Back in the 1970s in Mill Valley, CA, water in a hot tub gradually overheated (due to a faulty heater) and resulted in the deaths of the unsuspecting and drowsy individuals. You can compare this to other cases where if adverse conditions are increased gradually, humans will tolerate what otherwise would be completely unacceptable to them: smog, noise, pollution, crime, and so on.

Answers and Solutions for Chapter 16

Reading Check Questions

1. Loose electrons quickly move and transfer energy to other electrons that migrate through the material.
2. Conductivity of metals are much greater than conductivity of air.
3. Wood is a good insulator even when it's red hot, therefore very little thermal energy is transferred to the feet.
4. They are poor conductors, which makes them good insulators.
5. Insulation delays heat transfer.
6. Volume increases as air rises, and correspondingly cools.
7. Rebound speed increases; rebound speed decreases.
8. Speeds are increased with compression.
9. Speeds are decreased with expansion.
10. Her hand is not in steam, but in a jet of condensed vapor that has expanded and cooled.
11. Direction of winds change with changes in land and water temperatures. Air flow reverses as relative temperatures reverse.
12. Radiant energy travels in electromagnet waves.
13. High-frequency waves have short wavelengths.
14. Peak frequency and absolute temperature are directly proportional: $\bar{f} \sim T$.
15. Terrestrial radiation is that emitted by Earth's surface.
16. Terrestrial radiation is lower in frequency and intensity than solar radiation.
17. Temperatures don't continuously decrease because all object are also absorbing radiant energy.
18. Surrounding temperature determines whether an object is a net emitter or absorber.
19. A black pot both warms faster (and cools faster) than a silver pot.
20. A good absorber cannot at the same time be a good reflector because absorption and reflection are opposite processes.
21. The pupil appears black because light that enters the eye usually doesn't exit. With flash cameras, however, some of it does.
22. Temperature will drop when radiation exceeds absorption.
23. Poor conductivity means little heat from the ground and the object can cool by radiation to temperatures below that of the surrounding air temperature.
24. By Newton's law of cooling, the hot poker in the cold room radiates more due to the greater temperature difference between the poker and the room.
25. Yes, Newton's law of cooling also applies to warming.
26. With no greenhouse effect Earth would be a very cold place, with an average temperature about -18°C.
27. Glass allows high-frequency visible-light radiant energy in, but prevents low-frequency infrared re-radiated energy out. Likewise for the atmosphere acting as a one-way valve.
28. Weather is the state of the atmosphere at a particular time and place. Climate is the weather pattern over broader regions and longer times.
29. The Sun pours 1400 J of radiant energy per second per meter squared at the top of the atmosphere.
30. Heat transfer by conduction, convection, and radiation is inhibited in a Thermos bottle.

Think and Do

31. This activity nicely shows that metal is a good conductor of heat. Paper in a flame by itself easily reaches ignition temperature and catches fire. But this ignition temperature isn't reached when the paper is wrapped around a thick metal bar that absorbs energy from the flame, which then isn't absorbed by the paper.

32. The heat you feel is radiant energy, which passes through the glass, without heating the glass.
33. Tell Grandma how clouds re-radiate terrestrial energy back to Earth's surface. Examples abound about all objects both emitting and absorbing energy.

Plug and Chug

34. $Q = cm\Delta T$ = (1 cal/g·°C)(50 g)(100°C – 0°C) = 5,000 cal.
35. $Q = cm\Delta T$ = (1 cal/g·°C)(20 g)(90°C – 30°C) = 1,200 cal.

Think and Solve

36. From $Q = cm\Delta T$, $Q/m = c\Delta T$ = (800 J/kg·C°)(500°C) = 400,000 J/kg. (Q/m is the energy per kg, which is the same whatever the mass.) The time required is about (400,000J/kg)/(0.03 J/kg·yr) = 13 million years. Small wonder it remains hot down there!

37. The coffee decreases 25°C in temperature in eight hours. Newton's law of cooling tells us that its rate of cooling is proportional to the temperature difference. So when the temperature difference is half as great, the rate of cooling will be half as great. Hence, the coffee will lose 12.5 degrees in another eight hours, half as much as in the first eight hours, cooling from 50°C to 37.5°C.

38. Because of the 20-percent conversion efficiency, each square meter of collector will supply 40 watts of electric power on average. So to meet the 3 kW requirement you will need (3000 W)/(40 W/m^2) = 75 m^2 of collector area. This is the area of a square about 9 m or 28 ft on a side. It would fit in a typical yard, but is a little larger than a typical roof.

39. (a) Q gained by water = Q lost by nails, so $(cm\Delta T)_{water} = (cm\Delta T)_{nails}$.
(1.0 g°C)(100g)(T - 20°C) = (0.11 cal/g°C)(100 g)(40° - T), where T = 22°C.
(b) Although the masses are the same, the specific heats are widely apart, iron being very low and water incredibly high. It takes as much heat as the iron can release to raise water by about 2°C.

Think and Explain

40. The metal doorknob conducts heat better than wood.

41. Feathers (and the air they trap) are good insulators and thus conduct body heat very slowly to the surroundings.

42. No, the coat is not a source of heat, but merely keeps the thermal energy of the wearer from leaving rapidly.

43. Air at 70°F feels comfortable principally because it is a poor conductor. Our warmer skin is slow to transfer heat to the air. Water, however, is a better conductor of heat than air, so our warmer bodies in water more readily transfer heat to the water.

44. When the temperatures of the blocks are the same as the temperature of your hand, then no heat transfer occurs. Heat will flow between your hand and something being touched only if there is a temperature difference between them.

45. Energy "flows" from higher to lower temperature, from your hand to the ice. It is the energy, heat, flowing from your hand that produces the sensation of coolness. There is no flow from cold to hot; only from hot to cold.

46. Air is an excellent insulator. The reason that fiberglass is a good insulator is principally because of the vast amount of air spaces trapped in it.

47. In touching the tongue to very cold metal, enough heat can be quickly conducted away from the tongue to bring the saliva to sub-zero temperature where it freezes, locking the tongue to the metal. In the case of relatively nonconducting wood, much less heat is conducted from the tongue and freezing does not take place fast enough for sudden sticking to occur.

48. Heat from the relatively warm ground is conducted by the gravestone to melt the snow in contact with the gravestone. Likewise for trees or any materials that are better conductors of heat than snow, and that extend into the ground.

49. There is more air space in mittens than in gloves, which makes for warmer hands. Also, the fingers in mittens are next to one another which also keeps hands warmer.

50. Wood is a poor conductor whatever the temperature, so you can safely grab a pan by its wooden handle for a short time. Very little heat will be conducted to your hand. Touching the iron part of the pan is another story, for then heat is readily conducted to your hand. Ouch again!

51. The conductivity of wood is relatively low whatever the temperature—even in the stage of red-hot coals. You can safely walk barefoot across red hot wooden coals if you step quickly (like removing the wooden-handled pan with bare hands quickly from the hot oven in the previous exercise) because very little heat is conducted to your feet. Because of the poor conductivity of the coals, energy from within the coals does not readily replace the energy that transfers to your feet. This is evident in the diminished redness of the coal after your foot has left it. Stepping on red-hot *iron* coals, however, is a different story. That would be a resounding ouch!

52. Yes in both cases, as long as one has a higher temperature than the other. Differences in *temperature*, not internal energy, dictates heat flow.

53. The temperature will be in between because one decreases in temperature and the other increases in temperature.

54. It is thermal energy that flows—heat. It is therefore correct to say that thermal energy flows between the objects.

55. It is correct to say that the increase in *thermal energy* of one object equals the decrease in *thermal energy* of the other—not temperature. The statement is correct when the hot and warm objects are the same material and same mass.

56. Hydrogen molecules will be the faster moving when mixed with oxygen molecules. They will have the same temperature, which means they will have the same average kinetic energy. Recall that KE = 1/2 mv^2. Since the mass of hydrogen is considerably less than oxygen, the speed must correspondingly be greater.

57. As in the explanation of the previous exercise, the molecules of gas with the lesser mass will have the higher average speeds. A look at the periodic table will show that argon (A = 18) has less massive atoms than krypton (A = 36). The faster atoms are those of argon. This is the case whether or not the gases are in separate containers.

58. Molecules of gas with greater mass have a smaller average speed. So molecules containing heavier U-238 are slower on the average. This favors the diffusion of the faster gas containing U-235 through a porous membrane (which is how U-235 was separated from U-238 by scientists in the 1940s).

59. As with the previous question, the faster molecules with U-235 will diffuse faster than the slower molecules with heavier U-238.

60. More molecules are in the cooler room. The greater number of slower-moving molecules there produce air pressure at the door equal to the fewer number of faster-moving molecules in the warmer room.

61. The smoke, like hot air, is less dense than the surroundings and is buoyed upward. It cools with contact with the surrounding air and becomes more dense. When its density matches that of the surrounding air, its buoyancy and weight balance and rising ceases.

62. If ice cubes were at the bottom they wouldn't be in contact with the warmest part of the tea at the surface, so cooling would be less. Ice cubes are preferable at the surface to decrease the temperature of the warmer part of the tea.

63. Both the molecule and the baseball are under the influence of gravity, and both will accelerate downward at *g*. When other molecules impede downward fall, then the free-fall acceleration *g* isn't maintained.

64. Faster-moving (warm air) molecules migrate upward through the "open window" in the atmosphere, producing upward convection.

65. Because of the high specific heat of water, sunshine warms water much less than it warms land. As a result, air is warmed over the land and rises. Cooler air from above the cool water takes its place and convection currents are formed. If land and water were heated equally by the Sun, such convection currents (and the winds they produce) wouldn't be established.

66. When we warm a volume of air, we add energy to it. When we expand a volume of air, we normally take energy out of it (because the expanding air does work on its surroundings). So the conditions are quite different and the results will be different. Expanding a volume of air actually lowers its temperature.

67. No. However ceiling fans can create a "wind chill" effect that can make you feel up to five degrees cooler. Ceiling fans do not reduce the temperature in the room, but merely circulate air, making you feel cooler.

68. In winter you want warm air near the floor, so the fan should push warmer ceiling air downward. In summer you want cooler air near the floor, so the fan should pull air upward.

69. The mixture expands when it is ejected from the nozzle, and therefore cools. At the freezing temperature of 0°C, ice forms.

70. Radiation requires no medium for transfer.

71. A good emitter, by virtue of molecular-or-whatever design, is also a good absorber. A good absorber appears black because radiation that impinges upon it is absorbed; just the opposite of reflection.

72. Human eyes are insensitive to the infrared radiated by objects at average temperatures.

73. If good absorbers were not also good emitters, then thermal equilibrium would not be possible. If a good absorber only absorbed, then its temperature would climb above that of poorer absorbers in the vicinity. And if poor absorbers were good emitters, their temperatures would fall below that of better absorbers.

74. A good reflector is a poor radiator of heat, and a poor reflector is a good radiator of heat.

75. The energy given off by rock at the Earth's surface transfers to the surroundings practically as fast as it is generated. Hence there isn't the buildup of energy that occurs in the Earth's interior.

76. Heat radiates into the clear night air and the temperature of the car goes down. Normally, heat is conducted to the car by the relatively warmer ground, but the rubber tires prevent the conduction of heat from the ground. So heat radiated away is not easily replaced and the car cools to temperatures below that of the surroundings. In this way frost can form on a below-freezing car in the above-freezing environment.

77. Under open skies, the ground radiates upward but the sky radiates almost nothing back down. Under the benches, downward radiation of the benches decreases the net radiation from the ground, resulting in warmer ground and, likely, no frost.

78. When it is desirable to reduce the radiation that comes into a greenhouse, whitewash is applied to the glass to simply reflect much of the incoming radiation. Energy reflected is energy not absorbed.

79. For maximum warmth, wear the plastic coat on the outside and utilize the greenhouse effect.

80. If the upper atmosphere permitted the escape of more terrestrial radiation than it does presently, more energy would escape and the Earth's climate would be cooler.

81. Because warm air rises, there's a higher temperature at the ceiling than at the walls. With a greater difference in inside and outside temperatures, thicker insulation is needed to slow the transfer of heat.

82. Open-ended.

Think and Discuss

83. Copper and aluminum are better conductors than stainless steel, and therefore more quickly establish a uniform temperature over the bottom of the pan and transfer heat to the cookware's interior.

84. The main reason for serving potatoes wrapped in aluminum foil is to increase the time that the potatoes remain hot after being removed from the oven. Heat transfer by radiation is minimized as radiation from the potatoes is internally reflected, and heat transfer by convection is minimized as circulating air cannot make contact with the shielded potatoes. The foil also serves to retain moisture.

85. The snow and ice of the igloo is a better insulator than wood. You would be warmer in the igloo than the wooden shack.

86. Agree, for your friend is correct. The gases will have the same temperature, which is to say they'll have the same average kinetic energy per molecule.

87. Disagree, for although the mixture has the same temperature, which is to say, the same KE per molecule, the lighter hydrogen molecules have more speed than heavier nitrogen for the same KE.

88. Air molecules in your room have the same *average* kinetic energy, but not the same average speed. Air is made up of molecules of different *mass*—some nitrogen, some oxygen, and a small percentage of other gases. So even though they have the same average kinetic energy, they won't have the same average speed. The lighter molecules will have average speeds greater than the heavier molecules.

89. They ride in "thermals," updrafts of air.

90. At the same temperature, molecules of helium, nitrogen, and oxygen have the same average kinetic energy. But helium, because of its smaller mass, has greater average speed. So some helium atoms, high in the atmosphere, will be moving faster than escape speed from the Earth and will be lost to space. Through random collisions, every helium atom will eventually surpass escape speed.

91. Kelvins and Celsius degrees are the same size, and although ratios of these two scales will produce very different results, *differences* in kelvins and *differences* in Celsius degrees will be the same. Since Newton's law of cooling involves temperature differences, either scale may be used.

92. Put the cream in right away for at least three reasons. Since black coffee radiates more heat than white coffee, make it whiter right away so it won't radiate and cool so quickly while you are waiting. Also, by Newton's law of cooling, the higher the temperature of the coffee above the surroundings, the greater will be the rate of cooling—so again add cream right away and lower the temperature to that of a reduced cooling rate, rather than allowing it to cool fast and then bring the temperature down still further by adding the cream later. Also—by adding the cream, you increase the total amount of liquid, which for the same surface area, cools more slowly.

93. Turn your heater off altogether and save fuel. When it is cold outside, your house is constantly losing heat. How much is lost depends on the insulation and the difference in inside and outside temperature (Newton's law of cooling). Keeping ΔT high consumes more fuel. To consume less fuel, keep ΔT low and turn your heater off altogether. Will more fuel be required to reheat the house when you return than would have been required to keep it warm while you were away? Not at all. When you return, you are replacing heat lost by the house at an average temperature below the normal setting, but if you had left the heater on, it would have supplied more heat, enough to make up for heat lost by the house at its normal, higher temperature setting. (Perhaps your instructor will demonstrate this with the analogy of leaking water buckets.)

94. Turn the air conditioner off altogether to keep ΔT small, as in the preceding answer. Heat leaks at a greater rate into a cold house than into a not-so-cold house. The greater the rate at which heat leaks into the house, the greater the amount of fuel consumed by the air conditioner.

95. If the Earth's temperature increases, its rate of radiating will increase. And if much of this extra terrestrial radiation is blocked, and the temperature of the Earth increases more, then its rate of radiating simply increases further. A new and higher equilibrium temperature is established.

96. The photovoltaic cell converts solar energy into electrical energy.

97. Assuming 1.0 kW of solar energy over 1 m^2 at Earth's surface, the question is how many square feet are in one square meter, which is a bit more than 10 square feet.
1.0 kW = 1000 W. So 1000 W/10 = 100 W, as with a 100-W bulb.

98. Every mathematical equation illustrates that you can't only change one thing. Change a term in the left side of any equation, and a corresponding change occurs in the right side. This is a lesson nature teaches us.

99. In the Industrial Era coal was burned to produce the energy that created the industrial revolution. Plastics and many modern materials are made from fossil fuels, which in the long term, should prove to be much more valuable than turning coal and oil to heat and smoke.

100. Humans consume energy. More humans consume more energy. Consumption relates to energy waste and pollution. Simply put, more humans, more pollution.

17 Change of Phase

That's nephew John Suchocki walking barefoot on hot coals in the chapter opening photo 1. John is my co-author, with my daughter Leslie, on *Conceptual Physical Science* textbooks. In his uncle's footsteps, he's written *Conceptual Chemistry*, Fifth Edition, published by Benjamin Cummings, a beautiful book. In photo 2 lab manual author Dean Baird demonstrates regelation, and quite happily the chapter opens with his personal profile. Photo 3 is Ron Hipschman, who has been a physicist at the Exploratorium since its inception back in the Frank Oppenheimer days. Three cheers for Ron! The doggies belong to family friend Tammy Tunison.

The profile of this chapter is lab-manual author, Dean Baird.

Material from this chapter is not prerequisite to the chapters that follow. As with Chapter 16, the emphasis is on bodies of water and the atmosphere.

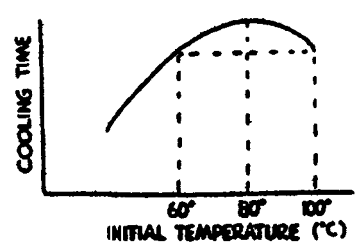
Some textbooks speak of change of *state*. Here we use change of *phase*. Either is acceptable, but change of phase has the benefit of not being confused with energy states.

Change of phase is wonderfully employed in crystal heat pouches of recent years. Latent heat is released when crystallization of sodium acetate occurs. Repeatable. (Arbor Scientific, CRYSTALHEAT P3-1015.)

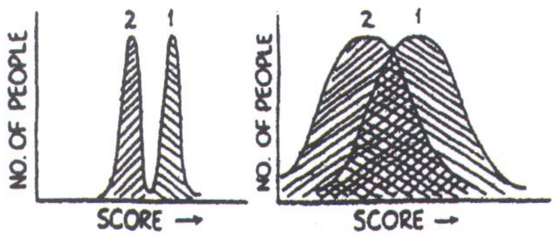
Note that the units calories are primary in this chapter, particularly with heats of fusion and vaporization of water. Values for heats of fusion and vaporization, 80 and 540 calories/g are easier figures than SI units 334.88 kJ/kg and 2.26 MJ/kg respectively. Both units are used.

Thanks to physics professor David Willey for his firewalking photo, Figure 17.21. Are there still people out there who attribute firewalking to mind over matter rather than straight-forward physics?

The considerable amount of energy that goes into vaporization explains why under some conditions hot water will freeze faster than warm water. This occurs for water hotter than about 80°C, and is evident when the surface area that cools by rapid evaporation is large compared to the amount of water involved—like washing a car with hot water on a cold winter day, or flooding a skating rink to melt and smooth out the rough spots and freeze quickly. The 540 calories per gram of water that evaporates is substantial. This is treated in Practice Page 77. Will boiling water freeze before cold water? No. But boiling water will freeze before water warmer than 60°C. A plot showing freezing times (thanx to Jearl Walker) is shown at the right. Surprisingly, water at 80°C takes longer to freeze than water at 99°C. But for water temperatures less than 80°C, common sense prevails.



In a conversation with Richard Feynman, just 3 months before he died, we discussed the rapid freezing of hot water. He speculated that the lesser amount of trapped air in hot water may contribute to its quick freezing.



If you wish to introduce the idea of distribution curves in your course, this is a good place to do it. Treat the cooling produced by evaporation with plots of relative numbers of molecules in a liquid versus their speeds, and show how the distribution shifts as the faster-moving molecules evaporate. You may wish to point to the bell-shape distribution curves that represent the distributions of so many things, from molecular speeds to examination scores to people's IQ scores. Regrettably, many people tend to regard such distributions not as bell-shaped, but as spikes. This makes a difference in attitudes. For example, suppose you compare the grade distributions for two sections of your course, Group 1 and Group 2, and that the average score for Group 1 is somewhat greater than that for Group 2. For whatever reason, Group 1 outperforms Group 2. With this information can we make any judgment about individuals from either group? One who looks at these distributions as spiked shaped behaves as if he can—he'll say (or not say but think) that individuals from Group 1 are "better" than particular individuals from Group 2. On the other hand, one who thinks in terms of the broad shape of the bell-shaped distribution will not make any assumptions about such individuals. He is well aware of the region of overlap in the two distribution curves. His attitude toward individuals from either group is unbiased by unwarranted prejudice. Hence the difference between narrow-mindedness and broad-mindedness!

The explanation of ice melting under pressure with regard to ice-skating has been controversial for several years now. Conceptually, it is easy to visualize the pressure of the ice blade crushing the open structures of ice crystals, accounting for the layer of water that results on the surface, which provides the slipperiness. Investigation indicates that water molecules on the surface of ice vibrate faster than their temperatures suggest, forming a quasi liquid layer even at temperatures well below freezing. So this mobile surface may better explain how skating and skiing are possible.

The drinking bird demo, Figure 17.4, is available from Arbor Scientific (P3-5001), or with a discovery pack of more gas-laws goodies (P1-2070). A "giant" 25-cm tall drinking bird (P3-5014).

Are you using the check-your-neighbor technique in your lectures? As emphasized already, it makes a substantial positive difference.

Practicing Physics Book:
• Ice, Water, and Steam • Our Earth's Hot Interior • Evaporation

Problem Solving Book:
Ample problems to complement this chapter

Laboratory Manual:
• Cooling While Boiling *Atmospheric Pressure and Boiling Point* (Demonstration)
• Heating While Freezing *Heat of Fusion* (Experiment)

Next-Time Questions:
• Steam to Melt Ice
• Evaporating Hot Water
• Evaporation
• Boiling
• Ice Melt

Hewitt-Drew-It! Screencasts: •*Evaporation and Condensation* •*Crunching Can and Dipping Bird* •*Energy Changes of Phase* •*More on Phase Changes*

SUGGESTED LECTURE PRESENTATION

Evaporation
Begin by citing the familiar case of leaving the water when bathing and feeling chilly in the air, especially when it is windy. Explain the cooling of a liquid from an atomic point of view, and reinforce the idea of temperature being a measure of the average molecular kinetic energy, and acknowledge molecules that move faster and slower than the average.

> CHECK QUESTION: Why does cooling occur in the water of a leaky canvas water bag? [Water seeps through the canvas. More faster-moving molecules leak and vaporize, leaving less energy per molecule behind.]

> CHECK QUESTION: Cite at least two ways to cool a hot cup of coffee. [You can increase evaporation by blowing on it or pouring it into the saucer to increase the evaporating area. You can cool it by conduction by putting silverware in it, which absorbs heat and provides a radiating antenna.]

Make a sketch a bell-shaped distribution curve to represent the wide array of molecular speeds in a container of water. The peak of the curve represents the speeds that correspond to the temperature of the water. (It is not important to distinguish here between the mean speed, the rms speed, and the most probable speeds.) Stress the many lower and higher speeds to the left and right of the peak of your curve at any moment in the water. Which molecules evaporate? The fast ones, which you clip from the right hand tail of your curve. What is the result? A shift toward the left of the peak of the curve—a lowering of temperature. (Actually, this approach is highly exaggerated, for the molecules that do penetrate the surface and escape into the air have energies that correspond to 3400K! See my article on page 492 of *The Physics Teacher*, back in October, 1981.)

The relatively strong bond between water molecules (hydrogen bonding) prevents more evaporation than presently occurs. It also enhances condensation.

Condensation
If evaporation is a cooling process, what kind of process would the opposite of evaporation be? This is condensation, which is a warming process.

> CHECK QUESTION: Why is it that many people after taking a shower will begin drying in the shower stall before getting outside? [While still in the shower region, appreciable condensation offsets the cooling by evaporation.]

Make the point that a change of phase from liquid to gas or vice versa is not merely one or the other. Condensation occurs while evaporation occurs and vice versa. The net effect is usually what is spoken about. If you haven't shown the collapsing can demo in your atmospheric pressure lecture, and for some reason you're not treating Chapter 18, now is a good time.

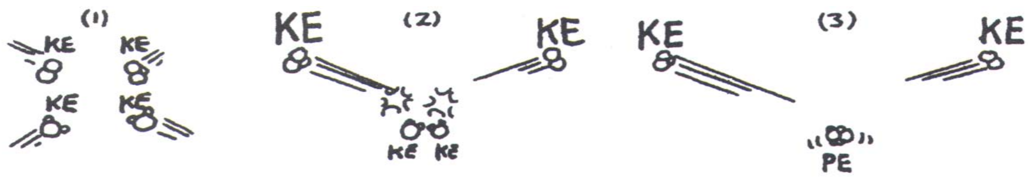
> DEMONSTRATION (as treated in Chapter 18): Heat some aluminum soda pop cans on a burner, empty except for a small amount of water that is brought to a boil to make steam. With a pot holder or tongs, pick up a can and quickly invert it into a basin of water. Crunch! The atmospheric pressure immediately crushes the can with a resounding WHOP! Very impressive! Do this first by inverting cans into a cold basin of water. It is evident that condensation of the steam and vapor on the inside takes place, pressure is correspondingly reduced, and the atmospheric pressure on the outside crunches the can. Then repeat but this time invert cans into a basin of very hot water, just short of the boiling temperature. Crunch again, but less forceful than before. Steam molecules stick to the water surface, hot or cool, like flies sticking to fly paper (and like the "kissing molecules" of Figure 17.8). Then repeat, but this time invert cans into *boiling* water. No crunch because boiling is supplying molecules as others condense—a stand off. Lead your class into the explanation wherein the *net* effect is no change, as condensation of steam is met with just as much vaporization from the boiling water. The punch line of this demo is shown in the box

THERMODYNAMICS DRAMATIZED on page 346 in the next chapter—the reason for condensation in a steam turbine—to reduce pressure on the backside of the turbine blades.

Condensation in the Atmosphere

An interesting way to present the condensation of water vapor to droplets is the following: Ask why a glass containing an iced drink becomes wet on the outside, and why a ring of moisture is left on the table. I inject a bit of humor here and state that the reason is... and then write the number 17.8 on the board. Then ask why the walls of the classroom would become wet if the temperature of the room were suddenly reduced. State that the answer is...then underline 17.8. Ask why dew forms on the morning grass, and state the answer is ... another underline for 17.8. Ask why fog forms, and how the clouds form, and back to your 17.8. By now some of your class is wondering about the significance of 17.8. Announce you're discussing Figure 17.8, and with class attention and interest continue discussion of the formation of fog and clouds (and even rain, hail, and snow). [Snow crystallizes from vapor; hail is rain that freezes when tossed upward, often repeatedly, by strong updrafts.]

The mechanics of energy release to the surrounding air by water vapor when it condenses can be understood with billiard-ball physics. H_2O molecules simply give most of their KE to the air during their last collision before condensation. The details are shown in the three sketches below.



Consider two pairs of molecules, say with equal KEs before collision (Sketch 1). After collision, individual KEs may be quite unequal, for molecules that transfer much of their KE to others are left with corresponding less KE of their own (Sketch 2). So far, there is no change in the air's total KE score. But if the slower molecules happen to be H_2O, they are candidates for condensation if their next collisions are with other H_2Os that have similarly just given most of their KE to neighboring molecules (Sketch 3). Upon condensation of the slow-moving H_2Os, molecules left in the air have an increase in average KE. Voila! *H_2O molecules transfer KE to the surrounding air during their last collision while in the gaseous phase*—the collision that immediately precedes condensation. The energy gained by the air is the well-known heat of vaporization—about 540 calories per gram of condensed H_2O for an ambient temperature of 100°C. It's greater for lower temperatures (molecules bopped to high speeds in a low-speed environment gain more energy than molecules bopped to the same high speeds in higher-speed environments). So all things being equal, a rainy day really is warmer than a cloudy day.

Condensation is enhanced by the presence of ions, dust, or tiny particles that act as the nuclei of droplets. London became much foggier when coal burning provided more particles in the air to initiate condensation. This occurred big time in Beijing, China, in 2013.

Cloud formation is a "4-C process": 1. Convection upward and expansion, 2. Cooling due to expansion, 3. Condensation due to cooling, and 4. Cloud formation.

Boiling

Discuss boiling and the roles of adding heat and pressure in the boiling process. A tactic I use throughout my teaching is to ask the class members to pretend they are having a one to one conversation with a friend about the ideas of physics. Suppose a friend is skeptical about the idea of boiling being a cooling process. I tell my class just what to say to convince the friend of what is going on. I tell them to first point out the distinction between heating and boiling. If the friend knows that the temperature of boiling water remains at 100°C regardless of the amount of heat applied, point out that this is so because the water is cooling by boiling as fast as it is being warmed by heating. Then if this still is not convincing, ask the friend to hold her hands above a pot of boiling water—in the steam. She knows she'll be burned. But burned by what? By the steam. And where did the steam get its energy? From the boiling water; so energy is leaving the

water—that's what we mean by cooling! Bring in the role of pressure on boiling, and illustrate this with the pressure cooker.

> CHECK QUESTIONS: In bringing water to a boil in the high mountains, is the time required to bring the water to a boil longer or shorter than at sea level? Is the time required for cooking longer or shorter? (Preface this second question with the statement that you are posing a different question, for any confusion about this is most likely due to failing to distinguish between the two questions.)

> DEMONSTRATION: Evacuate air from a flask of room-temperature water, enough so that the water in the flask will boil from the heat of the students' hands as it is passed around the classroom. (Take care that the flask is strong enough so that it doesn't implode!)

Geyser: Explain how a geyser, Figure 17.12, is like a pressure cooker (or the old-time coffee percolators).

Boiling and Freezing at the Same Time
This must be seen to be appreciated!

> DEMONSTRATION: The triple-point demonstration, Figure 17.14. [The apparatus for freezing water by air evacuation at the Exploratorium in San Francisco is briefly shown in the video on Evaporation in the *Conceptual Physics Alive!* series and in the chapter photo opener of Ron Hipschman with the "Water Freezer" Exploratorium exhibit.]

Melting and Freezing

> DEMONSTRATION: Regelation of an ice cube with a copper wire, Figure 17.16. Dean Baird demonstrated this in the chapter opener photo. (The wire must be a good heat conductor for this to work, as discussed in the footnote on page 328.)

Energy and Changes of Phase
Ask if it is possible to heat a substance without raising its temperature, and why a steam burn is more damaging than a burn from boiling water at the same temperature. In answering these, discuss the change-of-phase graph of Figure 17.17, and then relate it to Figure 17.15. After citing examples of changes of phase where energy is absorbed, cite examples where energy is released—like raining and snowing. People sometimes say that it is too cold to snow. Explain that this statement arises from the fact that when it is snowing, the air temperature is higher than would otherwise be the case—that whenever it *is* snowing the air is relatively warm, so it is really never too cold to snow. Ask about cooling a room by leaving the refrigerator door open, and compare it to putting an air conditioner in the middle of a room instead of mounting it in a window. Ask what the result would be of mounting an air conditioner backwards in a window.

Air Conditioning
In view of the ozone-destroying chemicals used as refrigerants, cite present efforts you are acquainted with in developing alternative systems. Freon is now replaced by a refrigerant called HFC-134a. Alternative air conditioning systems will likely be in the forefront of news on new technologies. They're needed.

Chicanery
In recent years scams have been popular that extract a fee to learn to walk barefoot on red-hot coals of wood. The explanation given was a "mind over matter" one. As it so happens, the feat is better explained by simple physics. When the surfaces of coals with a low heat conductivity transfer heat to a foot that steps on them, sufficient time is required before appreciable internal energy from the inside a coal reheats the surface. So low heat conductivity is the central part of the feat, not mind over matter. All the mind over matter in the world wouldn't protect a person who walks on red-hot coals of a good conductor, like pieces of metal.

Answers and Solutions for Chapter 17

Reading Check Questions

1. The four common phases of matter are solids, liquids, gases, and plasmas.
2. In a liquid are a wide variety of molecular speeds.
3. Evaporation is a change of phase from liquid to gaseous.
4. Evaporation is called a cooling process because the remaining liquid has given some of its KE to the gas and has cooled.
5. Sublimation is the change of phase from solid to gas directly.
6. They are opposite processes, evaporation from liquid to gas and condensation from gas to liquid.
7. Steam contains more energy than boiling water of the same temperature.
8. On a muggy day you experience condensation from the air, which cancels the cooling due to evaporation.
9. Humidity is a measure of how much water vapor is in the air; relative humidity is the ratio of how much water is in the air to the largest amount of water vapor the air can hold at a given temperature.
10. Slower-moving molecules stick upon collision and therefore condense (Figure 17.8).
11. As the air rises, it cools and condenses to form clouds.
12. Altitude distinguishes fog from a cloud.
13. When evaporation occurs beneath the surface of a liquid, it is said to be boiling.
14. Increased atmospheric pressure increases the boiling point of water.
15. Higher temperature, not boiling, cooks food faster.
16. Water at the bottom of a geyser is under pressure and won't boil at 100°C.
17. When water above gushes out, pressure at the bottom is reduced, and then water boils.
18. More energy input means more energy output as boiling (and therefore cooling) occurs. Hence boiling water stays at its boiling temperature.
19. The boiling point of water is reduced when pressure of air above is reduced.
20. Evidence that water can boil at 0°C occurs when water freezes while it's boiling (as Ron Hipschman demonstrates in the photo opener.)
21. Increasing temperature means increased motion, which means more chance of molecule separation.
22. Decreasing temperature means decreased motion, which means more chance of molecules sticking together.
23. Foreign ions decrease the number of water molecules at the interface between ice and water where freezing occurs.
24. The open hexagonal structure of ice can be crushed with sufficient pressure.
25. The block doesn't separate into two pieces because water above the wire refreezes when pressure on it is reduced.
26. A liquid absorbs energy when it changes to a gas.
27. A liquid releases energy when it changes to a solid.
28. Heat is discharged by condensation.
29. One calorie; 80 calories; 540 calories.
30. One reason feet don't burn involves low conductivity of hot coals. The other reason is energy that goes to the water on the feet does not go to the feet directly.

Think and Do

31. A geyser and a coffee percolator work on the same principle.

32. This activity (Figure 16.8 in the previous chapter) demonstrates that steam is the invisible part of the vapor stream from a spout. A candle flame in the condensed part extinguishes.

33. The rainfall seen resembles actual rain, in that condensation of vapor leads to drops of water. It differs in that natural rain is the result of cooling in clouds of vapor, rather than by condensation on a chilled surface.

34. The salted water has a higher boiling point.

35. When you do this, the ice will end up intact!

36. Clarify what is meant by saying boiling is a cooling process.

Think and Solve

37.(a) 1 kg 0°C ice to 0°C water requires 80 kilocalories.

(b) 1 kg 0°C water to 100°C water requires 100 kilocalories.
(c) 1 kg 100°C water to 100°C steam requires 540 kilocalories.
(d) 1 kg 0°C ice to 100°C steam requires (80 + 100 + 540) = 720 kilocalories or 720,000 calories.

38. From -273°C "ice" to 0°C ice requires (273)(0.5) = 140 calories.
From 0°C ice to 0°C water requires 80 calories.
From 0°C water to 100°C water requires 100 calories.
The total is 320 calories.
Boiling this water at 100°C takes 540 calories, considerably more energy than it took to bring the water all the way from absolute zero to the boiling point! (In fact, at very low temperature, the specific heat capacity of ice is less than 0.5 cal/g°C, so the true difference is even greater than calculated here.)

39. First, find the number of calories that 10 g of 100°C steam will give in changing to 10 g of 0°C water.
10 g of steam changing to 10 g of boiling water at 100°C releases 5400 calories.
10 g of 100°C water cooling to 0°C releases 1000 calories.
So 6400 calories are available for melting ice.
$\frac{6400 \text{ cal}}{80 \text{ cal/g}}$ = 80 grams of ice.

40. The final temperature of the water will be the same as that of the ice, **0°C**. The quantity of heat given to the ice by the water is $Q = cm\Delta T$ = (1 cal/g°C)(50 g)(80°C) = 4000 cal. This heat melts ice. How much? From $Q = mL$, $m = Q/L$ = (4000 cal)/(80 cal/g) = 50 grams. So water at 80°C will melt an equal mass of ice at 0°C.

41. The quantity of heat lost by the iron is $Q = cm\Delta T$ = (0.11 cal/g°C)(50 g)(80°C) = 440 cal. The iron will lose a quantity of heat to the ice $Q = mL$. The mass of ice melted will therefore be $m = Q/L$ = (440 cal)/(80 cal/g) = 5.5 grams. (The lower specific of heat of iron shows itself compared with the result of the previous problem.)

42. $mgh = mL$, so $gh = L$ and $h = L/g$.
h = (334000 J/kg)/(9.8 m/s^2) = 34000 m = 34 km.
Note that the mass cancels and that the unit J/kg is the same as the unit m^2/s^2. So in the ideal case of no energy losses along the way, any piece of ice that freely falls 34 km will completely melt upon impact.

43. PE = Q; 0.5$mgh = cm\Delta T$
$\Delta T = 0.5mgh/cm = 0.5gh/c$ = (0.5)(9.8 m/s^2)(100 m)/(450 J/kg°C) = 1.1°C. Mass cancels out.

44. Note that the heat of vaporization of ethyl alcohol (200 cal/g) is 2.5 times more than the heat of fusion of water (80 cal/g), so in a change of phase for both, 2.5 times as much ice will change phase; 2.5 × 2 kg = 5 kg. Or via formula, the refrigerant would draw away $Q = mL$ = (2000 g)(200 cal/g) = 4×10^5 calories. The mass of ice formed is then (4×10^5 cal)/(80 cal/g) = 5000 g or 5 kg.

Think and Rank

45. A, B, C.
46. C, B, A.

Think and Explain

47. The water evaporates rapidly in the dry air, gaining its energy from your skin, which is cooled.

48. When sweat evaporates it carries energy from the skin, producing cooling.

49. When you blow over the top of a bowl of hot soup, you increase net evaporation and its cooling effect by removing the warm vapor that tends to condense and reduce net evaporation.

50. The temperature of the water lowers.

51. The energy that keeps the dunking duck in operation comes from the Sun, lamps, or whatever is heating the lower chamber where evaporation is taking place. To see this, simply direct heat energy to the lower chamber of the duck and you'll see an increase in the number of times per minute the duck dunks.

52. If the perfume doesn't evaporate it will produce no odor. The odor of a substance is evidence for its evaporation. Don't invest in this invention!

53. A fan does not cool the room, but instead promotes evaporation of perspiration, which cools the body.

54. The wet cloth cools by evaporation. As evaporation progresses, the temperature of the water in the cloth drops, and cools the bottle to a temperature below that of the bucket of water.

55. The body maintains its temperature at a normal 37°C by the process of evaporation. When the body tends to overheat, perspiration occurs, which cools the body if the perspiration is allowed to evaporate. (Interestingly enough, if you're immersed in hot water, perspiration occurs profusely, but evaporation and cooling do not follow—that's why it is inadvisable to stay too long in a hot bath.)

56. Visibility of the windows is impaired if there is any condensation of water between the panes of glass. Hence the gas between the panes should contain no water vapor.

57. Air above the freezing temperature is chilled in the vicinity of an iceberg and condensation of the water vapor in the air results in fog.

58. Aside from the connotation of kissing molecules and parking on a cool night, the warm moist air generated in the car's interior meets the cold glass and a lowering of molecular speed results in condensation of water on the inside of the windows.

59. On a day where the outside of the windows is warmer than the inside, condensation will occur on the outside of the windows. You can also see this on the windshield of your car when you direct the air conditioner against the inside of the glass.

60. A temperature gradient normally exists in a room, with cooler air near the bottom. Hence frost forms on the colder part of the window, the bottom.

61. Air swept upward expands in regions of less atmospheric pressure. The expansion is accompanied by cooling, which means molecules are moving at speeds low enough for coalescing upon collisions; hence the moisture that is the cloud.

62. Clouds tend to form over islands because land has a lower specific heat capacity than water, so the land is warmed faster than the surrounding water. This causes updrafts above the warmed land; the rising air laden with H_2O expands and cools, allowing the H_2O molecules to coalesce (Figure 17.8).

63. Enormous thermal energy is released as molecular potential energy is transformed to molecular kinetic energy in condensation. (Freezing of the droplets to form ice adds even more thermal energy.)

64. When water is boiling, it is being cooled by the boiling process as fast as it is being heated by the stove. Hence its temperature remains the same—100°C.

65. As the bubbles rise, less pressure is exerted on them.

66. Decreased pressure lessens the squeezing of molecules, which favors their tendency to separate and form vapor.

67. When the jar reaches the boiling temperature, further heat does not enter it because it is in thermal equilibrium with the surrounding 100°C water. This is the principle of the "double boiler."

68. The hot water is below the boiling point for the very high pressure there, somewhat like the higher boiling point of water in a pressure cooker.

69. No. Food is cooked by the high temperature it is subjected to, not by the bubbling of the surrounding water. For example, put room-temperature water in a vacuum and it will boil. But an egg in this boiling water won't cook at all!

70. As in the answer to the previous exercise, high temperature and the resulting internal energy given to the food are responsible for cooking—if the water boils at a low temperature (presumably under reduced pressure), the food isn't hot enough to cook.

71. Moisture in the cloth will convert to steam and burn you.

72. Both heat and pressure are involved in boiling. Reduction of pressure only can produce boiling (see Figure 17.14).

73. The ice is indeed cold. Why cold? Because rapid evaporation of the water cooled the water to the freezing point.

74. The air in the flask is very low in pressure, so that the heat from your hand will produce boiling at this reduced pressure. (Your instructor will want to be sure that the flask is strong enough to resist implosion before handing it to you!)

75. Cooking time will be no different for vigorously boiling water and gently boiling water, for both have the same temperature. The reason spaghetti is cooked in vigorously boiling water is simply to ensure the spaghetti doesn't stick to itself and the pan. For fuel economy, simply stir your spaghetti in gently boiling water.

76. The lid on the pot traps heat that quickens boiling; the lid also slightly increases pressure on the boiling water that raises its boiling temperature. The hotter water correspondingly cooks food in a shorter time, although the effect is not significant unless the lid is held down as on a pressure cooker.

77. The boiling point of water is higher in a nuclear reactor because of increased pressure. The reactor behaves like a pressure cooker.

78. After a geyser has erupted, it must refill and then undergo the same heating cycle. If the rates of filling and heating don't change, then the time to boil to the eruption stage will be the same.

79. Water in the pressurized radiator doesn't boil, even when its temperature exceeds 100°C (like water in a pressure cooker). But when the radiator cap is suddenly removed, pressure drops and the high-temperature water immediately boils. Do not have your head above a hot radiator when removing the cap!

80. Yes, ice can be much colder than 0°C, which is the temperature at which ice will melt when it absorbs energy. The temperature of an ice-water mixture in equilibrium is 0°C. Iced tea, for example, is 0°C.

81. The moisture on your skin freezes only at a temperature below 0°C because it contains salt. Very cold ice in contact with your hand freezes the moisture on your skin and bonding takes place between your skin and the ice. That's why it's sticky.

82. Both freezing point and melting points are the same for a pure substance.

83. Snowfall certainly is possible on very cold days. But when snow forms, the temperature of the air increases due to the change of state of the H_2O from gas to solid or from liquid to solid. So one's observation is warmness when snowing, and one's misinterpretation is therefore that snowfall can't happen if it is cold. (Similarly, it is a fact that our ears continue to grow all through life. So old people usually have big ears. Some people who see children with big ears mistakenly say they are destined to have a long life.)

84. The water that freezes is pure water. Melt the ice and you'll have pure water.

85. The weight of the ice above crushes ice crystals at the bottom, making a liquid layer upon which the glacier slides.

86. Regelation would not occur if ice crystals weren't open structured. The pressure of the wire on the open network of crystals caves them in and the wire follows. With the pressure immediately above the wire relieved, the molecules again settle to their low energy crystalline state. Energy given up by the water that refreezes above the wire is conducted through the wire thickness to melt the ice being crushed beneath. The more conductive the wire, the faster regelation occurs. For an insulator like string, regelation won't occur at all. Try it and see!

87. The wood, because its greater specific heat capacity means it will release more energy in cooling. Due to the metal blocks greater conductivity, it will do its melting of ice more quickly.

88. The H_2O absorbs energy in the change of phase from ice to water. If this energy is supplied by the surrounding air, then the temperature of the surrounding air is decreased.

89. Your eyeglasses are colder than the inside air and condensation of the air in the room occurs on your eyeglasses—another example of Figure 17.8.

90. Water in the soda expands when it turns to ice, bulging the ends of the soda can.

91. Sugar doesn't freeze with the water in the punch, so half-frozen punch has the sugar of the original mixture—twice the original concentration.

92. Condensation occurs on the cold coils, which is why the coils drip water.

93. The practice of wrapping newspaper around ice in an icebox is inadvisable, unless one only wants to make the ice last longer at the expense of reducing the cooling effect. The insulating newspaper slows the melting process, which diminishes the extraction of heat from the surroundings. The surroundings are cooled principally because the ice melts. To inhibit this melting is to reduce the desired cooling process.

94. The temperature of nearby air decreases due to energy absorbed by the melting ice.

95. Every gram of water that undergoes freezing releases 80 calories of thermal energy to the cellar. This continual release of energy by the freezing water keeps the temperature of the cellar from going below 0°C. Sugar and salts in the canned goods prevent them from freezing at 0°C. Only when all the water in the tub freezes will the temperature of the cellar go below 0°C and then freeze the canned goods. The farmer must, therefore, replace the tub before or just as soon as all the water in it has frozen.

96. The answer to this is similar to the previous answer, and also the fact that the coating of ice acts as an insulating blanket. Every gram of water that freezes releases 80 calories, much of it to the fruit; the thin layer of ice then acts as an insulating blanket against further loss of heat.

97. The device is a heat pump. In both modes of operation, it is moving heat from a cooler to a warmer place.

98. Dogs have no sweat glands (except between the toes for most dogs) and therefore cool by the evaporation of moisture from the mouth and the respiratory tract. So dogs literally cool from the inside out when they pant.

99. Open ended.

Think and Discuss

100. Alcohol produces more cooling because of its higher rate of evaporation.

101. When a wet finger is held to the wind, evaporation is greater on the windy side, which feels cool. The cool side of your finger is windward.

102. Hot coffee poured into a saucer cools because (1) the greater surface area of the coffee permits more evaporation to take place, and (2) by the conservation of energy, the internal energy that heats the saucer comes from the coffee, cooling it.

103. In this hypothetical case evaporation would not cool the remaining liquid because the energy of exiting molecules would be no different than the energy of molecules left behind. Although internal energy of the liquid would decrease with evaporation, energy per molecule would not change. No temperature change of the liquid would occur. (The surrounding air, on the other hand, would be cooled in this hypothetical case. Molecules flying away from the liquid surface would be slowed by the attractive force of the liquid acting on them.)

104. Water leaks through the porous canvas bag, evaporating from its outer surface and cooling the bag. The motion of the car increases the rate of evaporation and therefore the rate of cooling, just as blowing over a hot bowl of soup increases the rate at which soup cools (Think and Discuss 102).

105. You can add heat without changing temperature when the substance is undergoing a change of phase.

106. You can add heat to ice when it's temperature is below 0°C without melting it. When it reaches 0°C, then additional heat melts it.

107. You can withdraw heat without changing temperature when the substance is undergoing a change of phase.

108. The pressure of surrounding water acts like a pressure cooker and prevents boiling.

109. The predominant gas in a bubble of boiling is H_2O. Did you think this was a tricky question?

110. This is another example that illustrates Figure 17.8. Water vapor in the warm air condenses on the outer surfaces of the cold metal coils of the unit.

18 Thermodynamics

In the photo opener, it is a pleasure to show Dan Johnson, active in a physics classroom. Dan is better known to environmentalists as Huey D. Johnson, founder of both The Trust for Public Land, and currently Resource Renewal Institute. Dan and I have been close friends since we met in graduate school at Utah State University back in the 1960s. Friends from Sweden, P.O. Zetterberg and Barbara and Tomas Brage take Dan's demonstration a giant step further! And Norwegian friends Ole Anton Haugland and Asge Mellem show an intriguing way to blow up a toy balloon.

These photos, followed by a personal profile of Kelvin, begin this chapter.

In keeping with the preceding chapters on heat, this chapter focuses on the environment. Particular emphasis is given to the atmosphere. What do most people talk about in casual conversations? The weather, of course. This chapter provides some physics insights that underlie the weather.

After several years in Hawaii and viewing hot lava flowing into the ocean, I have always been struck by the failure of onlookers to correctly answer my question, "Why is the lava so hot?" This is addressed in Practice Page 78, *Our Earth's Hot Interior*. There are trace amounts of radioactive materials in common rock. In common granite, for example, there are 4 parts per million uranium, 13 parts per million of thorium, and 4 parts per million of potassium. In one year the energy liberated by these radioactive atoms in a 1-kg sample is about 0.03 J. This information is the basis of the Practice Page.

The only weight-loss plan endorsed by the First Law of Thermodynamics: Burn more calories than you consume and you will lose weight—guaranteed.

Gaining in popularity are geothermal heat pumps that move heat from beneath Earth's surface into homes in winter. Whereas conventional furnaces and air conditioners heat air by means of combustion and chill it through mechanical compression, the geothermal pump circulates fluid through pipes buried underground. In winter, the pump in effect pulls heat out of the ground and pushes it into the home. The Earth's warmth is then distributed throughout the building, typically via an air-duct system. In the cooling mode, the process is reversed. They're proving to be very economical.

Watch also for the rise in the popularity of fuel cells.

The topics absolute zero and internal energy were introduced in Chapter 15 and merit more detail in this chapter. This chapter concludes Part 3 and is not prerequisite to chapters that follow. It may be skipped if a brief treatment of heat is required.

Practicing Physics Book:
• Absolute Zero

Problem Solving Book:

Yes, thermodynamics problems!

Next-Time Questions:
•Lamp Efficiency •Airplane Air Conditioners •Twice as Hot •Nellie's Fuel •Whopped Can

Hewitt-Drew-It! Screencast: •*Thermodynamics*

SUGGESTED LECTURE PRESENTATION

Absolute Zero
Review the temperature scales and lead into the thermodynamic temperature scale. If you did not discuss "Celsius, the Village Tailor," related in the suggested lecture for Chapter 15, this would be the time to do so. Begin by considering the ordering of a piece of hot apple pie and then being served cold pie—ice cold pie, at 0°C. Suppose you ask the waiter to put the pie in the oven and heat it up. How hot? Say twice as hot. Question: What will be the temperature of the pie? Move your class to the "check-your-neighbor" routine. Change your mind about the initial 0°C piece of pie and ask if the problem is easier if you begin with, say, a 10°C piece of pie. Tell your class to beware of neighbors who say the problem is simplified, and the answer is 20°C. This should spark interest. Now you're ready for "Celsius, the Village Tailor" story.

> Celsius, the Village Tailor: Hold a measuring stick against the wall of the lecture room (so that the bottom of the vertically-oriented stick is about 1 meter above the floor) and state that you are Celsius, the village tailor, and that you measure the heights of your customers against the stick, which is firmly fastened to the wall. You state that there is no need for the stick to extend to the floor, nor to the ceiling, for your shortest and tallest customers fall within the extremities of the stick. Mention that all tailors using the same method could communicate meaningfully with each other about the relative heights of their customers providing the measuring sticks in each shop were fastened the same distance above the "absolute zero" of height. It just so happens that the distance to the floor, the "absolute zero," is 273 notches—the same size notches on the stick itself. Then one day, a very short lady enters your shop and stands against the wall, the top of her head coinciding with the zero mark on the measuring stick. As you take her zero reading, she comments that she has a brother who is twice her height. Ask the class for the height of her brother. Then ask for the temperature of the twice-as-hot apple pie. When this is understood, ask why the pie will not *really* be 273°C. Or that for the initially 10°C pie, the temperature will not really be 293°C. (We've simplified here, omitting the role of energy in any phase changes.)

Internal Energy
Distinguish internal energy from temperature. A neat example is the 4th-of-July-type sparklers, even if you've mentioned it earlier. The sparks that fly from the firework and strike your face have temperatures about 2000°C, but they don't burn. Why? Because the energy of the sparks is extremely low. They have a low internal energy. It is the amount of energy you receive that burns, not the ratio of energy/molecule. Even with a high ratio (high temperature), if a relatively few molecules are involved, the energy transfer is low. (Again, this is similar to the high voltage of a balloon rubbed against your hair. It may have thousands of volts, which is to say thousands of joules per charge. But if there are a relatively small number of charges, the total energy they carry is small.)

First Law of Thermodynamics
Introduce the first law of thermodynamics by citing the findings of Count Rumford (Chapter 15 personal profile): when cannon barrels were being drilled and became very hot, it was friction of the drills that produced the heating. In accord with the definition of work, *force* x *distance*, cite how the metal is heated by the frictional force x distance over the various parts of the drill motion. Have your students rub their hands together and feel them warm up. Or warm part of the chair they sit on by rubbing.

Follow this up with the account of Joule with his paddle wheel apparatus to measure the mechanical equivalent of heat. Of interest is Joule's attempt to extend this experiment to a larger scale while on his honeymoon in Switzerland. Joule and his bride honeymooned near the Chamonix waterfall. According to Joule's conception of heat, the gravitational potential energy of the water at the top should go into

increasing the internal energy of the water when at the bottom. Joule made a rough estimate of the increased difference in water temperature at the bottom of the waterfall. His measurements did not substantiate his predictions, however, because considerable cooling occurred due to evaporation as the water fell through the air. Without this added complication, however, his predictions would have been supported. What happens to the temperature of a penny, after all, when you transfer the KE of a swinging hammer to it? Likewise with water. Emphasize that the first law is simply the law of energy conservation for thermal systems.

Adiabatic Processes

Cite the opposite processes of compression and expansion of air and how each affects the temperature of the air. It's easy to see that compressing air into a tire warms the air; and also that when the same air expands through the nozzle in escaping, it cools. Discuss cloud formation as moist air rises, expands, and cools.

> CLASS DEMONSTRATION: Blow on your hands first with wide-open mouth, and then with puckered lips so the air expands. This is a first-hand demo of adiabatic cooling!

If you have a model of an internal combustion engine, as indicated in Figure 18.13, strongly consider showing and explaining it in class. Many of your students likely have little idea of the process. (It still amazes me that internal combustion automobile engines are as quiet as they are!)

Meteorology and the First Law

Discuss the adiabatic expansion of rising air in our atmosphere. Ask if it would be a good idea on a hot day when going for a balloon ride to only wear a T-shirt. Or would it be a good idea to bring warm clothing on a balloon ride? A glance at Figure 18.6 will be instructive.

Discuss the Check Question in the text about yanking down a giant dry-cleaner's garment bag from a high altitude and the changes in temperature it undergoes. Quite interesting.

There is more to Chinook winds than is cited in the text. As Figure 18.7 suggests, warm moist air that rises over a mountain cools as it expands, and then undergoes precipitation where it is gains latent heat energy as vapor changes phase to liquid (rain) or solid (snow). Then when the energetic dry air is compressed as it descends on the other side of the mountain, it is appreciably warmer than if precipitation hadn't occurred. Without the heat given to the air by precipitation, it would cool a certain amount in adiabatically expanding and warm the same amount in adiabatically compressing, with have no net increase in temperature.

Discuss temperature inversion and the role it plays in air pollution; or at least in confining air pollution. On the matter of pollution, even rain is polluted. Acid rain has wrecked havoc with the environment in many parts of the world. Interestingly enough, pure rainwater is naturally acidic. Ever-present carbon dioxide dissolves in water vapor to form carbonic acid. Decomposing organic matter, volcanoes, and geysers can release sulfur dioxides that form sulfuric acid. Lightning storms can cause nitric acid formation. The environmental problem of acid rain, however, is not the small amount caused by natural sources. Fossil fuel combustion is the largest single source of acid-producing compounds. On an almost amusing note, it isn't the destruction of vast forests or poisoning of wildlife or the eroding of works of art that have evoked the loudest public outcry—acid rain dulls the high-tech finishes on automobiles, and *that,* for many proud auto owners, is going too far!

On pollution: Romans in ancient times smelted lead in great open-air furnaces. Recent borings in the Greenland ice core suggest pollution from those smelters equaled that of the later Industrial Revolution.

If you haven't crunched soda pop cans in the lecture for the previous chapter, do it now. And relate it to the reduced pressure needed on turbine blades in a steam turbine. This is shown by Erik and Allison Wong in the 3 photos on page 346. Heat some aluminum soda pop cans on a burner, empty except for a small amount of water that is brought to a boil to make steam. With a pot holder or tongs, pick up a can and quickly invert it into a basin of water. Crunch! The atmospheric pressure immediately crushes the can with a resounding WHOP! Very impressive! Do this first by inverting cans into a cold basin of water.

It is evident that condensation of the steam and vapor on the inside takes place, pressure is correspondingly reduced, and the atmospheric pressure on the outside crunches the can. Then repeat but this time invert cans into a basin of very hot water, just short of the boiling temperature. Crunch again, but less forceful than before. Steam molecules stick to the water surface, hot or cool, like flies sticking to fly paper (and like the "kissing molecules" back in Figure 17.8). Then repeat, but this time invert cans into *boiling* water. No crunch because boiling is supplying molecules as others condense—a stand off. Lead your class into the explanation wherein the *net* effect is no change, as condensation of steam is met with just as much vaporization from the boiling water. The punch line of this demo is shown in Figure 18.14—the reason for condensation in a steam turbine—to reduce pressure on the backside of the turbine blades.

Second Law
Introduce the second law by discussing Think and Discuss 86 about immersing a hot tea cup in a large container of cold water. Stress that if the cup were to become even warmer at the expense of the cold water becoming cooler, the first law would not be violated. You're on your way with the second law.

According to my friend Dave Wall who worked for a couple of years in the Patent Office in Washington, D.C., the greatest shortcoming of would-be inventors was their lack of understanding the first and second laws of thermodynamics. The Patent Office has long been besieged with schemes that promise to circumvent these laws. This point is worth discussion, which you can direct to Carnot's efficiency equation and its consequences, like why better fuel economy is achieved when driving on cold days. [Remember in pre-SI days we talked of "mileage"—now it's fuel economy, because "kilometerage" just doesn't have the right ring yet.]

> CHECK QUESTION: Temperatures must be expressed in kelvins when using the formula for ideal efficiency, but may be expressed in either Celsius or kelvins for Newton's law of cooling. Why? [In Carnot's equation, ratios are used; in Newton's law of cooling, only differences.]

> CHECK QUESTION: Now there are new "electronic bulbs" that use a quarter of the energy that standard bulbs use to emit the same amount of light (these bulbs generate a radio signal that mixes with the same gas used in conventional fluorescent lamps). Can it be said that these bulbs generate less heat? [Yes, of course.]

> CHECK QUESTION: Still common incandescent lamps are typically rated only 5 to 10% efficient, and common fluorescent lamps are only 20% efficient. Now we say that incandescent lamps are 100% heat efficient. Isn't this contradictory? [5 to 10% and 20% efficient as *light* sources, but 100% efficient as *heat* sources. All the energy input, even that which becomes light, very quickly becomes heat.]

Ask why for ratios of temperatures, kelvins must be used. For differences either kelvins or Celsius may be used, for the difference is the same either way.

Efficiency points
When windows of a car are open, air drag is increased. With windows closed, as when the air conditioner is operating, air drag is decreased. At some driving speed, keeping the air con operating compensates for the extra fuel used to overcome air drag. So driving at low speeds with air con on consumes more fuel, while driving at high speed with air con on and windows closed, consumes less fuel. Another point; cars with tinted windows use less gasoline because they need less power for air conditioning.

Entropy
Conclude your treatment of this chapter with your best ideas on entropy—the measure of messiness.

Answers and Solutions for Chapter 18

Reading Check Questions

1. The meaning is “movement of heat.”
2. Thermodynamics is mainly concerned with macroscopic processes.
3. Its volume decreases by 1/273 for each 1°C temperature change.
4. Its pressure decreases by 1/273 for each 1°C temperature change.
5. Volume approaches zero.
6. Lowest temperature is -273°C; 0 K.
7. Principle concern is changes in energy.
8. The first law is a restatement of the conservation of energy.
9. A system refers to a well-defined group of atoms, molecules, or objects.
10. Heat added equals change in internal energy plus work done.
11. When work is done, both internal energy and temperature increases.
12. The adiabatic condition is that no heat enters or leaves the system.
13. Increase when work done on the system; decrease when work done by the system.
14. Air temperature rises as heat is added or pressure increased.
15. Air temperature rises (or falls) as pressure increases (or decreases).
16. Temperature of rising air falls; but rises for sinking air.
17. Temperature inversion is a condition wherein upper regions of air are warmer than lower regions.
18. Adiabatic processes apply to all fluids.
19. Heat never of itself flows from a cold object to a hot object.
20. Three processes are gaining heat, converting some to mechanical work, and expelling the remainder.
21. Thermal pollution is expelled heat that is undesirable.
22. Only some of the work done on an engine operating between two temperatures can be converted to work, with the rest expelled.
23. Condensation reduces pressure on the backside of turbine blades, allowing a net force to turn them while water is being recycled.
24. High-quality energy is organized; lower-quality, disorganized.
25. High-quality energy tends to transform into lower-quality energy.
26. Natural systems tend to transform from higher to lower quality energy states.
27. A measure of disorder is called entropy.
28. No exceptions occur for the first law of thermodynamics; but exceptions do occur for the second law.
29. The third law states that no system can have its absolute temperature reduced to zero.
30. The zeroth law states that if two systems, each in thermal equilibrium with a third system are in equilibrium with each other.

Think and Do

31. Yes, collapse occurs, although not as violent, when warm water is used for the pan.

32. Its warmth is due to both the blow of the hammer and the work done by the wood to bring the nail to a stop.

Plug and Chug

33. Ideal efficiency = $\dfrac{T_{\text{hot}} - T_{\text{cold}}}{T_{\text{hot}}}$ = (3000 K – 300 K)/(3000 K) = 90%.
34. Ideal efficiency = $\dfrac{T_{\text{hot}} - T_{\text{cold}}}{T_{\text{hot}}}$ = (2700 K – 200 K)/(2700 K) = 93%.

Think and Solve

35. Converting to absolute temperatures, 600°C = 273 + 600 = 873 K; 320°C = 273 + 320 = 593 K. Then ideal efficiency is (873 - 593)/873 = 0.32 or 32%. If Celsius values were inserted into the equation, an incorrect 47% would result. Not so!
36. Converting to kelvins; 25°C = 298 K; 4°C = 277 K. So Carnot efficiency = $\dfrac{T_h - T_c}{T_h} = \dfrac{298 - 277}{298} =$ 0.07, or 7%. This is very low, which means that large volumes of water (which there are) must be processed for sufficient power generation.

37. If by “twice as cold” she means one-half the absolute temperature, the temperature would be (1/2)(273 +10) = 141.5 K. To find how many Celsius degrees below 0°C this is, first subtract 141.5 K from 273 K; this is 273 K - 141.5 K = 131.5 K below the freezing point of ice, or **-131.5°C**. (Or simply, 141.5 K - 273 K = -131.5°C.) *Very* cold!

38. Adiabatic compression would heat the confined air by about 10°C for each kilometer decrease in elevation. That means the -35°C air would be heated 100°C and have a ground temperature of about (-35 + 100) = 65°C. (This is 149°F, roasting hot!)

39. (a) Wally’s mistake is not converting to kelvins. 300°C = 273 + 300 = 573K, and 25°C = 273 + 25 = 298 K. (b) Then ideal efficiency is (573 K – 298 K)/(573 K) = 0.48, or 48%.

40. Heating each kg of water through 3 degrees takes 3°C $\times$ 1 kg $\times$ 4,184 J/kg°C = 12,550 J. The number of joules of heat supplied to the water each second is 1.5 $\times$ 10^8, so the number of kilograms of water heated each second is (1.5 $\times$ 10^8 J)/(12,550 J/kg) = 12,000 kg. Or, $Q = cm\Delta T$ = (4,184 J/kg°C)(1 kg)(3°C) = 12,552 kg (about 12,000 kg).

41. The work the hammer does on the nail is $F \times d$, and the temperature change of the nail can be found from $Q = cm\Delta T$. First, we get everything into convenient units for calculating: 6.0 g = 0.006 kg; 8.0 cm = 0.08 m. Then we see that $F \times d$ = 600 N $\times$ 0.08 m = 48 J, and 48 J = (0.006 kg)(450 J/kg·°C)(ΔT) which we can solve to get ΔT = 48J/(0.006 kg $\times$ 450 J/kg ·°C) = 17.8°C. (You will notice a similar effect when you remove a nail from a piece of wood. The nail that you pull out is noticeably warm.)

42. Seven is most likely because there are more combinations that give seven than any other sum. Of the 36 possible combinations, 6 gives seven.

Think and Explain

43. In the case of the 500-degree oven it makes a lot of difference. 500 kelvins is 227°C, quite a bit different than 500°C. But in the case of the 50,000-degree star, the 273 increments either way makes practically no difference. Give or take 273, the star is still 50,000 K or 50,000°C when rounded off.

44. No, for as in the previous exercise, a difference of 273 in 10,000,000 is insignificant.

45. Not ordinarily. They undergo the same change in *internal energy*, which translates to the same temperature change when both objects are the same mass and composed of the same material.

46. Its absolute temperature is 273 K. Double this and you have 546 K. When expressed in Celsius; 546 - 273 = 273 °C.

47. You do work on the liquid when you vigorously shake it back and forth, which increases its internal energy. This is noted by an increase in temperature. (In the mid-nineteenth century, James Joule, by measuring the temperature of a liquid before and after doing known work with a stirring paddle, revealed what he called “the mechanical equivalent of heat,” a discovery that led to the general law of energy conservation.)

48. You do work in compressing the air, which increases its internal energy. This is evidenced by an increase in temperature.

49. The change in internal energy is 100 J – 80 J = 20 J.

50. The pump gets hot because you are *compressing* the air within. The tire valve feels cool because the escaping air is *expanding*. These are adiabatic processes.

51. You compress air when you blow up a balloon, warming the balloon. When air expands in leaving, it cools. Both are adiabatic processes.

52. Gas pressure increases in the can when heated, and decreases when cooled. When heated the faster-moving molecules hit the can’s wall harder and more often. When cooled, they hit less hard and less often.

53. It warms because it is adiabatically compressed.

54. Solar energy. The terms renewable and non-renewable really refer to time scales for regeneration—tens of years for wood versus millions of years for coal and oil.

55. Solar energy is the ultimate source of energy.

56. It is advantageous to use steam as hot as possible in a steam-driven turbine because the efficiency is higher if there is a greater difference in temperature between the source and the sink (see Sadi Carnot's equation in the chapter).

57. In accord with Carnot's equation, efficiency is higher with greater difference in temperature between the heat source (combustion chamber in the engine) and sink (air surrounding the exhaust). Also, lowering the temperature of the environment also increases the ideal efficiency.

58. When the temperature is lowered in the reservoir into which heat is rejected, efficiency increases; substitution of a smaller value of T_{cold} into $(T_{hot} - T_{cold})/T_{hot}$ will confirm this. (Re-express the equation as $1 - T_{cold}/T_{hot}$ to better see this.)

59. Only when the sink is at absolute zero (0 K) will a heat engine have an ideal efficiency of 100%.

60. As in the preceding exercise, inspection will show that decreasing T_{cold} will contribute to a greater increase in efficiency than by increasing T_{hot} by the same amount. For example, let T_{hot} be 600K and T_{cold} be 300K. Then efficiency = (600 - 300)/(600) = 1/2. Now let T_{hot} be increased by 200K. Then efficiency = (800 - 300)/(800) = 5/8. Compare this with T_{cold} decreased by 200K, in which case efficiency = (600 - 100)/(600) = 5/6, which is clearly greater.

61. No. In this case the heat sink is also in the room. That's why the condensation coils are in a region *outside* the region to be cooled. Temperature of the room actually increases because the refrigerator motor warms the surrounding air.

62. Yes. Unlike the cooling wished for in the previous exercise, the energy given to the room by the open oven raises room temperature.

63. You *are* cooled by the fan, which blows air over you to increase the rate of evaporation from your skin, but you are a small part of the overall system, which warms.

64. Work must be done to establish a temperature difference between the inside of the refrigerator and the surrounding air. The greater the temperature difference to be established, the more work and hence more energy is consumed. So the refrigerator uses more energy when the room is warm rather than cold.

65. It doesn't violate the second law of thermodynamics because an external agent does work on the system.

66. The gas is more compact—density increases.

67. You do work in compressing the gas, which increases the internal energy.

68. Most people know that electric lights are inefficient when converting electrical energy into light energy, so they are surprised to learn there is a 100% conversion of electrical energy to thermal energy. If the building is being heated electrically, the lights do a fine job of heating, and it is not at all wasteful to keep them on when heating is needed. It is a wasteful practice if the air conditioners are on and cooling is desired, for the energy input to the air conditioners must be increased to remove the extra thermal energy given off by the lights.

69. It does what heat engines do, namely convert energy of one kind (solar) into mechanical energy (the rocking of the bird).

70. As the gas streams out of the nozzle, some of its kinetic energy becomes kinetic energy of the rocket, so temperature drops. Expansion of the gas also contributes to its lower temperature.

71. Energy in the universe is tending toward unavailability with time. Hotter things are cooling as cooler things are warming. If this is true, the universe is tending toward a common temperature, the so-called

"heat death," when energy can no longer do work. (But we don't know for sure that the laws of thermodynamics apply to the universe as a whole, since we don't understand the ultimate source of the vast churning energy that is now apparent throughout the universe. Nature may have some surprises for us!)

72. The universe is moving toward a more disordered state.

73. Adiabatic parcels occur in both the atmosphere and the oceans.

74. More energy would be used to extract the energy than would be available from it. So although extracting ocean energy is possible, it is not practical, and cannot produce net power.

75. There are more ways for molecules in the liquid phase to move, resulting in more random and chaotic motion.

76. No, the entropy principle has not been violated because the order of the salt crystals is at the expense of a greater disorder of the water in the vapor state after evaporation. Even if we confine the system to the crystals themselves, there would be no violation of entropy because there is work input to the system by sunlight or other means.

77. No, the freezing of water is not an exception to the entropy principle because work has been put into the refrigeration system to prompt this change of state. There is actually a greater net disorder when the environment surrounding the freezer is considered.

78. Entropy of the overall system, of which the chicken is a small part, increases. So when the larger system is taken into account, there is no violation of the principle of entropy.

79. Such machines violate at least the second law of thermodynamics, and the first law as well. These laws are so richly supported by so many experiments over so long a time that the Patent Office wisely assumes that there is a flaw in the claimed invention rather than in the laws of thermodynamics.

Think and Discuss

80. A given amount of mechanical energy can be easily and commonly converted to thermal energy; any body moving with kinetic energy that is brought to rest by friction transforms all its kinetic energy into thermal energy (for example, a car skidding to rest on a horizontal road). The converse is not true, however. In accord with the 2nd law of thermodynamics, only a fraction of a given amount of thermal energy can be converted to mechanical energy. For example, even under ideal conditions, less than half of the heat energy provided by burning fuel in a power plant can go into mechanical energy of electric generators.

81. No—internal energy, unlike temperature, is not an average quantity.

82. When a blob of air rises in the atmosphere it expands while doing work on the surrounding lower-pressure air. This work output reduces internal energy, as evidenced by a lower temperature. Hence the temperature of air at the elevation of mountain tops is usually less than down below.

83. A breeze on a hot day reduces the thickness of this thermal blanket, and even removes it, which is followed by overheating of the body. The reverse outcome occurs on a cold day when your skin feels colder as a result of the breeze.

84. Blood leaving your brain is warmer than blood that enters, carrying away excess heat generated by brain activity so your head doesn't overheat. Overheating diminishes concentration!

85. To say one place is twice as hot as another is to say the temperatures given are absolute temperatures. A temperature in Boston of 40°F is about 4°C, which is 277K. Twice 277K is 554K, which is 281°C, which is higher than 500°F. So an 80°F day in Florida is not twice as hot as a 40°C day in Boston!

86. This transfer would not violate the 1st law because energy has been transferred without loss or gain. It would violate the 2nd law because internal energy will not freely transfer from a cooler to a warmer object.

87. The term pollution refers to an undesirable by-product of some process. The desirability or undesirability of a particular by-product is relative, and depends on the circumstances. For example, using waste heat from a power plant to heat a swimming pool could be desirable whereas using the same heat to warm a trout stream could be undesirable.

88. The can is crushed by atmospheric pressure when vapor pressure in the can has been significantly reduced. Reduction of vapor pressure in the can is accomplished by condensation of the vapor on the surface of water entering the opening in the can. If that water is boiling, then it supplies vapor at about the same rate as condensation occurs, resulting in no net condensation and no crunching. But even hot water, if its temperature is less than 100°C, will result in net condensation and a crushed can.

89. Some of the electric energy that goes into lighting a lamp is transferred by conduction and convection to the air, some is radiated at invisible wavelengths ("heat radiation") and converted to internal energy when it is absorbed, and some appears as light. Very little energy is converted to light in an incandescent lamp, with somewhat more in a fluorescent lamp. Even then, all of the energy that takes the form of light is converted to internal energy when the light is absorbed by materials upon which it is incident. So by the 1^{st} law, all the electrical energy is ultimately converted to internal energy. By the second law, organized electrical energy degenerates to the more disorganized form, internal energy. The thermodynamics laws are not violated.

90. It is fundamental in that it governs the general tendency throughout nature to move from order to disorder, yet it is inexact in the sense that it is based on probability, not certainty.

91. A perpetual motion machine would work only if there were no friction, *zero* friction. In practice, in the large-scale world there is always friction, so perpetual motion would require that energy increase, violating the conservation of energy principle. Atoms and molecules, on the other hand, are in continual perpetual motion, rebounding elastically from one anther, so they don't dissipate energy or "run down."

92. Your classmate isn't distinguishing between perpetual motion and perpetual motion machines. Your classmates is correct about perpetual motion being the normal state of the universe, but what is not possible is a perpetual motion machine that puts out more energy (including friction loss) than is put in.

93. (a) Yes, very likely. Two heads would come up on average one throw out of four. (b) Not likely. The chance for ten coins to come up all heads is only about 1 in 1000. (c) Extremely unlikely, even with a lifetime of trying. The laws of thermodynamics are based on the statistics of large numbers.

19 Waves and Vibrations

The darling little gal on the Part Four Opener is Abby Dimanjo, daughter of Stella and Jojo Dimanjo. Stella was my last CCSF teaching assistant before I retired in 2000. She is now a dentist with her own practice and Jojo is nicely employed at Google.

Chapter photo openers begin with Diane Reindeau, a prize-winning physics teacher at Deerfield High School in Deerfield, IL, and a column editor for The Physics Teacher magazine of AAPT. She has also written Think and Rank questions for both this and my high-school book. Photos 1 and 2 are friend Frank Oppenheimer, one of the most humble of great men I have known. His devotion to elevating the thinking of youngsters was unparalleled—what the Exploratorium that he founded was all about. Photo 4 is Jill Johnsen and Diane Markham of CCSF, and lastly, photo 5 is my multi-talented nephew, John Suchocki.

Some teachers begin the study of physics with waves, vibrations, and sound, topics that have greater appeal to many students than mechanics. Your course could begin with Part 4 and then move to Part 6, Light. If this chapter is used as a launch point, only the concept of speed needs to be introduced, which your students intuitively understand anyway.

Water waves are thought to be simple, but they're not. For most waves, gravity is the restoring force governing wave displacement, whereas for very short waves, like ripples of wavelength less than a few millimeters, surface tension provides the restoring force. The speed of waves depends on the depth of the water compared with the wavelength of the waves. Waves on the open sea, caused by winds, are rarely longer than 300 meters and never travel more than 100 km/h. Tsunami waves, caused by earthquakes and land slides, on the other hand, often measure 150 km from crest to crest and in deep water can travel as fast as a jetliner—some 800 km/h. Since they may be less than a meter high, they pass completely unnoticed by ships at sea. A tsunami, interestingly, may consist of ten or more waves forming what is called a "tsunami wave train." The individual waves follow one behind the other, between 5 and 90 minutes apart. Tsunamis are of particular interest to the author, especially when living in Hilo, Hawaii where two devastating tsunamis have occurred in the past half-century.

The treatment of shock waves in this chapter is quite simplified. Be advised that actual shock waves can be more complex than I've indicated.

This chapter serves as a necessary background for the following two chapters, as well as a useful background to the chapters in Part 5.

A Doppler ball is a 5-inch foam ball within which is a battery-powered buzzer. Start the buzzer and play catch, or swing it in a circle from the end of a piece of string. It is available from Arbor Scientific (Product #P7-7120).

Practicing Physics Book:

• Vibration and Wave Fundamentals • Shock Waves

Problem Solving Book:
An ample supply of problems involving vibrations and waves

Laboratory Manual:
• Slow-Motion Wobbler *Slowing Vibrations with a Strobe Light* (Demonstration)
• Water Waves in an Electric Sink *Wave Mechanics Simulation* (Tech Lab)

Next-Time Questions in Instructors Resource DVD:
• Standing Wave • Shock Wave • Flash Frequency

Hewitt-Drew-It! Screencasts: •*Good Vibrations and Waves* •*Types of Waves*

SUGGESTED LECTURE PRESENTATION

Vibration of a Pendulum: Demonstrate the periods of pendula of different lengths, and compare the strides of short and tall people, and animals with short and long legs. (Relate this to rotational inertia, as studied in mechanics.)

Wave Description: Move a piece of chalk up and down, tracing and retracing a vertical straight line on the board. Call attention to how "frequently" you oscillate the chalk, and relate this to the definition of frequency. Also discuss the idea of amplitude. With appropriate motions, show different frequencies and different amplitudes. Then do the same while walking across the front of the board tracing out a sine wave. Show waves of different wavelengths.

> DEMONSTRATION: Show waves on a Bell Telephone torsion type wave machine shown in the chapter opener photo (if you're fortunate enough to have one).
>
> DEMONSTRATION: In jest, do as Tom Gordon at Bronx High School does and suspend a harmonica from a spring, bob it up and down, and ask, "What do we have here?" [Answer: Simple "harmonica" motion!]

Swing a pendulum to-and-fro and discuss the reciprocal relationship between frequency and period: $f = 1/T$, and $T = 1/f$. Or $fT = Tf = 1$.

Distinguish between wiggles in time—vibrations, and wiggles in space and time—waves. Stress the sameness of the frequency of a wave and the frequency of its vibrating source.

Wave Speed: Explain or derive the wave speed = frequency x wavelength formula. Support this with examples, first the freight car question early in the chapter, and then the water waves as in Think and Solve 36. If you discuss electromagnetic waves, be sure to contrast them with longitudinal sound waves and distinguish between them. You may refer ahead to the family of electromagnetic waves in Figure 26.3 later in the book.

Transverse and Longitudinal Waves:

DEMONSTRATION: You and a student hold the ends of a stretched spring or a Slinky and send transverse pulses along it, stressing the idea that only the disturbance rather than the medium moves along the spring. Shake it and produce a sine wave. Then send a stretch or compression down the spring, showing a longitudinal pulse, and wave. After some discussion, produce standing waves. (Impressive interference demos of sound are treated in the lecture for the next chapter.)

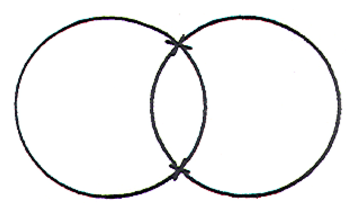
Interference: Explain interference, beginning with water waves, and then apply your explanation to standing waves. If you still have an overhead projector, overhead transparencies showing various interference patterns may simplify your presentation.

CHECK QUESTION: Can waves overlap in such a way as to produce a zero amplitude? [Yes, this is the destructive interference that is characteristic of all waves.]

Doppler Effect: Introduce the Doppler Effect by throwing a ball, perhaps sponge rubber or Styrofoam, around the room. In the ball you first place an electronic whistle that emits a sound of about 3000 Hz. Relate this to the sound of a siren on a fire engine (Figure 19.17) and radar of the highway patrol. (Note that sound requires a medium; radar is an E & M wave and requires none.)

DEMONSTRATION: Show a Slinky lying on a table, slightly stretched. Put your hand in the middle and move it, say, to the right. Your class easily notices the compression of the part of the Slinky to the right and the corresponding rarefaction to the left. This shows that waves are bunched in the direction of motion and stretched in the opposite direction.

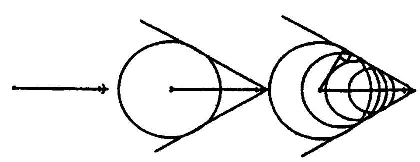
Wave Barriers, Bow Waves, and Shock Waves: Describe the Doppler effect via the bug in water sequence as treated in the text. From this lead into bow and shock waves. After sketching Figures 19.15, 19.16, and 19.18, ask the class to consider the waves made by two stones thrown in the water. Sketch the overlapping waves as shown to the right. Ask where the water is highest above the water level, then indicate the two places where the waves overlap with X's. Then show that this is what happens with a bow wave, that a series of such overlaps make up the envelope of many circular waves forming a V-shape. Then discuss the shock waves produced by supersonic aircraft.



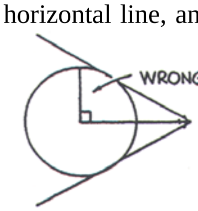
Note in Figure 19.19 I similarly position X's where the waves overlap. For more and closer waves than is shown in the drawing, the regions of overlap would be closer to the edge. I've been criticized for not placing the X's on the edge in this figure. But doing so would contradict the drawing above.

The analogy between bow waves in water and shock waves in air is very useful. Questions raised by students about shock waves and the sonic boom can be effectively answered by translating the question from one of an aircraft in the air to one of a speedboat knifing through the water, much easier-to-visualize.

Shock Wave Construction: Parallel the exercise on page 83 of the Practicing Physics book and construct a shock wave on the board by the following sequence: First place your chalk on the board anywhere to signify time zero. Draw a meter-long horizontal line, say to the right, to represent how far an aircraft has traveled in a certain time. Suppose it travels twice the speed of sound (Mach 2). Then during the time it travels your one meter, the sound it made initially has traveled half this distance, which you mark on the midpoint of your line. State that the initial sound has expanded spherically, which you represent two-dimensionally by drawing a circle as shown.



Explain that this circle represents only one of the nearly infinite circles that make up the shock wave, which you draw. The shock wave should be a 60 degrees wedge (30 degrees above your horizontal line, and 30 degrees below). The next line you draw is important: Draw the radius of the circle, from its center to a point tangent to the shock wave. Explain how the speed of the craft is simply the ratio of the horizontal line to this radial distance. (If your students are science students, at this point and not before, introduce the sine function). Now your test of all this: Construct a shock wave of a different angle on the board and ask your class to estimate the speed of the craft that generated it. In making constructions, working backwards now, the most common student error is constructing the right angle from the horizontal line rather than from the shock wave line that is tangent to the circle.



Answers and Solutions for Chapter 19

Reading Check Questions

1. A wiggle in time is a vibration; a wiggle in space and time is a wave.
2. The source of all waves is a vibration.
3. The period is the time for a complete to-and-fro swing.
4. A long pendulum has a longer period.
5. A sine curve is a pictorial representation of a wave.
6. Period, the time for a complete vibration; amplitude, the maximum displacement of a wave; wavelength, the length of one cycle of a wave; frequency, the rate of vibration.
7. There are 101.7 million vibrations per second.
8. Frequency and period are reciprocals of each other.
9. Energy.
10. The medium does not travel with a wave.
11. In a transverse wave vibrations are perpendicular to the direction of wave travel.
12. In a longitudinal wave, vibrations are parallel to wave travel.
13. The wavelength of a longitudinal wave is the distance between successive compressions or rarefactions.
14. Wave speed = frequency x wavelength.
15. When more than one wave occupies the same space at the same time the displacements add at every point.
16. When constructive interference occurs, waves build up. When destructive interference occurs, waves are diminished.
17. All waves can show interference.
18. A node is the part of a standing wave with zero or minimum displacement; an antinode is a part of a standing wave having maximum displacement.
19. Standing waves can be formed in either transverse or longitudinal waves.
20. What changes in the Doppler effect is frequency, not wave speed.
21. The Doppler effect can be observed with both transverse and longitudinal waves.
22. A blue shift refers to the Doppler effect for waves from an incoming source; red shift for waves from a receding source.
23. To keep up with produced waves, the bug must swim at wave speed; to produce a bow wave, faster than wave speed.
24. A supersonic aircraft, by definition, can fly faster than the speed of sound.
25. The faster the source, the narrower the V shape.
26. A shock wave in air is 3-dimensional.
27. False; the source may have exceeded the speed of sound earlier.
28. False; a speeding bullet or a circus whip can produce a sonic boom.

Think and Do

29. An activity to do!
30. Standing waves can be produced in both a wine glass and a metal bowl (with some practice).
31. Open ended.

Plug and Chug

32. (a) $f = 1/T = 1/0.10\text{ s} = 10\text{ Hz}$;
    (b) $f = 1/5 = 0.2\text{ Hz}$;
    (c) $f = 1/(1/60)\text{ s} = 60\text{ Hz}$.
33. Using $T = 1/f$, (a) 0.10 s.
    (b) 5 s.
    (c) $^1/_{60}$ s.
34. $v = f\lambda = (2\text{ Hz})(1.5\text{ m}) = 3\text{ m/s}$.
35. $v = f\lambda = (200\text{ Hz})(1.7\text{ m}) = 340\text{ m/s}$.

Think and Solve

36. The skipper notes that 15 meters of wave pass each 5 seconds, or equivalently, that 3 meters pass each 1 second, so the speed of the wave must be

    $$\text{Speed} = \frac{\text{distance}}{\text{time}} = \frac{15\text{ m}}{5\text{ s}} = 3\text{ m/s}.$$

    Or in wave terminology:
    Speed = frequency × wavelength = (1/5 Hz)(15 m) = 3 m/s.

37. (a) Frequency = 2 bobs/second = 2 hertz;

(b) Period = 1/f = 1/2 second;
(c) and the amplitude is the distance from the equilibrium position to maximum displacement, one-half the 20-cm peak-to-peak distance or 10 cm.

38. $d = vt$ = (340 m/s)(1/600 s) = 0.57 m. Or use speed = wavelength $\times$ frequency to get wavelength = speed/frequency = (340 m/s)/(600 Hz) = 0.57 m.

39. (a) Period = 1/frequency = 1/(256 Hz) = 0.00391 s, or 3.91 ms.
(b) Speed = wavelength $\times$ frequency, so wavelength = speed/frequency = (340 m/s)/(256 Hz) = 1.33 m.

40. Speed of plane = 1.41 $\times$ speed of sound (Mach 1.41). In the time it takes sound to go from A to C, the plane goes from A to B. Since the triangle A-B-C is a 45-45-90 triangle, the distance AB is $\sqrt{2}$ = 1.41 times as long as the distance AC.

41. T = (75 s)/(15 swings) = 5.0 s. From period $T = 2\pi\sqrt{L/g}$, solving for g, we get $g = 4\pi^2 L/T^2 = 4\pi^2(1.00\text{m})/(5\text{ s})^2 = 1.6\text{ m/s}^2$.

Think and Rank

42. a. D, B, A = C
b. D, A, B, C
c. C, B, A, D
d. D, A, B, C
43. A, B, D, C
44. B, A, C
45. A, C, B

Think and Explain

46. The period of a pendulum does not depend on the mass of the bob, but does depend on the length of the string.

47. A shorter pendulum swings to and fro with a higher frequency and shorter period.

48. The period of a pendulum depends on the acceleration due to gravity. Just as in a stronger gravitational field a ball will fall faster, a pendulum will swing to and fro faster. (The exact relationship, $T = 2\pi\sqrt{L/g}$, is shown in Footnote 1 in the chapter). So at mountain altitudes where the gravitational field of the Earth is slightly less, a pendulum will oscillate with a slightly longer period, and a clock will run just a bit slower and will “lose” time.

49. Assuming the center of gravity of the suitcase doesn’t change when loaded with books, the pendulum rate of the empty case and loaded case will be the same. This is because the period of a pendulum is independent of mass. Since the length of the pendulum doesn’t change, the frequency and hence the period are unchanged.

50. The period is actually less when you stand on a playground swing, for the pendulum is effectively shorter. That’s because the center of mass of the pendulum “bob” (you) is raised and is closer to the pivot.

51. The period increases, for period and frequency are reciprocals of each other.

52. Lower frequency produces wave crests farther apart, so wavelength increases. Wavelength and frequency are reciprocals of each other.

53. The wavelength is lengthened to twice. Speed and frequency are directly proportional.

54. Letting $v = f\lambda$ guide thinking, twice the speed means twice the frequency.

55. The periods are equal. Interestingly, an edge-on view of a body moving in uniform circular motion is seen to vibrate in a straight line. How? Exactly in simple harmonic motion. So the up and down motion of pistons in a car engine are simple harmonic, and have the same period as the circularly rotating shaft that they drive.

56. The wad of clay increases rotational inertia and it vibrates slower. When the clay is in the middle, its rotational inertia is less than when at the end, and vibration speed is increased. Rotational inertia is Chapter 8 material. (Interestingly, whereas the period of a pendulum isn't affected by mass, the period of the hacksaw blade is. Why? Because the hacksaw blade's restoring force is not gravity, but the elastic properties of the steel. More mass means more rotational inertia without any more torque, so the period increases.)

57. Wave frequency and shaking frequency are the same, which doesn't depend on the type of wave, for the frequency of all waves is the same as the frequency of the vibrating source.

58. Shake the garden hose to-and-fro at right angles to the hose to produce a sine-like curve.

59. To produce a transverse wave with a Slinky, shake it to and fro in a direction that is perpendicular to the length of the Slinky itself (as with the garden hose in the previous exercise). To produce a longitudinal wave, shake it to-and-fro along the direction of its length, so that a series of compressions and rarefactions is produced.

60. (a) Longitudinal. (b) Transverse (c) Transverse.

61. Violet light has the greater frequency.

62. Frequency and period are reciprocals of one another; $f = 1/T$, and $T = 1/f$. Double one and the other is half as much. So doubling the frequency of a vibrating object halves the period.

63. The frequency of the second hand of a clock is one cycle per minute; the frequency of the minute hand is one cycle per hour; for the hour hand the frequency is one cycle per 12 hours. To express these values in hertz, we need to convert the times to seconds. Then we find for the second hand the frequency = 1/60 hertz: for the minute hand the frequency = 1/3600 hertz; for the hour hand the frequency = 1/(12 × 3600) = 1/(43,200) hertz.

64. As you dip your fingers more frequently into still water, the waves you produce will be of a higher frequency (we see the relationship between "how frequently" and "frequency"). The crests of the higher-frequency waves will be closer together—their wavelengths will be shorter.

65. The frequency of vibration and the number of waves passing by each second are the same.

66. Think of a period as one cycle in time, and a wavelength as one cycle in space, and a little thought will show that in a time of one period, a wave travels a full wavelength. Formally, we can see this as follows:
distance = speed × time
where speed = frequency × wavelength, which when substituted for speed above, gives
distance = frequency × wavelength × time.
distance = 1/period × wavelength × period = wavelength.

67. For mechanical waves, something that vibrates. For E&M waves, vibrating electric charges.

68. Not including endpoints, there are 3 nodes in a wave two wavelengths long, and 5 nodes in a wave three wavelengths long. (Make a drawing and count them!)

69. The energy of a water wave spreads along the increasing circumference of the wave until its magnitude diminishes to a value that cannot be distinguished from thermal motions in the water. The energy of the waves adds to the internal energy of the water.

70. The circular patterns made by expanding waves are evidence that the wave speeds are the same in all directions, because all parts of the circle have gone equal distances from the center in equal times.

71. The speed of light is 300,000 km/s, about a million times faster than sound. Because of this difference in speeds, lightning is seen a million times sooner than it is heard.

72. The nodes are at the fixed points, the two ends of the string. The wavelength is twice the length of the string (see Figure 19.14a).

73. The frequency is doubled.

74. They are higher frequency due to the Doppler effect.

75. (a) The frequency increases. (b) The wavelength decreases. (c) The speed is unchanged (because the air remains motionless relative to you).

76. The Doppler effect is a change in frequency as a result of the motion of source, receiver, or both relative to each other. So if you move toward a stationary sound source, yes, you encounter wave crests more frequently and the frequency of the received sound is higher. Or if you move away from the source, the wave crests encounter you less frequently, and you hear sound of a lower frequency.

77. No, the effects of shortened waves and stretched waves would cancel one another.

78. There is no appreciable Doppler effect when motion of the sound source is at right angles to the listener. In this case, the source is neither approaching and crowding waves, nor receding and spreading waves. (For the record, however, there is a small “quadratic” transverse Doppler effect.)

79. Police use radar waves that are reflected from moving cars. From the shift in the returned frequencies, the speed of the reflectors (car bodies) is determined.

80. Oops, careful. The Doppler effect is about changes in *frequency*, not speed.

81. The bow or shock wave is actually the superposition of many lesser amplitude waves that interfere constructively. When the crest of one wave overlaps the crest of another, and then another, a wave of greater amplitude is produced.

82. A boat that makes a bow wave is traveling faster than the waves of water it generates.

83. A shock wave and the resulting sonic boom are produced whenever an aircraft is supersonic, whether or not the aircraft has just become supersonic or has been supersonic for hours.

84. The speed of the sound source rather than the loudness of the sound is crucial to the production of a shock wave. At subsonic speeds, no overlapping of the waves will occur to produce a shock wave. Hence no sonic boom is produced.

85. Yes, a supersonic fish in water would produce a shock wave and hence a sonic boom for the same reason it would if traveling faster than sound in air.

86 and 87. Open-ended.

Think and Discuss

88. The period is the same, for mass doesn’t affect period.

89. The frequency of a pendulum depends on the restoring force, which is gravity. Similarly, mass doesn’t affect free fall acceleration as is evident in Figure 19.1.

90. That gas can be heard escaping from a gas tap before it is smelled indicates that the pulses of molecular collisions (the sound) travel more quickly than the molecules migrate. (There are three speeds to consider: (1) the average speed of the molecules themselves, as evidenced by temperature—quite fast, (2) the speed of the pulse produced as they collide—about $^3/4$ the speed of the molecules themselves, and (3) the very slow speed of molecular migration.)

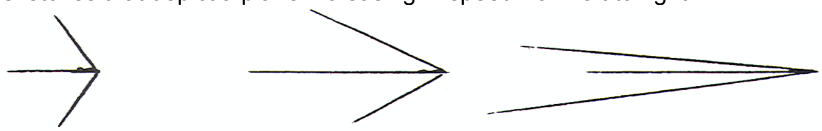
91. It’s important to note that wave speed involves the rate of travel while wave frequency involves how frequently vibration occurs. Two different concepts!

92. The Doppler shifts show that one side approaches while the other side recedes, evidence that the Sun is spinning.

93. The fact that you hear an airplane in a direction that differs from where you see it simply means the airplane is moving, and not necessarily faster than sound (a sonic boom would be evidence of supersonic flight). If the speed of sound and the speed of light were the same, then you’d hear a plane

where it appears in the sky. But because the two speeds are so different, the plane you see appears ahead of the plane you hear.

94. The conical angle of a shock wave becomes narrower with increased speeds. We see this in the sketches that depict a plane increasing in speed from left to right.



20 Sound

The most influential physicist in my career is my dear friend Ken Ford, to whom the previous edition of this book was dedicated. He is shown in the photo opener in his passionate pursuit of flying—particularly soaring. He has written a book about this passion—*In Love With Flying*, H Bar Press, 2007. I gladly use his profile to open this chapter. The second opening photo is physics friends Chris Chiaverina and Tom Rossing. For a great teaching resource, read their *Teaching Light and Color* (AAPT 2001), a collection of scientific papers, articles, and brief excerpts from books intended to provide source material for teaching light and color with references to 281 books, papers, and websites. Photo 3 is Norwegian physics friends Cathrine W. Tellefsen and Ellen K. Henriksen, enchanting their class with a novel display of waves. The fourth photo is family friend little Emily Ackerman of San Francisco.

This chapter lends itself to interesting lecture demonstrations: A ringing doorbell inside a vacuum jar being evacuated—the easily seen vibrations of a tuning fork illuminated with a strobe lamp—resonance and beats with a pair of tuning forks mounted on sound boxes—and the movie (8-mm film loop) of the "Tacoma Narrows Bridge Collapse."

I incorporate the Tacoma Narrows film loop in my treatment of resonance in *Conceptual Physics Alive*! DVD on Sound II. I kid around and claim, in the voice-over, that a cat is responsible for the collapse. So if you show the DVD and that type of humor is not your style, consider turning the audio off.

Forced vibrations, resonance, and interference provide a very useful background for the same concepts applied to light in Chapters 26, and 27. A great sounding-board demo is placing a music box mechanism on your chalkboard or whiteboard, and comparing the loud sound it produces with the almost imperceptible sound when held in air. Arbor Scientific has these (Product P7-7330).

J. David Gavenda (University of Texas at Austin) points out that *propagate* is a better term than *conductor* for the transmission of sound. Conduction infers diffusion; a process such as occurs in electrical and thermal conduction. The transmission of sound through wood, steel, and other materials involves media boundaries that reflect waves and confine them so they can't spread in 3 dimensions. Also, a speaking tube is analogous to a light pipe; both have one-dimensional propagation because of internal reflection.

Practicing Physics Book:
• Wave Superposition

Problem Solving Book:
A chapter with ample numbers of sound problems
Laboratory Manual:

• How Quiet Low Sound *Sound Wave Manipulation and Interpretation* (Experiment)
• Fork it Over *Determination of the Speed of Sound in Air* (Experiment)
• Sound Off *Sound Wave Cancellation* (Demonstration)
• Wah-Wahs and Touch Tones *Sound Wave Interference* (Tech Lab)

Next-Time Questions:
• Concert Hall •Sound From a Train

Hewitt-Drew-It Screencasts:
•*Reflection and Refraction of Sound* •*Resonance of Sound* •*Wave Interference*

SUGGESTED LECTURE PRESENTATION

Origin of Sound: Begin by stating that the source of sound or all wave motion, is a vibrating object. Ask your class to imagine a room filled with Ping-Pong balls and that you hold a giant Ping-Pong paddle. When you shake the paddle to-and-fro you set up vibrations of the balls. Ask how the frequency of the vibrating balls will compare with the frequency of the vibrating paddle. Sound is understood if we "think small."

> DEMONSTRATION: Tap a large tuning fork and show that it is vibrating by dipping the vibrating prongs in a cup of water. The splashing water is clear evidence that the prongs are moving! (Small forks do not work as well.)
>
> DEMONSTRATION: Hold an aluminum rod (a meter long or so) horizontally at the midpoint and strike one end with a hammer. You will create vibrations that travel and reflect back-and-forth along the length of the rod. The sustained sound heard is due to energy "leaking" from the ends, about 1% with each reflection. So at any time the sound inside is about 100 times as intense as that heard at the ends. (This is similar to the behavior of light waves in a laser.) Shake the rod to-and-fro as Paul Doherty does and illustrate the Doppler effect.
>
> DEMONSTRATION: Rub some pine pitch or rosin on your fingers and stroke the aluminum rod. If you do it properly, it will "sing" very loudly. Do this while holding the rod at its midpoint and then at different places to demonstrate harmonics. (Of course you practiced this first!)

Nature of Sound in Air:

> DEMONSTRATION: Ring the doorbell suspended in a bell jar that is being evacuated of air. While the loudness of sound diminishes, discuss the movement of sound through different media—gases, liquids, and solids. Ask why sound travels faster in warm air—then faster through moist air.

Media That Transmit Sound: Discuss the speed of sound through different media—four times as fast in water than in air—about eleven times as fast in steel. The elasticity of these materials rather than their densities accounts for the different speeds. Cite how Native Americans used to place their ears to the ground to hear distant hoof beats. And how one can put the ear to a track to listen for distant trains.

Speed of Sound: Discuss the speed of sound and how one can estimate the distance from a lightning storm.

Compute or state that a radio signal takes about $^1/_8$ second to go completely around the world, while in the same time sound travels about 42.5 m. Pose the following: Suppose a person attends a concert that is being broadcast over the radio, and that he sits about 45 m from the stage and listens to the radio broadcast with a transistor radio over one ear and the nonbroadcast sound signal with the other ear. Which signal will reach his ear first? The answer is that the radio signal would reach his ear first, even if the radio signal traveled completely around the world before reaching his radio! Note the Next-Time Question that features this idea.

Reflection of Sound: Bats and echoes, charting of the ocean bottom, reverberations in the shower, and acoustics in music halls—go to it.

Refraction of Sound: Explain refraction with a chalkboard drawing similar to Figure 20.9. As an example different than the sound of the bugle waking the dog, consider the temperature inversion over a lake at night, and how one can hear whispers of people on the opposite side of the lake. You may want to follow this up with the similar case of refraction by wind, where wind speed is greater higher up than near the ground.

Ultrasound technology is a useful medical application of sound refraction (Figure 20.10).

An even more fascinating example of reflection and refraction of sound is the dolphin. Dolphins have been doing all along what humans have just learned to do. Add to the material about dolphins in the chapter, that unlike humans, dolphins breathe voluntarily. They cannot be put to sleep for medical operations because they will cease breathing and die. They are subject to drowning, as any mammal is. When in trouble other dolphins hold the troubled dolphin at the surface so breathing can take place. When sick, they will beach themselves so they won't drown. Many shipwrecked sailors owe their lives to dolphins who have beached them. Fascinating creatures!

Forced Vibrations, Natural Frequency: Tap various objects around you and explain what is happening at the atomic level—that crystalline or molecular structures are made to vibrate, and that due to the elasticity and bonding of the material constituents, natural modes of vibration are produced. Objects have their own characteristic frequencies. The organs of humans have a natural frequency of about 7 hertz.

Resonance:

> DEMONSTRATION: Show resonance with a pair of tuning forks, explaining how each set of compressions from the first fork push the prongs of the second fork in rhythm with its natural motion. That's family friend Ryan Patterson in Figure 20.13. Compare resonance to pushing somebody on a playground swing (as my grandson Manuel Hewitt shows in Figure 20.16). If you have a strobe-light handy, illuminate resonating forks with it and see glee in your students!

When you are adjusting the frequency of one of your tuning fork boxes, by moving the weights up or down the prongs, call attention to the similarity of this with tuning a radio receiver. When one turns the knob to select a different station, one is adjusting the frequency of the radio set to resonate with incoming stations.

Cite other examples of resonance—the chattering vibration of a glass shelf when a radio placed on it plays a certain note—the loose front end of a car that vibrates at only certain speeds—crystal wine glass shattering by a singer's voice—troops breaking step in bridge crossing.

Conclude your treatment of resonance with the exciting film loop "The Tacoma Narrows Bridge Collapse." This short film is a most impressive physics film. (Again, it is on "Sound II" of the *Conceptual Physics Alive!* DVD.) If you show it, be prepared to answer to my assertion in the film that a cat brought down the bridge due to resonance with its steady steps as it crossed the bridge. When challenged myself on this point, I say it's in the book. <u>Then</u> my students read about the mild gale. How carefully do <u>your</u> students read the text?

Interference: Introduce interference by sketching a sine wave on the board—a water wave. Then superpose another identical wave on it and ask what happens. Nothing spectacular, simply a wave of twice the amplitude. Now repeat and superpose the second wave a half-wavelength out of step. State that physics types don't say "out of step," but "out of phase." Same thing.

> DEMONSTRATION: Play a stereo radio, tape or CD player, on a mono setting and demonstrate the different quality of sound when the speakers, set apart from each other, are out of phase. I have mine connected to a DPDT switch to flip the phase. The difference in sound is obvious, especially for students on the center line. You might point out in Figure 20.18 that in position *b* cancellation

will occur for a few particular wavelengths, whereas in position *a* cancellation can occur for all wavelengths—when both speakers emit the same signal. Of course, wall reflections fill in any pure cancellations. In an acoustic chamber, however, cancellation would occur.

DEMONSTRATION: Do the demo shown in Figure 20.19 and face the stereo speakers toward each other, at arm's length apart. Flip one speaker out of phase and gradually bring them closer. The volume of sound fades dramatically as they are brought face to face. Interference. This may likely be one of the more memorable of your demos.

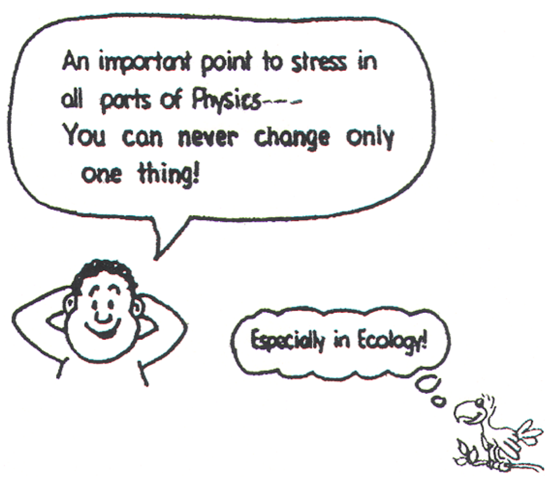
The question may arise as what happens to the sound energy when sound cancels. Interestingly, each radio loudspeaker is also a microphone. When the speakers face each other they "drive" each other, inducing back voltages in each other that reduce the currents in each. Thus energy is diminished, but not canceled.

DEMONSTRATION: Show the reason for speakers mounted in boxed enclosures by producing a bare speaker connected to a music source. The sound is "tinny." State why; that as compressions are produced by one side of the speaker cone, rarefactions are produced by the other. Superposition of these waves results in destructive interference. Then produce a square piece of board (plywood or cardboard) close to a meter on a side with a hole the size of the speaker in its center. Place the speaker at the hole and let your class hear the difference in the fullness of the sound that results. You have diminished the superposition of waves that previously canceled. The effect is dramatic.

I kid around about my keen ability to completely cancel sound by striking one tuning fork and then the other at precisely the time to produce cancellation. When I do this I quickly grab and release the prongs of the sounding fork while not really making contact with the second. It is especially effective for students who weren't watching carefully. I exclaim that when I'm lucky enough to achieve complete cancellation on the first try, I never repeat it. Is this real physics? No, but it's a mood elevator so that my students are receptive to the real physics I discuss the rest of the time.

Beats: Acknowledge you were kidding around before about producing interference with the pair of tuning forks, but now you're for real with them. Strike the slightly different frequency forks and hear the beats. This is even nicer when your students see an oscilloscope trace what they hear.

DEMONSTRATION: Do as Paul Hickman does and sound a tuning fork mounted on a sounding board and position the open end at various places from a reflecting wall. Areas of cancellation and reinforcement are readily located.



Answers and Solutions for Chapter 20

Reading Check Questions

1. Sound is a form of energy.
2. The higher the frequency, the higher the pitch.
3. A young person can normally hear from 20 to 20,000 hertz.
4. Infrasonic sound is less than 20 hertz, while ultrasonic is above 20,000 hertz.
5. Air is a poorer conductor than solids and liquids.
6. In a vacuum there is no medium to compress and expand.
7. A compression is a region of compressed air; a rarefaction is a region of low-pressure air.
8. Both compressions and rarefactions travel in the same direction of the wave they comprise.
9. Sound speed depends on wind conditions, temperature, and humidity of air. It does not depend on loudness or frequency of the sound.
10. Sound speed is 340 m/s in 20°C dry air.
11. Sound travels faster in warm air.
12. There is more energy in ordinary light than in ordinary sound.
13. Sound energy dissipates to thermal energy.
14. An echo is reflected sound.
15. A reverberation is sound multiply reflected.
16. Refraction is caused by bending due to differences in sound speed.
17. Sound bends downward when speed is less near the ground.
18. Sound refracts in water due to different speeds in different water temperatures.
19. Ultrasound is sound composed of frequencies higher than the range of human hearing.
20. Sound is louder due to more surface vibrating.
21. An object's elasticity, size, and shape determine natural frequency.
22. When forced vibrations match natural frequency, resonance occurs.
23. By tuning the radio to a certain frequency, you are adjusting the receiver circuit to vibrate at that station's frequency only.
24. Wind-generated resonance destroyed the bridge.
25. Waves will cancel when they are identical and out of phase.
26. All waves exhibit interference.
27. The result is cancellation of sound.
28. Interference is the phenomena underlying beats.
29. A beat frequency of 4 Hz results.
30. A radio wave is electromagnetic, while a sound wave is a mechanical phenomenon.

Think and Do

31. Sound should be louder beneath the water. Tub resonance can be fun.

32. Note the different patterns with different types of music.

Think and Solve

33. Wavelength = speed/frequency = $\frac{340 \text{ m/s}}{340 \text{ Hz}}$ = 1 m.

    Similarly for a 34,000 hertz wave; wavelength = $\frac{340 \text{ m/s}}{34\,000 \text{ Hz}}$ = 0.01 m = 1 cm.

34. $v = f\lambda$, so $\lambda = v/f$ = (1530 m/s)/7 Hz = **219 m**.

35. The ocean floor is 4590 meters down. The 6.0-second time delay means that the sound reached the bottom in 3.0 seconds. Distance = speed $\times$ time = 1530 m/s $\times$ 3.0 s = 4590 m.

36. Assuming the speed of sound to be 340 m/s, the cave wall is 17 meters away. This is because the sound took 0.10 second to reach the wall (and 0.05 second to return).

    Distance = speed x time = 340 m/s $\times$ 0.05 s = 17 m.

37. The single blow you hear after you see Sally stop hammering originated with the next-to-last blow you saw. The very first blow would have appeared as silent, and succeeding blows synchronous with successive strikes. In one second sound travels 340 meters in air, the distance between you and Sally.

38. Sound goes from Rip to the mountain in 4 hours and back in another 4 hours to wake him. The distance from Rip to the mountain = speed of sound $\times$ time = 340 m/s $\times$ 3600 s/h $\times$ 4 h = 4.9×10^6 m = 4900 km. (Very far, and due to the inverse-square law, also very weak!)

39. There are 3 possible beat frequencies: 2 Hz, 3 Hz, and 5 Hz. These are of differences in fork frequencies: 261 - 259 = **2 Hz**; 261 - 256 = **5 Hz**; 259 - 256 = 3 Hz.

40. Wavelength = speed/frequency = (1,500 m/s)/(57 Hz) = 26 m. Alternate method: For sounds of the same frequency in different media, wavelengths are proportional to wave speed. So (wavelength in water)/(wavelength in air) = (speed in water)/(speed in air) = (1,500 m/s)/(340 m/s) = 4.4. Multiply 6 m by 4.4 to get 26 m.

Think and Rank

41. B, C, A
42. B, A, C, D

Think and Explain

43. Light travels about a million times faster than sound, hence the delay between what you see and what you hear.

44. Sound does not travel in a vacuum.

45. Between us and other planets is a vacuum. Sound does not travel in a vacuum.

46. The same. The circles formed are relative to the water, and both will travel downstream together.

47. Bees buzz when in flight because they flap their wings at audio frequencies.

48. The shorter wavelengths are heard by bats (higher frequencies have shorter wavelengths).

49. The carrier frequency of electromagnetic waves emitted by the radio station is 101.1 MHz.

50. The wavelength of the electromagnetic wave will be much longer because of its greater speed. You can see this from the equation speed = frequency $\times$ wavelength, so for the same frequency greater speed means greater wavelength. Or you can think of the fact that in the time of one period—the same for both waves—each wave moves a distance equal to one wavelength, which will be greater for the faster wave.

51. The wavelength of sound from Source A is half the wavelength of sound from Source B.

52. Letting $v = f\lambda$ guide thinking, as frequency increases wavelength decreases.

53. Light travels about a million times faster than sound in air, so you see a distant event a million times sooner than you hear it.

54. The electronic starting gun does not rely on the speed of sound through air, which favors closer runners, but gets the starting signal to all runners simultaneously.

55. When sound passes a particular point in the air, the air is first compressed and then rarefied as the sound passes. So its density is increased and then decreased as the wave passes.

56. At the instant that a high pressure region is created just outside the prongs of a tuning fork, a low pressure region is created between the prongs. This is because each prong acts like a Ping-Pong paddle in a region full of Ping-Pong balls. Forward motion of the paddle crowds Ping-Pong balls in front of it, leaving more space between balls in back of it. A half-cycle later when the prongs swing in toward the center, a high pressure region is produced between the prongs and a low-pressure region is produced just outside the prongs.

57. Because snow is a good absorber of sound, it reflects little sound—hence quietness.

58. The fact that we can see a ringing bell but can't hear it indicates that light is a distinctly different phenomenon than sound. When we see the vibrations of the "ringing" bell in a vacuum, we know that

light can pass through a vacuum. The fact that we can't hear the bell indicates that sound does not pass through a vacuum. Sound needs a material medium for its transmission; light does not.

59. The Moon is described as a silent planet because it has no atmosphere to transmit sounds.

60. If the speed of sound were different for different frequencies, say, faster for higher frequencies, then the farther a listener is from the music source, the more jumbled the sound would be. In that case, higher-frequency notes would reach the ear of the listener first. The fact that this jumbling doesn't occur is evidence that sound of all frequencies travel at the same speed. (Be glad this is so, particularly if you sit far from the stage, or if you like outdoor concerts.)

61. If the frequency of sound is doubled, its speed will not change at all, but its wavelength will be "compressed" to half size. The speed of sound depends only on the medium through which it travels, not on its frequency, wavelength, or intensity (until the intensity gets so great that a shock wave results).

62. Sound travels slower in cold air because the air molecules that compose cold air themselves travel slower and therefore take a bit longer before they bump into each other, which results in slower sound.

63. Refraction is the result of changing wave speeds, where part of a wave travels at a different speed than other parts. This occurs in non-uniform winds and non-uniform temperatures. Interestingly, if winds, temperatures, or other factors could not change the speed of sound, then refraction would not occur. (The fact that refraction does indeed occur is evidence for the changing speeds of sound.)

64. The tremor in the ground can be felt before a distant explosion is heard because sound travels faster in the solid ground than in air.

65. Sound is more easily heard when the wind traveling toward the listener at elevations above ground level travels faster than wind near the ground. Then the waves are bent downward as is the case of the refraction of sound shown in Figure 20.9.

66. In accord with the inverse-square law, the intensity decreases to 1/9 when distance is tripled.

67. An echo is weaker than the original sound because sound spreads and is therefore less intense with distance. If you are at the source, the echo will sound as if it originated on the other side of the wall from which it reflects (just as your image in a mirror appears to come from behind the glass). Also, the wall is likely not a perfect reflector.

68. If a single disturbance at some unknown distance sends longitudinal waves at one known speed, and transverse waves at a lesser known speed, and you measure the difference in time of wave arrival, you can calculate the distance. The wider the gap in time, the greater the distance—which could be in any direction. If you use this distance as the radius of a circle on a map, you know the disturbance occurred somewhere on that circle. If you telephone two friends who have made similar measurements of the same event from different locations, you can transfer their circles to your map, and the point where the three circles intersect is the location of the disturbance.

69. First, in outer space there is no air or other material to carry sound. Second, if there were, the faster-moving light would reach you before the sound.

70. Marchers at the end of a long parade will be out of step with marchers nearer the band because time is required for the sound of the band to reach the marchers at the end of a parade. They will step to the delayed beat they hear.

71. Soldiers break step when crossing a bridge so they will not set the bridge into forced vibration or resonance, which could tear the bridge apart.

72. A harp produces relatively softer sounds than a piano because its sounding board is smaller and lighter.

73 Agree with the speed of sound, but not the frequency. Sound's frequency depends only on the vibration of the source itself, not the medium.

74. There are two principal reasons why bass notes are more distinctly heard through walls than higher-frequency notes. One is that waves that vibrate more often per second transfer sound energy into heat more rapidly than waves of lower frequency. The higher-frequency waves are thermally “eaten up” by the material in the walls, while the lower-frequency vibrations pass with less loss through the material. Another reason is that the natural frequency of large walls, floors, and ceilings, is lower than the natural frequency of smaller surfaces. The large surfaces are more easily set into forced vibrations and resonance.

75. The lower strings resonate with the upper strings.

76. Certain dance steps set the floor into vibration that may resonate with the natural frequency of the floor. When this occurs, the floor heaves.

77. These noise-canceling devices use interference to cancel the sound of the jackhammer in the ears of its operator. Because of the resulting low jackhammer noise in the ears of the operator, he can hear your voice clearly. But you, however, without the earphones experience no such cancellation of sound, so the voice of the operator is drowned out by the loud jackhammer noise.

78. Think of pushing a child on a swing: If you pushed twice as often as the child’s period, you would push against the child’s motion with every other push, and similarly with increased multiples of frequency. Pushing more often than once each period disrupts the motion. On the other hand, if you pushed the child every other swing, your pushes would match the child’s motion and amplitude would increase. So sub-multiple pushes will not disrupt motion. Similarly with sound.

79. By resonance, when the buildup of vibrations in the glass exceed the breaking point of the glass.

80. Beats result from interference, and not the Doppler effect.

81. No, for the same word refers to different aspects of music. The beat of music involves rhythm, and the beats of sound involve throbbing due to interference.

82. Waves of the same frequency can interfere destructively or constructively, depending on their relative phase, but to *alternate* between constructive and destructive interference, two waves have to have different frequencies. Beats arise from such alternation between constructive and destructive interference.

83. The piano tuner should loosen the piano string. When 3 beats per second is first heard, the tuner knows he was 3 hertz off the correct frequency. But this could be either 3 hertz above or 3 hertz below. When he tightened the string and increased its frequency, a lower beat frequency would have told him he was on the right track. But the greater beat frequency told him he should have been loosening the string. When there is no beat frequency, the frequencies match.

84. The possible frequencies are 264 + 4 = 268 Hz, or 264 – 4 = 260 Hz.

85. You’ll hear sound at a frequency of 2 kHz, the beat frequency of the two higher frequencies.

Think and Discuss

86. The pitch of the tapped glass decreases as the glass is filled. As the mass of the system (glass plus water) increases, its natural frequency decreases. For systems of a given size, more mass usually means lower frequency. This can be seen on a guitar, where the most massive string has the lowest natural pitch. (If you’ve answered this exercise without actually trying it, shame on you!)

87. Sound travels faster in moist air because the less massive water vapor molecules, H_2O, travel faster than the more massive N_2 and O_2 molecules at the same temperature. This faster motion results in sound traveling faster as discussed in Question 62.

88. The short wavelengths of ultrasound allow the imaging of smaller objects. This is similar to the smaller detail seen by short-wavelength blue light in microscopes, and the still smaller detail seen with ultra-short-wavelength electron microscopes, briefly discussed in Chapter 11. (We will see later in Chapter 29 that shorter wavelengths produce clearer images by decreasing a wave effect called *diffraction*.)

89. The rule is correct: This is because the speed of sound in air (340 m/s) can be rounded off to 1/3 km/s. Then, from distance = speed $\times$ time, we have distance = (1/3) km/s $\times$ (number of seconds). Note that the time in seconds divided by 3 gives the same value.

90. When you are equally distant from the speakers, their tones interfere constructively. When you step to one side, the distance to one speaker is greater than the distance to the other speaker and the two waves are no longer in phase. They interfere destructively. (If you step far enough to one side, they will interfere constructively again.)

91. Long waves are most canceled, which makes the resulting sound so tinny. For example, when the speaker cones are, say, 4 centimeters apart, waves more than a meter long are nearly 180° out of phase, whereas 2-centimeter waves will be in phase. The higher frequencies are least canceled by this procedure. This must be tried to be appreciated.

21 Musical Sound

Photo openers begin with my granddaughter Gracie (who is seen again opening Part 8 on page 657). The second photo is CCSF's finest, Norm Whitlatch, whose teaching career wonderfully emphasized the laboratory. Photo 2 is the niece and daughter of Stella and Jojo Dimamco. Mirium, at the right, is the sister of Abby who opens Part Four of this edition. Photo 4 is of physics instructor Lynda Williams of Santa Rosa Junior College in California. Lynda enjoys her musical performances, and especially enjoys entertaining at physics teacher functions.

The personal profile is of Jean Baptiste Fourier.

As in the preceding chapter, this chapter should be supported with lively lecture demonstrations. This material is not prerequisite to following material, and the entire chapter can be disregarded if a short treatment of sound is desired. In any event, the material in this chapter should be treated lightly. Like the periodic table, please make it clear that you don't expect this detailed material to be learned. Learning that there's physics in music is enough. Let this be a light-weight chapter.

Jojo Dijamco tells me that equal-tempered tuning is a compromise of scales so the frequency ratios are imperfect. In practice, equal-tempered tuning is adjusted for individual instruments (e.g., a piano or harp) so that the imperfections are minimized. Musicians consider the imperfections acceptable. Ideal tuning would require an instrument to be retuned whenever the key changes. This is not practical and is the reason that the compromise offered by the equal-tempered tuning is preferred. Johann Sebastian Bach wrote the *Well-Tempered Clavier* in the mid 1700s to show that equal-tempered tuning could work musically.

On the helium high-pitched voice: In the voice box are vocal folds. The higher-speed sound in helium enhances the higher frequencies in the voice spectrum. Thus the quality of the voice is changed, not the fundamental frequency.

If you don't know the names of the celebrities throughout the chapter, your students likely will. They are Jennifer Lopez on page 392, Mick Jagger and Jay-Z on page 393, Paul McCartney on page 395, Beyonce on page 396, Adele on page 397, and Bob Marley on page 398.

The sound emitted 10 cm away from some bats ranges from 122 to 134 decibels. Home fire alarms reach about 108 decibels. Fortunately for humans, we can't hear the high-frequency sound of bats. Otherwise they'd drive people batty.

There are no **Practicing Physics** worksheets, no problems in the **Problems Book,** no **Laboratory** experiments or activities, no **Hewitt-Drew-It! Screencasts** for this chapter. There are, however, four **Next-Time Questions** on musical sounds and pitch.

If you play a musical instrument, play it briefly for your class, explaining the physics of the instrument. Whereas anyone else doing the same would be no big deal, your students will love seeing and hearing you play music. Too often we're seen as nerds who can relate only to physics. Break this stereotype and add glee to your classroom! Feynman, who never fit the nerd profile, helped the image of physicists enormously by his drum playing.

SUGGESTED LECTURE PRESENTATION

Bring out the oscilloscopes, the audio oscillator, microphones, loudspeakers, and musical instruments.

Pitch, Loudness, and Quality: Waveforms can be displayed on the screen of an oscilloscope. An audio oscillator connected to a loudspeaker and an oscilloscope will demonstrate the relationships between pitch, frequency, and wavelength, and between amplitude and loudness. You can speak into the loudspeaker and display a wave pattern on the oscilloscope screen, showing that the loudspeaker serves as a microphone. (It may or may not be appropriate to briefly discuss the electromagnetic induction that takes place in the electromagnet of the loudspeaker at this point.) The waveforms of various musical instruments can be displayed and compared on the oscilloscope screen. Show the different harmonics for the same notes played on different instruments. Discuss quality.

If you display a decibel meter, show that for mid-range frequencies a decibel is the just-noticeable sound level difference that humans can detect.

Demonstrate Chladni figures with a fastened metal plate, violin bow, and fine sand. Or show the Ealing Film Loop of the same (perchance you have any of those still around). Discuss nodes and antinodes.

Musical Instruments: Although *standing longitudinal waves* are not treated in the text, you may wish to introduce this topic and relate it to musical instruments. If so, begin by demonstrating the resonance of standing air columns with a resonance water tube (a long glass tube partially filled with water, the level of which can be adjusted by raising or lowering an external reservoir). Hold a vibrating tuning fork over the open tube and adjust the water level until the air in the tube resonates loudly to the sound being sent into it by the fork. Show and explain that several heights will result in resonance. Measure the wavelengths of a high and a low frequency sound. Consider doing as Paul Hickman does and drop a couple of Alka-Seltzer tablets into the water. The air column above soon is filled with CO_2 and the tone of the reverberating sound undergoes a marked change. Relate the relative sizes of the respective sound cavities to the relative sizes of musical instruments; the bigness of a bass fiddle, and the smallness of a piccolo. These ideas underlie the tones one produces when blowing over the top of a soda pop bottle.

If you demonstrate resonance with the standard tube of water, consider a non-water alternative. Do as James Warden does and use a short piece of dowel that just slips in a vertical tube and suspend it with a string. Position the tuning fork at the bottom of the pipe instead of at the top. Since the sliding node can be moved much more quickly and accurately than a water column, you or your students can locate resonances within a few seconds. (Page 308, *The Physics Teacher*, May 2005.)

Tom Senior with novel sound producing items (photo with Think and Explain 56), shares simple physics on the Internet. (http://www.youtube.com/results?search_query=thomasjsenior&search_type=&aq=f)

Fourier Analysis: You may want to discuss Fourier Analysis and the superposition of waves and show on the board how the composite wave in Figure 21.6 is a sum of the fundamental and the second and third harmonics.

Figure 21.6 is also reinforced in the **Practice Book** page on wave superposition for the previous chapter.

Ask your class how many grooves there are on a typical record. (Remember them?) [The answer is one!]

DVDs are treated in the chapter. Interestingly, DVD and CD technology was preceded by digital audio players beginning in 1979 with the famed Sony Walkman audio cassette player. Portable music went digital in the 1980s. Technology continually changed the means of getting music from musicians to consumers. The music industry's salvation today, if any, may come from paid access to songs streaming from the Internet. (My classroom videos also are now streamed by Arbor Scientific!) The technology moves so fast, and to us who have been around for awhile, the fact that CDs are now history, is astounding!

Answers and Solutions **for Chapter 21**

Reading Check Questions

1. Music is composed of periodic notes; noise is irregular.
2. The three characteristics are pitch, loudness, and quality.
3. High-pitched notes have high frequencies.
4. The highest pitch decreases with age.
5. A decibel is a measure of sound intensity.
6. Zero decibels corresponds to the lowest-intensity of sound we can hear.
7. A sound of 30 dB is 1000 times more intense than the threshold of hearing.
8. Loudness is more subjective.
9. The loudest sounds we can tolerate have intensities a trillion times greater than the faintest sounds.
10. The fundamental frequency is the lowest pitch of a note.
11. The frequency of the second harmonic is twice, or 400 Hz.
12. The frequency of the third harmonic is three times, or 600 Hz.
13. Musical quality is determined by the variety of partial tones.
14. The different sounds are the result of different partial tones.
15. The three classes are vibrating strings, vibrating air columns, and percussion.
16. Stringed instruments have lower efficiency at producing sound so must be more numerous to balance fewer and louder wind instruments.
17. Fourier discovered that complex waves can be disassembled into simple sine waves that add together.
18. The purpose of the extended range is to better approximate the original sound.
19. Phonographs captured sound by analog, CDs by digital.
20. Blue light is of a higher frequency and shorter wavelength, which means more information can fit in the same-sized space, which means higher resolution.

Think and Do

21. First find a clock that ticks!

22. And what is your range if you should be a singer?

23. This activity can be interesting!

Think and Solve

24. For the highest frequencies, $\lambda = v/f$ = (340 m/s)/(20,000 Hz) = 0.017 m or 17 mm. For the lowest frequencies, $\lambda = v/f$ = (340 m/s)/(20 Hz) = 17 m.

25. Period = $1/f$ = 1/440 second (0.0023 s, or 2.3 ms).

26. Period = $1/f$ = 1/264 second (0.0038 s, or 3.8 ms).

27. The decibel scale is based upon powers of 10. The ear responds to sound intensity in logarithmic fashion. Each time the intensity of sound is made 10 times larger, the intensity level in decibels increases by 10 units. So a sound of
    (a) 10 dB is ten times more intense than the threshold of hearing.
    (b) 30 dB is one thousand times more intense than the threshold of hearing.
    (c) 60 dB is one million times more intense than the threshold of hearing.

28. Sound at 40 dB is 10 thousand times more intense (each *additive* increment of 10 dB corresponds to a *factor* 10 in intensity).

29. A sound of 40 dB is ten times as intense as a sound of 30 dB.

30. One octave above 1000 Hz is 2000 Hz, and two octaves above 1000 Hz is 4000 Hz. One octave below 1000 Hz is 500 Hz, and two octaves below 1000 Hz is 250 Hz.

31. The second harmonic is the first octave (twice the fundamental frequency) and the fourth harmonic is the second octave (four times the fundamental frequency), so there is one harmonic, the third, between the first and second octaves. The third octave, with a frequency eight times the frequency of the fundamental, is the same as the eighth harmonic, so there are three harmonics (the fifth, sixth, and seventh) between the second and third octaves. (You can also get the answers by thinking about

wavelengths. The second harmonic has half the wavelength of the fundamental, the third harmonic has one-third the wavelength, the fifth harmonic has one-fifth the wavelength, and so on. The wavelengths of the octaves are one-half, one-fourth, one-eighth, and so on, so they correspond to the second, fourth, eighth, and so on harmonics.)

Think and Rank

32. a. C, B, A
    b. C, B, A
    c. A, B, C

33. A, C, B

Think and Explain

34. Agree, for pitch is the subjective form of frequency.

35. Higher pitch means higher frequency.

36. Agree.

37. The strings warm up and expand during play. Hence they should be tuned while warm so re-tuning is minimized while on stage.

38. Amplitude likely increases.

39. A low pitch will be produced when a guitar string is (a) lengthened, (b) loosened so that tension is reduced, and (c) made more massive, usually by windings of wire around the string. That's why bass strings are thick—more inertia.

40. Pitch depends on frequency. It does not depend on loudness or quality.

41. The frequencies of the sound and the oscillating string are the same.

42. Different strings have different mass and different tension. For a single string, a finger can change the length of vibrating part.

43. If the wavelength of a vibrating string is reduced, such as by pressing it with your finger against a fret, the frequency of the vibration increases. This is heard as an increased pitch.

44. The wavelength is the length of two loops, 60 cm.

45. The longer tines have greater rotational inertia, which means they'll be more resistant to vibrating, and will do so at lower frequency.

46. The greater mass increases the inertia of the string, which decreases the frequency at which it will vibrate.

47. The thinner string has less mass and less inertia, and therefore a higher frequency.

48. The sounding board of the guitar presents more area of vibration, which produces louder sound. With no sounding board on the work bench, the sound is not as loud.

49. A plucked guitar string would vibrate for a longer time without a sounding board because less air is set into motion per unit of time, which means the energy of the vibrating string decreases more slowly.

50. The fundamental for a string occurs when only two nodes exist; one at each end of the string, so that it vibrates in one segment. By touching the midpoint, a third node is imposed there and the string vibrates in two segments. The wavelength is diminished by one-half, so the frequency increases by two. (Note the speed of the wave along the string doesn't change; speed = frequency x wavelength.)

51. In addition to pieces of paper at the supporting ends of the string, when a string vibrates in two segments a piece may be placed at the node in its center. For three segments, two pieces can be supported, each one third the total distance from each end.

52. Both produce different quality sounds because of different intensity overtones.

53. The amplitude in a sound wave corresponds to the overpressure of the compression or equivalently the underpressure of the rarefaction.

54. The pattern shown to the left has the higher frequency and therefore the higher pitch.

55. The pattern on the right has the greater amplitude and is therefore louder.

56. The lower pitch is produced by longer standing waves set up in longer straws. Likewise for the long larger pipes behind Tom. Lower pitches for both.

57. Sound intensity is a purely objective and physical attribute of a sound wave and can be measured by various acoustical instruments. Loudness, though closely related, is a physiological sensation, and can vary from person to person or for one person at different times.

58. The person with the more acute hearing is the one who can hear the faintest sounds—the one who can hear 5 dB.

59. An electronic organ produces the sounds of various musical instruments by duplicating and superimposing the sine waves that make up the overall waves produced by these instruments.

60. Helium, nitrogen, and oxygen molecules molecules at the same temperature have the same kinetic energies. Kinetic energy equals ½ mv^2. Helium, with its smaller mass is compensated for by a greater speed (Chapter 17).

61. Your voice sounds fuller in a shower principally because of the small enclosure that causes your voice to reverberate as it reflects from wall to wall.

62. The limited range of frequencies transmitted by a telephone can't match the full range in music. Especially, it cuts off the higher-frequency overtones of music that contribute to its quality.

63. The range of human hearing, from about 20 Hz to about 20,000 Hz, is a factor of about 1000. This is ten octaves because ten doublings of frequency gives a factor of approximately 1000 (1024 to be exact). The range of a piano is a little more than seven octaves.

64. The second harmonic has twice the frequency, 524 Hz.
65. Frequency of second harmonic is twice the fundamental, or 440 Hz. The third is three times the harmonic, or 660 Hz.

66. The first harmonic is the fundamental, which is the same 440 Hz. The second harmonic is twice this, 880 Hz. The third harmonic is three times the first, 3 times 440 = 1320 Hz.

67. Not including endpoints, there are 5 nodes in a standing wave three-wavelengths long, and 7 nodes in a standing wave four-wavelengths long. (Make a drawing and count them!)

68. Although the speed of sound past a listener on a windy day will change, the wavelength also correspondingly changes, resulting in no change in frequency or pitch. Look at it this way: Suppose a friend is placing bottles on a conveyor belt, say at a "frequency" of one each second. Then you, at the other end of the belt, take off one bottle each second. Now suppose your friend increases the speed of the belt, but still places one bottle on each second. Can you see that the bottles (farther apart now) will still arrive to you at the rate of one per second?

69. A Fourier analyzer is a device that sorts out the individual sine waves from a mixture of two or more sine waves, which is just what the human ear does. You hear the pure tones that make up a complex tone.

70. Blue light is higher-frequency light, with shorter waves that allow closer spacing of the pits.

71. Open-ended.

Think and Discuss

72. The sound of commercials is concentrated at frequencies to which the ear is most sensitive. Whereas the overall sound meets regulations, our ears perceive the sound as distinctly louder.

73. The length of a flute is crucial to the notes it plays. Expansion or contraction of the flute with temperature can change its pitch, and therefore change the tuning between the instruments.

74. Agree, for your friend is correct.

75. When the piano string is struck it will oscillate not only in its fundamental mode of 220 Hz when tuned, but also in its second harmonic at 440 Hz. If the string is out of tune, this second harmonic will beat against the 440 Hz tuning fork. You tune the string by listening for those beats and then either tightening or loosening the string until the beating disappears.

76. By controlling how hard he blows and how he holds his mouth, the bugler can stimulate different harmonics. The notes you hear from a bugle are actually harmonics; you don't hear the fundamental.

77. We each perceive what we have been taught or have learned to perceive. This applies to our appreciation of art, our taste for food, and drink, and to the value we give to that which we smell, and to the textures we touch. Our perception of what is real in terms of religious beliefs, political beliefs, and our notions about where we fit in the scheme of things, is a product of what we have learned (or have not learned).

78. The likelihood is high that you subject yourself to louder sounds than your grandparents experienced—particularly via earphones.

22 Electrostatics

The Part Five opening photo is my granddaughter Megan Abrams, daughter of Leslie and Bob Abrams.

Photo openers for the chapter begin with physicist Jim Stith operating a Wimhurst generator that the rest of us would love to have for our electrostatic demos. Photos 3 and 4 are classroom shots at a laboratory school on the outskirts of Istanbul, Turkey. Teacher Z. Tugba Kahyaoglu is a friend of mine and my wife Lillian.

If Benjamin Frankin weren't born, the United States as we know it, wouldn't be. So it is pleasing to open this chapter with a profile of this great man.

The study of electricity begins with electrostatics. The material in this chapter should be supported with lecture demonstrations, such as the electrophorus (a metal plate charged by induction that rests on a sheet of Plexiglas which has been charged with cat's fur, or equivalently, a pizza pan that rests on a charged phonograph record), the Wimshurst generator (nice if as impressive as the one Jim Stith plays with), and the Van de Graaff generator (that Tugba playfully uses in her class).

Electric shielding and the zero E field inside metals is briefly treated in the chapter, but not explained. Instead, reference is made to the similar case of the zero *G* field inside a hollow spherical shell back on page 172, Figure 9.25. You may want to expand this idea in lecture.

You may note also, as Paul Doherty pointed out to me, that different colored balloons acquire different amounts of charge, likely due to the different effects of dyes in the rubber.

Bill Blunk gives a bit of good advice for charging hair with the Van de Graaff generator. Charge yourself and then hold a metal object with sharp points near the head of the person whose hair is to stand on end. You charge the person's head, and when she takes your place at the generator, the charge she already has makes for a more pronounced display of standing hair.

Web info tells us that meteorologists estimate that, at any given moment, some 1,800 thunderstorms are in progress over Earth's surface, with some 18 million a year around the world. Approximately 100,000 to 125,000 thunderstorms occur in the United States each year. Of that total anywhere from 10 to 20 percent may be severe.

Arbor Scientific supplies van de Graaff generators, a spiffy one (P6-3300), and a hand-cranked economy one (P6-3400). There's a small one that produces up to 200 kV (P6-3200).

Beware: The danger from car batteries is not so much electrocution, as it is explosion. If you touch both terminals with a metal wrench, for instance, you can create a spark that can ignite hydrogen gas in the battery and send pieces of battery and acid flying. It is also good practice to electrically discharge yourself before pumping gasoline at a service station.

Superconducting wire is expected to play a major role in wind turbines, particularly those at sea where maintenance is expensive.

This chapter is prerequisite to the following chapters in Part 5.

Practicing Physics Book:
• Static Charge
• Electric Potential

Problem Solving Book:
Good electrostatic problems

Laboratory Manual:
• A Force to be Reckoned *Introduction to Electrostatic Force* (Activity)
• Electroscopia *Conduction, Induction, Conductors, and Insulators* (Experiment)
• Charging Ahead *The Van de Graaff Generator* (Demonstration)
• Electric Field Hockey *Field Manipulation Challenge Simulation* (Tech Lab)
• Greased Lightning *Carpet Shock Puzzle Simulation* (Tech Lab)

Next-Time Questions:
• Alpha Particle and Electron •Battery and Balloon • Polarized Water Stream • Electron Gravity
• Van de Graaff Generator •Shocking Tale

Hewitt-Drew-It Screencasts: •*Electricity* •*Coulomb's Law* •*Electric Fields* •*Electric Potential*

The order of topics in the lecture sequence below departs somewhat from the order of topics in the chapter. The ideas of each demo flow nicely to the next. Have your lecture table set up with rods, pith ball, and charging demos at one end of the table, then an electrophorus, then a Wimshurst or whatever electrostatic generating machine, and finally the Van de Graaff generator. Then your lecture begins at one end of the table and proceeds in order to the opposite end.

SUGGESTED LECTURE PRESENTATION

Electrical forces: Begin by comparing the strength of the electric force to gravitational force—billions of billions of times stronger. Acknowledge the fundamental rule of electricity: that *like charges repel and unlike charges attract*. Why? Nobody knows. Hence we say it is fundamental.

Electric Charges: Electrical effects have to do with electric charges, minus for the electron and plus for the proton. Discuss the near balance that exists in common materials, and the slight imbalance when electrons transfer from one material to another. Different materials have different affinities for electrons, which explains why charge transfers from fur to rubber when rubbed. It also explains why it's painful for people with silver fillings in their teeth to chew aluminum spitballs. Silver has more affinity for acquiring electrons than aluminum. The mildly acidic saliva in your mouth facilitates a flow of electrons, which when transmitted to the nerves of your teeth produce that familiar unpleasant sensation. Discuss **charging**.

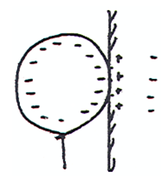
> DEMONSTRATION: Bring out the cat's fur, rubber and glass rods, and suspended pith balls. An alternative to the pith ball is a copper-painted Ping-Pong ball. Explain the transfer of electrons

when you rub fur against rubber rod (and silk against glass). Explain what it means to say an object is electrically charged, and discuss the **conservation of charge**.

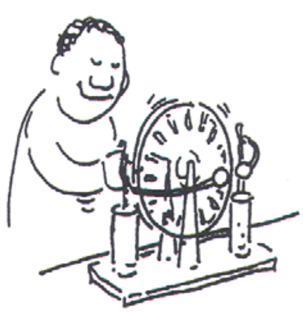
Rubbing a rubber rod on cat's fur or a glass rod on silk illustrates charging by friction, but charge separation can occur without friction, by the simple contact between dissimilar insulating materials. In this case charge simply peels from one material to another, like dust is peeled from a surface when a piece of sticky tape is peeled from it.

DEMONSTRATION: Show the effects of electrical force and **charge by induction** by holding a charged rod near the ends of a more-than-a-meter-long wooden 2 × 4, that balances and easily rotates sideways at its midpoint on a protrusion such as the bottom of a metal spoon. You can easily set the massive piece of wood in motion. This is quite impressive!

DEMONSTRATION: Rub a balloon on your hair and show how it sticks to the wall. Draw a sketch on the board (Figure 22.14) and show by induction how the attracting charges are slightly closer than the repelling charges. Closeness wins and it sticks!



DEMONSTRATION: Charge the electrophorus, place the insulated metal disk on top of it, and show that the disk is not charged when removed and brought near a charged pith ball. Why should it be, for the insulating surface of the electrophorus has more grab on the electrons than the metal plate. But rest the plate on the electrophorus again and touch the top of the plate. You're grounding it (producing a conducting path to ground for the repelling electrons). Bring the plate near the pith ball and show that it is charged. Then show this by the flash of light produced when the charged metal plate is touched to the end of a gas discharge tube—or a fluorescent lamp. Engage neighbor discussion of the process demonstrated. Only after this is generally understood, proceed to the next demo.

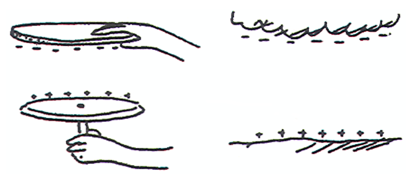


DEMONSTRATION: Move up the lecture table to the Wimshurst generator, explaining its similarity to the electrophorus (actually a rotating electrophorus). You'll be lucky if you have access to a fine one as shown by Jim Stith in the photograph that opens this chapter. Show sparks jumping between the spheres of the machine and so forth, and discuss the sizes (radii of curvature) of the spheres in terms of their capacity for storing charge. [The amount of charge that can be stored before discharge into the air is directly proportional to the radius of the sphere.] Fasten a metal point, which has a tiny radius of curvature and hence a tiny charge storing capacity, to one of the Wimshurst spheres and demonstrate the leakage of charge.

If you wish to expand upon charge leakage from a point, you might simplify it this way: On the surface of an electrically charged flat metal plate, every charge is mutually repelled by every other charge. If the surface is curved, charges on one part of the plate will not interact with charges on some distant part of the plate because of the **shielding** effect of the metal—they are "out of the line of sight" of each other. Hence for the same amount of work or potential, a greater number of charges may be placed on a curved surface than on a flat surface. The more pronounced the curvature, the more shielding and the more charge may be stored there. To carry this idea further, consider a charged needle. Under mutual repulsion, charges gather to the region of greatest curvature, the point. Although all parts of the needle are charged to the same electric potential, the charge density is greatest at the point. The **electric field** intensity about the needle, on

the other hand, is greatest about the point, usually great enough to ionize the surrounding air and provide a conducting path from the charge concentration. Hence charge readily gathers at points and readily leaks from points. DEMONSTRATE this leakage and the reaction force (ion propulsion) with a set of metal points arranged to rotate when charged. This is the “ion propulsion” that science fiction buffs talk about in space travel. Interestingly enough, this leaking of charge from points causes static with radio antennas; hence the small metal ball atop automobile antennas.

Discuss **lightning rods** and show how the bottoms of negatively charged clouds and the resulting induced positive charge on the surface of the Earth below are similar to the electrophorus held upside down; where the charged Plexiglas plate is analogous to the clouds and the metal plate is analogous to the Earth. After sketching the charged clouds and Earth on the chalkboard, be sure to hold the inverted electrophorus pieces against your drawing on the board in their respective places. Discuss the lightning rod as a preventer of lightning while showing the similar function of the metal point attached to the Wimshurst generator. [Notice that one idea is related to the next in this sequence—very important, as the ideas of electricity are usually difficult to grasp the first time through. So be sure to take care in moving through this sequence of demonstrations and their explanations.]



Benjamin Franklin’s kite, by the way, was not struck by lightning. If it had, he would likely have not been around to report his experience. Franklin showed that the kite collected charges from the air during a thunderstorm. Hairs on the kite string stood apart, implying that lightning was a huge electric spark.

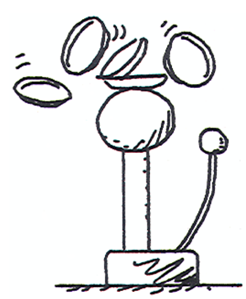
Storage of electric charge is accomplished with a **capacitor**. My dear Egyptian friend Mona El Tawil Nassar (my adopted sister) sets parallel plates in Figure 22.27.

> DEMONSTRATION: Show one of the most impressive capacitors, the Leyden Jar, and a sparking demonstration.

After establishing the idea that charge capacity depends on the size and curvature of the conductor being charged, advance to what your students have been waiting for: The Van de Graaff generator (invented by the way, by Robert Generator—this quip was with his permission! In previous editions my editors allowed this humor in the text itself, with a qualifying footnote)☺.

> DEMONSTRATION: When showing the long sparks that jump from the dome of the generator to the smaller grounded sphere, do as Bruce Bernard suggests and hold a lightning rod (any sharp pointed conductor) in the vicinity of the dome and the sparking will stop. Bring the lightning rod farther away and the frequency of sparking will resume.

> DEMONSTRATION: Set a cup of puffed rice or puffed wheat on top of the Van de Graaff generator. Your students will like the fountain that follows when you charge it. Or do as Marshall Ellenstein does and place a stack of aluminum pie plates on the dome and watch them one by one levitate and fly away. Or as Tugba does with aluminum foil as shown in the photo openers to this chapter. Then snuff out a match by holding it near the charged dome. Introduce (or reintroduce) the idea of the **electric field** at this time, the aura of energy that surrounds all charged things. Compare electric and gravitational fields.



Fields are called “force fields” because forces are exerted on bodies in their vicinity, but a better term would be “energy field,” because energy is stored in a field. In the case of an electric field, any charges in the vicinity are energized. We speak about the potential energy that electrically charged bodies have in a

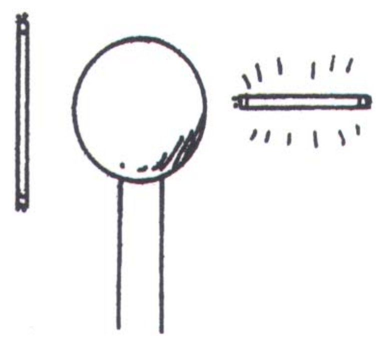
field—or more often, the potential energy compared to the amount of charge—**electric potential**. Explain that the field energy, and correspondingly the electric potential, is greatest nearest the charged dome and weaker with increased distance (**inverse-square law**).

DEMONSTRATION: Hold a fluorescent lamp tube in the field to show that it lights up when one end of the tube is closer to the dome than the other end. Relate this to potential difference, and show that when both ends of the fluorescent tube are equidistant from the charged dome, light emission ceases. (This can be affected when your hand is a bit closer to the dome than the far end of the tube, so current does not flow through the tube when the dome discharges through you to the ground. There is no potential difference across the tube and therefore no illuminating current, which sets the groundwork for your next lecture on electric current.)

My wife Lil grew her hair long for the photo of Figure 22.29. After the shot was deemed successful, she then had her hair cut to her preferred shorter length. Hey, she, like me, wraps her life around physics!

The Van de Graaff generator nicely illustrates the difference between **electric potential energy** and **electric potential**: Although it is normally charged to thousands of volts, the amount of charge is relatively small so the electric potential energy is relatively small. That's why you're normally not harmed when it discharges through your body. Very little energy flows through you. In contrast, you wouldn't intentionally become the short-circuit for household 110 volts because although the voltage is much lower, the transfer of energy is appreciable. Less energy per charge, but many many more charges!

NEXT-TIME QUESTION: Why does current flow when one end of the fluorescent tube is held closer to the charged Van de Graaff generator, but not when both ends are equidistant? [The simplified answer you're looking for at this point is that the close end is in a stronger part of the field than the far end. More energy per charge means more voltage at the near end. With a voltage difference across the tube, you get a current. When both ends are equidistant, there is no voltage difference across the tube, and no current. This leads into the next chapter. Strictly speaking, the current path is more than simply between the ends of the tube; it goes through you also and the ground where it returns to the generator.]



Answers and Solutions for Chapter 22

Reading Check Questions

1. Electrostatics is the term for electricity at rest.
2. Electrical forces cancel out, leaving weaker gravity predominant.
3. The nucleus and its protons are positively charged; electrons are negatively charged.
4. The charge of one electron is identical to the charge on all electrons, and is equal and opposite for protons.
5. The normal net charge is zero.
6. A positive ion is an atom with one or more fewer electrons than protons. A negative ion is an atom with one or more extra electrons.
7. Conservation of charge means charge cannot be created or destroyed, but merely transferred.
8. Quantized means that there is a smallest possible amount of charge of which all other amounts of charge are multiples.
9. One quantum unit of charge is that of an electron (or proton).
10. A coulomb is much larger than the charge of an electron; one coulomb is the charge of 6.25×10^{19} electrons!
11. Both laws are inverse-square laws. How they differ is mainly that gravitation is only attractive, whereas electrical forces can repel.
12. Atoms of metals are good conductors because of their free outer electrons
13. Atoms of insulators are poor conductors because of their strong hold on their electrons.
14. A semiconductor can be made to conduct or insulate.
15. A transistor is composed of thin layers of semiconducting materials. Functions include controlling the flow of electrons, amplifying signals, and acting as switches.
16. Flow in a superconductor is without electrical resistance.
17. Electrons are transferred from one place to another.
18. Sliding across plastic seating is charging by contact and by friction.
19. Charging by induction occurs during thunderstorms.
20. The primary purpose of the lightning rod is to prevent a lightning stroke.
21. A polarized object may have no net charge, whereas a charged object does.
22. An electric dipole is an object electrically polarized in its normal state.
23. An electric dipole is H_2O.
24. Gravitational and electric. (Magnetic fields also, that we'll learn about in Chapter 24.)
25. The direction of an electric field is the direction of force on a positive charge.
26. At the center of a charged spherical conductor all field components cancel out.
27. The electric field inside a conductor cancels to zero.
28. Each coulomb is given 1.5 joules of energy.
29. No. Several thousand volts is different than the *ratio* several thousand volts per coulomb. Voltage is measured in volts; voltage/coulomb is energy and measured in joules. Several thousand joules per coulomb isn't much energy if you have a tiny fraction of a coulomb.
30. The energy in a capacitor is stored in its electric field.

Think and Do

31. In dry climates this is a common nuisance!

32. Tell Grandpa that when inside any metal surface the electric field remains zero.

33. The stream is indeed deflected, due to the polarity of water molecules.

Plug and Chug

34. $F = k\dfrac{q_1q_2}{d^2} = 9.0 \times 10^9\ \text{N·m}^2/\text{C}^2\ \dfrac{(0.1\ \text{C})(0.1\ \text{C})}{(0.1\ \text{m})^2} = 9 \times 10^9\ \text{N}.$

35. $F = k\dfrac{q_1q_2}{d^2} = 9.0 \times 10^9\ \text{N·m}^2/\text{C}^2\ \dfrac{(0.1\ \text{C})(0.1\ \text{C})}{(0.2\ \text{m})^2} = 2.25 \times 10^9\ \text{N}.$

Think and Solve

36. By the inverse-square law, twice as far is 1/4 the force; **5 N**.
    The solution involves relative distance only, so the magnitude of charges is irrelevant.

37. From Coulomb's law, the force is given by $F = \frac{kq^2}{d^2}$, so the square of the charge is

$q^2 = \frac{Fd^2}{k} = \frac{(20\text{ N})(0.06\text{ m})^2}{9 \times 10^9\text{ N m}^2/\text{C}^2} = 8.0 \times 10^{-12}\text{ C}^2$. Taking the square root of this gives $q = 2.8 \times 10^{-6}$ C, or 2.8 microcoulombs.

38. From Coulomb's law, $F = k\frac{q_1q_2}{d^2} = (9 \times 10^9)\frac{(1.0 \times 10^{-6})^2}{(0.03)^2} = 10$ N. This is the same as the weight of a 1-kg mass.

39. $F_{grav} = mg = (9.1 \times 10^{-31}\text{kg})(9.8\text{ m/s}^2) = 8.9 \times 10^{-30}$ N. $F_{elec} = qE = (1.6 \times 10^{-19}\text{ C})(10{,}000\text{ V/m}) = 1.6 \times 10^{-15}$ N, more than 10^{14} times larger than the gravitational force!

40. $F_{grav} = Gm_1m_2/d^2 = (6.67 \times 10^{-11})\frac{(9.1 \times 10^{-31})(1.67 \times 10^{-27})}{(1.0 \times 10^{-10})^2} = 1.0 \times 10^{-47}$ N.

$F_{elec} = kq_1q_2/d^2 = (9 \times 10^9)\frac{(1.6 \times 10^{-19})^2}{(1.0 \times 10^{-10})^2} = 2.3 \times 10^{-8}$ N.

The electrical force between an electron and a proton is more than 1,000,000,000,000,000,000,000,000,000,000,000,000,000 times greater than the gravitational force between them! (Note that this ratio of forces is the same for any separation of the particles.)

41. Electric field is force divided by charge: $E = \frac{F}{q} = \frac{3.2 \times 10^{-4}\text{N}}{1.6 \times 10^{-10}\text{C}} = 2 \times 10^6$ N/C. (The unit N/C is the same as the unit V/m, so the field can be expressed as 2 million volts per meter.)

42. Energy is charge × potential: PE = qV = (2 C)(100 × 10^6 V) = 2 × 10^8 J.

43. Potential is defined as energy per unit charge, so V = PE/q = (0.1 J)/(1.0 × 10^{-6} C) = 1 × 10^5 V or 100,000 V.

44. (a) $\Delta V = \frac{\text{energy}}{\text{charge}} = \frac{12\text{ J}}{0.0001\text{ C}}$ = 120,000 volts.

(b) ΔV for twice the charge is $\frac{24\text{ J}}{0.0002}$ = same 120 kV.

45.(a) From $E = \frac{F}{q}$ we see that $q = \frac{F}{E} = \frac{mg}{E} = \frac{(1.1 \times 10^{-14})(9.8)}{1.68 \times 10^5} =$ 6.4×10^{-19} C.

(b) Number of electrons = $\frac{6.4 \times 10^{-19}\text{C}}{1.6 \times 10^{-19}\text{C/electron}}$ = 4 electrons.

Think and Rank

46. A, C, B

47. C, B, A

Think and Explain

48. Something is electrically charged when it has an excess or deficiency of electrons, compared with the number of protons in the atomic nuclei of the material.

49. Electrons are loosely bound on the outside of atoms, whereas protons are very tightly bound within the atomic nuclei.

50. The objects aren't charged because of their equal number of protons.

51. Clothes become charged when electrons from a garment of one material are rubbed onto another material. If the materials were good conductors, discharge between materials would soon occur. But

the clothes are nonconducting and the charge remains long enough for oppositely charged garments to be electrically attracted and stick to one another.

52. When wiped the DVD becomes charged, which polarizes and attracts dust particles.

53. Excess electrons rubbed from your hair leave it with a positive charge; excess electrons on the comb give it a negative charge.

54. The wires at toll-collecting stations are used to discharge the cars so that paying the toll is not a shocking experience for the driver or the collector.

55. In the previous century, before truck tires were made electrically conducting, chains or wires were commonly dragged along the road surface from the bodies of trucks. Their purpose was to discharge any charge that would otherwise build up because of friction with the air and the road. Today's electrically-conducting tires prevent the buildup of static charge that could produce a spark—especially dangerous for trucks carrying flammable cargoes.

56. The leaves, like the rest of the electroscope, acquire charge from the charged object and repel each other because they both have the same sign of charge. The weight of the conducting metal foil is so small that even tiny forces are clearly evident.

57. Cosmic rays produce ions in air, which offer a conducting path for the discharge of charged objects. Cosmic-ray particles streaming downward through the atmosphere are attenuated by radioactive decay and by absorption, so the radiation and the ionization are stronger at high altitude than at low altitude. Charged objects more quickly lose their charge at higher altitudes.

58. The charged body need not touch the ball of an electroscope. If a negative charge is simply brought near, some electrons in the ball are repelled and driven to the gold leaves, leaving the ball positively charged. Or if a positive charge is brought near the ball, some electrons will be attracted and move up to the ball to make it negative and leave the leaves positively charged. This is charge separation due to *induction*. (If by small chance you are attempting an answer to this question without having witnessed this, pity, pity, pity! Better that your time is spent studying the physics of familiar things.)

59. The crystal as a whole has a zero net charge, so any negative charge in one part is countered with as much positive charge in another part. So the net charge of the negative electrons has the same magnitude as the net charge of the ions. (This balancing of positive and negative charges within the crystal is almost, but not precisely, perfect because the crystal can gain or lose a few extra electrons.)

60. By induction: Bring the positively charged object near the object to be charged and the far side of the uncharged object will become positively charged. If you then touch the far side, you will in effect remove this charge because electrons will flow from your body to the positive charge. Remove your finger and the object then has a negative charge. (Interestingly enough, touching any side will produce the same result.)

61. Electrons are easily dislodged from the outer regions of atoms, but protons are held tightly within the nucleus.

62. It says that force decreases with the square of increasing distance, or increases as the square of decreasing distance.

63. The electrons don't fly out of the penny because they are attracted to the fifty thousand billion billion positively charged protons in the atomic nuclei of atoms in the penny.

64. By the inverse-square law, the force increases. It will be four times as great when at half the distance, and nine times as great when at one-third the distance.

65. The inverse-square law is at play here. At half the distance the electric force field is four times as strong; at 1/4 the distance, 16 times stronger. At four times the distance, one-sixteenth as strong.

66. Doubling the distance reduces the force to 1/4, whatever the sign of charge. This is in accord with Coulomb's law.

67. Doubling one charge doubles the force. The magnitude of the force does not depend on the sign of charge.

68. Doubling both charges quadruples the force. The magnitude of the force does not depend on the sign of charge.

69. The huge value of the constant *k* for electrical force indicates a relatively huge force between charges, compared with the small gravitational force between masses and the small value of the gravitational constant *G*.

70. Where lines are closer, the field is stronger.

71. By convention, the direction goes from positive to negative as the arrows indicate.

72. At twice the distance the field strength will be 1/4, in accord with the inverse-square law.

73. Electrical resistance disappears.

74. Planet Earth is negatively charged. If it were positive, the field would point outward.

75. They're taller to be closer to the clouds, closer to lightning.

76. The metal spikes penetrating into the ground reduce electrical resistance between the golfer and the ground, providing an effective electrical path from cloud to ground. Not a good idea!

77. A neutral atom in an electric field is electrically distorted (see Figure 22.11). If the field is strong enough, the distortion results in ionization, where the charges are torn from each other. The ions then provide a conducting path for an electric current.

78. The mechanism of sticking is charge induction. If it's a metal door, the charged balloon will induce an opposite charge on the door. It will accomplish this by attracting opposite charges to it and repelling like charges to parts of the door farther away. The balloon and the oppositely-charged part of the door are attracted and the balloon sticks. If the door is an insulator, the balloon induces polarization of the molecules in the door material. Oppositely-charged sides of the molecules in the surface of the door face the balloon and attraction results. So whether you consider the door to be an insulator or a conductor, the balloon sticks by induction.

79. The paint particles in the mist are polarized and are therefore attracted to the charged chassis.

80. An ion polarizes a nearby neutral atom, so that the part of the atom nearer to the ion acquires a charge opposite to the charge of the ion, and the part of the atom farther from the ion acquires a charge of the same sign as the ion. The side of the atom closer to the ion is then attracted more strongly to the ion than the farther side is repelled, making for a net attraction. (By Newton's third law, the ion, in turn, is attracted to the atom.)

81. The forces on the electron and proton will be equal in magnitude, but opposite in direction.

82. Because of the greater mass of the proton, its acceleration will be less than that of the electron, and be in the direction of the electric field. How much less? Since the mass of the proton is nearly 2000 times that of the electron, its acceleration will be about 1/2000 that of the electron. The greater acceleration of the electron will be in the direction opposite to the electric field.

83. The electron and proton accelerate in opposite directions.

84. The field is zero because the forces midway between the two test charges cancel to zero.

85. The electron will have the greater speed on impact. The force on both will be the same, the distance is the same, so work done by the field is the same and KE of the particles is the same. But for the same KE, the particle with the smaller mass, the electron, has the greater speed.

86. By convention only, the direction of an electric field at any point is the direction of the force acting on a positive test charge placed at that point. A positive charge placed in the vicinity of a proton is pushed away from the proton, hence, the direction of the electric field vector is away from the proton.

87. The bits of thread become polarized in the electric field, one end positive and the other negative, and become the electric counterparts of the north and south poles of the magnetic compass. Opposite forces on the end of the fibers (or compass needle) produce torques that orient the fibers along the field direction (look ahead to Figure 24.3 in the next chapter).

88. Charge will be more concentrated on the corners. (See Figure 22.21.)

89. Its change is 10 volts (10 joules per coulomb is 10 volts).

90. When released, its 10 joules of potential energy will become 10 joules of kinetic energy as it passes its starting position.

91. Voltage = (0.5 J)/0.0001 C = 5000 V.

92. In a thunder storm the metal affords a field-free region (called a Faraday cage). Charges on the surface of the metal arrange themselves such that the field in the interior cancels to zero.

93. The charges are of equal magnitude because the charge taken from one plate is given to the other. That's why the net charge of a capacitor is always zero.

94. Increase the area of the plates and you'll increase energy storage. (You can also increase energy storage by bringing the plates closer together, but not touching. Or you can insert a nonconducting material, called a *dielectric*, between the plates.)

95. It is dangerous because the capacitor may be still be charged.

96. 1 Mev is 1 million ev (10^6 eV); 1 Gev is 1 billion eV (10^9 eV), so a GeV is 1000 times larger than a MeV.

97. Zero, whether or not charge is on the outside.

98. No, nor inside any statically charged conducting body. Mutually repelling charges on the surface cancel the electric field inside the body to zero—true for solids as well as hollow conductors. (If the electric field were not zero, then conduction electrons would move in response to the field until electrical equilibrium was established—which is a zero electric field.)

99. Agree with your friend. The hairs act like leaves in an electroscope. If your arms were as light, they'd stand out too.

Think and Discuss

100. When the wool and plastic rub against each other, electrons are rubbed from the plastic onto the wool. The deficiency of electrons on the plastic bag results in its positive charge.

101. The charged wrap nicely polarizes nonconducting plastic rather than metal, resulting in better sticking on plastic than on metal.

102. When an object acquires a positive charge, it loses electrons and its mass decreases. How much? By an amount equal to the mass of the electrons that have left. When an object acquires a negative charge, it gains electrons, and the mass of the electrons as well. (The masses involved are incredibly tiny compared to the masses of the objects. For a balloon rubbed against your hair, for example, the extra electrons on the balloon comprise less than a billionth of a billionth of a billionth the mass of the balloon.)

103. The penny will be slightly more massive with a negative charge, for it will have more electrons than when neutral. If it were positively charged, it would be slightly lighter because of missing electrons.

104. For the outer electrons, the attractive force of the nucleus is largely canceled by the repulsive force of the inner electrons, leaving a force on the outer electrons little different from the force on the single electron in a hydrogen atom. For the inner electrons, on the other hand, all of the electrons farther from the nucleus exert no net force (it is similar to the situation within the Earth, where only the Earth below, not the Earth above, exerts a gravitational force on a deeply buried piece of matter). So the inner

electrons feel the full force of the nucleus, and a large amount of energy is required to remove them. Stripping all of the electrons from a heavy atom is especially difficult. Only in recent years have researchers at the University of California, Berkeley succeeded in removing all of the electrons from the atoms of heavy elements like uranium.

105. The law would be written no differently.

106. The tree is likely to be hit because it provides a path of less resistance between the cloud overhead and the ground. The tree and the ground near it are then raised to a high potential relative to the ground farther away. If you stand with your legs far apart, one leg on a higher-potential part of the ground than the other, or if you lie down with a significant potential difference between your head and your feet, you may find yourself a conducting path. That, you want to avoid!

107. The half ring has the greater electric field at its center because the electric field at the center of the whole ring cancels to zero. The electric field at the center of the half ring is due to a multitude of electric vectors, vertical components canceling, with horizontal components adding to produce a resultant field acting horizontally to the right.

108. Yes, in both cases we have a ratio of energy per something. In the case of temperature, the ratio is energy/molecule. In the case of voltage it is energy/charge. Even with a small numerator, the ratio can be large if the denominator is small enough. Such is the case with the small energies involved to produce high-temperature sparklers and high-voltage metal balls.

23 Electric Current

23.1 Flow of Charge and Electric Current
23.2 Voltage Sources
23.3 Electrical Resistance
23.4 Ohm's Law
    Ohm's Law and Electric Shock
23.5 Direct Current and Alternating Current
    Converting ac to dc
23.6 Speed and Source of Electrons in a Circuit
23.7 Electric Power
23.8 Lamps
    Fuel Cells
23.9 Electric Circuits
    Series Circuits
    Parallel Circuits
    Parallel Circuits and Overloading
    Safety Fuses

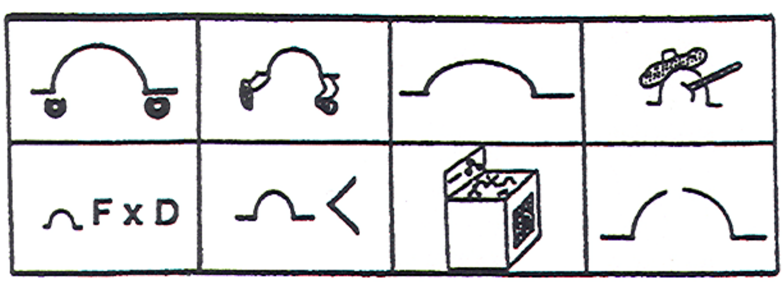
Four dear physics friends are in the photos that open this chapter: New Zealand David Housden, Southern California Juliet Layugan, San Franciscans Will Maynez, and Jill Johnsen.

Georg Simon Ohm provides the personal profile.

This chapter seeks to build a "basic understanding" of current electricity, and to dispel some of the popular misconceptions about electricity. The treatment of series and parallel circuits avoids the calculation of equivalent circuit resistances, multiple emfs, and the like. This chapter may be skipped, as a knowledge of elementary circuits is not needed elsewhere in the text.

The analogy of water pumped in a pipe is useful for understanding electric current in a circuit. When you buy a water pipe in a hardware store, the pipe comes with no water. You supply the water. When you buy an electron pipe (a wire), it comes *with* electrons—quite different than a water pipe.

If you're into puns in your lectures on rainy days, Marshall Ellenstein and coworkers Connie Bownell and Nancy McClure have a few pictorial Ohmwork puns on the symbol for resistance:



Answers in order are: Mobile Ohm; Ohm Run; Ohm Stretch; Ohm Sick; Ohmwork; Ohmless; Ohm on the Range; Broken Ohm.

The problems with power blackouts have more to do with overloading power grids than faulty generators. Triggering of outages often begins with overheated lines on hot days and when loads are high. Lines expand and sag, touching trees that short them out. We're very dependent upon electric power. To smooth the power needs of New York City, banks of lithium-ion batteries, the same kind that power cell phones

but enormously bigger, are charged up at nighttime when demand for power is low, and discharged during the day when power demand is high.

How batteries work is not treated in the chapter. In short: A battery is a collection of cells, each of which balances the charges within its innards by moving positively charged ions from the anode to the cathode through an electrolyte, which can be solid, liquid, or gelatinous. In the electrolyte, ions rather than electrons flow. So ions flow inside the battery and electrons flow in the external circuit. In this chapter we stress that the current in a battery is the same amount of current that powers the circuit. But the chapter overlooks the detail that an ion flowing in the electrolyte is in effect an electron flowing in the opposite direction.

Inside a lithium-ion battery is a graphite anode stuffed with lithium atoms and a cathode made of some lithium-based substance. When operating, the anode's lithium atoms release electrons into the external circuit, where they flow and then reach the electron-thirsty cathode. Flow continues until the anode runs out of lithium. That's where recharging comes in to reverse the process. Voltage applied between the two electrodes moves electrons and ions to the graphite side, which stores energy in the battery.

Volta invented the first battery by trial and error using metal electrodes and wet cardboard. At the time nobody knew about atoms, ions, or electrons. Only a century later did investigators understand how a battery works.

Interestingly but sadly, Andre Ampere was forced to witness the guillotine death of his father during the French Revolution.

Arbor Scientific supplies lots of E&M demos, one of which is a Series/Parallel Bulb Board (P6-1120).

Practicing Physics Book:
• Flow of Charge
• Parallel Circuits
• Ohm's Law
• Circuit Resistance
• Electric Power
• Electric Power in Circuits
• Series Circuits

Problem Solving Book:
An excellent overview of the terms of this chapter is presented in Practice Problem 1. And others also.

Laboratory Manual:
• The Lemon Electric Battery *Basics and a Basic Battery Puzzle* (Activity)
• Ohm, Ohm, on the Range *Connect Meters, Determine Resistance* (Experiment)
• Batteries and Bulbs *Electric Circuits* (Activity)
• An Open and Shut Case *Defective Circuits* (Activity)
• Be the Battery *Powering Circuits by Hand* (Activity)

Next-Time Questions:
• 3-Bulb Circuit
• Circuit Current
• 40- and 100-Watt Bulbs
• Glowing Tube
• Battery Demo
• Clay Resistance
• Power Lines
• Direct Current
• How Can Can Roll
• New Wire Resistance
• Battery Current
• The 3 Rs
• Equivalent Resistance

Hewitt-Drew-It! Screencasts: •*Ohm's Law* •*Voltage Drop* •*Water and Electron Circuits* •*Bulbs in Parallel* •*Electric Power* •*Equivalent Resistance* •*Circuit Resistances* •*Battery Demo* •*Battery Power* •*Circuit Medley*

SUGGESTED LECTURE PRESENTATION

Flow of Charge; Electric Current
Define electric current and relate it to the lighting of the lamp via the Van de Graaff generator at the end of your last lecture. Explain this in terms of current being directly proportional to a difference in voltage. That is, one end of the lamp was in a stronger part of the energy field than the other—more energy per charge on one end than the other—more voltage at one end than the other. Write on the board *Current-voltage difference*. (You're on your way to Ohm's law. Strictly speaking, the voltage term in Ohm's law implies the difference in potential, so voltage difference is redundant. Nevertheless, it underscores a point that may be missed, so go for it.)

Voltage Sources
Relate voltage to the idea of electrical pressure. Emphasize that a *difference* in electric potential must exist—or as above, a voltage difference. Cite how a battery provides this difference in a sustained way compared to suddenly discharging a Van de Graaff generator. Generators at power plants also provide a voltage difference across wires that carry this difference to consumers (more detail is in Chapter 25). Cite examples of voltage differences with birds sitting on bare high-voltage wires, walking unharmed on the third rail of electric-powered train tracks, and the inadvisability of using electric appliances in the bathtub.

Dimmed Headlights
An auto battery, like all batteries, has internal resistance. When charge flows in battery, there is a voltage drop across this resistance, and some heating occurs. This makes the voltage across the terminals drop as the current increases. When the car's starter is activated, considerable current is delivered by the battery, lowering the voltage output of the battery. This is evident in the dimmed headlights.

Discuss the function of the **third prong on electric plugs** (that it provides a ground wire between the appliance and the ground, Figure 23.8). The ground prong is longer than the pair of flat prongs. Why? (So it will be first to be connected when plugging it into a socket, establishing a ground connection slightly before the appliance is electrically connected. This path to ground prevents harm to the user if there is a short circuit in the appliance that would otherwise include the user as a path to ground.)

When a power line falls near you, don't walk from it—hop with both feet together. Why? Because there may be a voltage difference across the ground. If one foot is anchored to a voltage much different than where your other foot is, you could be electrocuted.

Discuss **electric shock** and why electricians put one hand behind their back when probing questionable circuits, which is to prevent a muscular contraction that keeps their hands gripping a wire, and to also prevent a difference in potential across the heart of the body. Discuss how being electrified produces muscle contractions that account for such instances as "not being able to let go" of hot wires, and "being thrown" by electric shock.

Electrical Resistance
Introduce the idea of electrical resistance, and complete Ohm's law. Compare the resistances of various materials, and the resistances of various thickness of wires of the same metal. Call attention to the glass supports on the wires that make up high-voltage power lines; the rubber insulation that separates the pair of wires in a common lamp cord.

Ohm's Law
Complete your chalkboard equation by introducing resistance and you have Ohm's law. Many instructors write Ohm's law in the form, $V = IR$. Ouch! It is conceptually easier to understand as $I = V/R$, just as Newton's second law is more conceptual as $a = F/m$ than $F = ma$.

> DEMONSTRATION: Connect two or three lamps to a battery and relate the current, as viewed by the emitted light, to the voltage of the battery and the resistance of the lamps. (Be sure the lamps are not bright enough to make viewing uncomfortable.) Interchange lamps of low and high resistance, relating this to the brightness of the lamps.

DC and AC
Discuss the differences between dc and ac. Compare the dc current that flows in a circuit powered with a battery to the ac current that flows in a household circuit (powered by a generator). A hydrodynamic analogy for ac is useful: imagine powering a washing-machine agitator with water power. Verbally describe with gestures a pair of clear plastic pipes connected to a paddle wheel at the bottom of the agitator, fashioned so water that sloshes to-and-fro in the pipes causes the agitator to rotate to-and-fro. Suppose the free ends of the plastic pipe are connected to a special socket in the wall. The socket is powered by the power utility. It supplies no water, but consists of a couple of pistons that exert a pumping action, one out and the other in, then vice versa, in rapid alternation. When the ends of the pipe containing water are connected to the pistons, the water in the pipes is made to slosh back-and-forth: Power is delivered to the washing machine. There is an important point to note here: The **source** of flowing substance, water or electrons, is supplied by you. The power company supplies no water, just as the power utilities supply no electrons! The greater the load on the agitator, the more energy the power company must deliver to the action of the alternating pistons. This analogy affords a visual model for household current—especially with the transparent plastic pipes where your students can "see" the sloshing water!

The water analogy also serves to show the function of a **capacitor** in smoothing the conversion of ac to dc, Figure 23.12.

Speed of Electrons in a Circuit
To impart the idea of how dc current travels in a circuit, use the following analogy. Ask the class to suppose that there is a long column of marchers at the front of the room, everyone standing at rest close together. Walk to the end of this imaginary column and give a shove to the "last person." Ask the class to imagine the resulting impulse traveling along the line until the first marcher is jostled against the wall. (Or use the analogy of loosely coupled railroad cars.) Then ask if this is a good analogy for how electricity travels in a wire. The answer is no. Such is a good analogy for how *sound* travels, but not electric current. Cite how slowly the disturbance travels, and how slowly sound travels compared to light or electricity. Again call attention to the column of marchers and walk to the far end and call out, "Forward march!" As soon as the command reaches each individual, each steps forward. The marcher at the beginning of the column, except for the slight time required for the sound to get to her, steps immediately. State that this is an analogy for electric current. Except for the brief time it takes for the electric *field* set up at the power source to travel through the wire, nearly the speed of light, electrons at the far end of the circuit respond immediately. State that the speed at which the command "forward march" travels is altogether different from how fast each marcher moved upon receiving that command—and that the velocity of the electric signal (nearly the speed of light) is very much different than the drift velocity of electrons (typically 0.01 cm/s) in a circuit.

> CHECK QUESTIONS: When you turn on your key to start your car, electrons migrate from the negative battery terminal through the electric network to the starter motor and back to the positive battery terminal. About how long is required for electrons to leave the negative terminal and go through the circuit and back again? Less than a millisecond? Less than a second? About a second or two? Or about a day? (Class interest should be high when you announce the latter answer!)

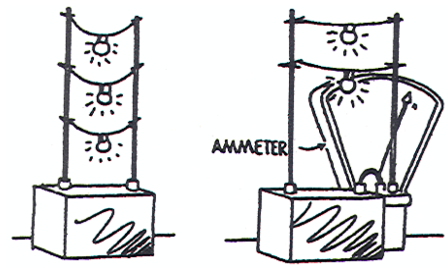
Ask for an estimate of the number of electrons pumped by the local power plant into the homes and industries locally in the past year. Then stress the idea that power plants do not sell electrons—that they sell *energy*. Discuss the origin of electrons in electric current flow.

Electric Power
Distinguish between energy and power. Electric power is usually expressed in kilowatts, and electric energy in kilowatt-hours. It is effective if you use an actual electric bill to make your point. Note that a kilowatt-hour is 1000 joules per second times 3600 seconds or 3600 kJ.

> CHECK QUESTION: Does a 40-W lightbulb *have* 40 watts, or does it use 40 watts when lit? [It uses (consumes) 40 W only when lit.]

Light Bulbs
Compact fluorescent light (CFL) bulbs are much more efficient than the incandescent bulbs invented by Edison. A downside is the CFLs contain mercury. Light-emitting diodes (LEDs) are hazard free and provide the color in many TV monitors. White-light LEDs are already in screw-socket form for home lighting (more on this in Chapter 30).

Electrical Circuits
You simply must use an automobile storage battery with extended terminals as shown here. The extended terminals are simply a pair of rigid rods, welding rods or simply pieces of thick wire. They are easily inserted and removed if female connectors are permanently fastened into the battery terminals. Also fasten alligator clips to the ends of short lengths of wire fastened to about three or so lamps of equal resistance. If you use a 6-volt battery and lamps designed for 12 volts, they'll glow at a brightness just right for viewing. Brighter lamps are too much for your students' eyes.



DEMONSTRATION: Connect the ends of one of the lamps directly to the battery terminals. It glows, evidence of current flow. Then insert the rods and repeat. It glows as before. Slide the lamp farther up the rods and its glow is the same. It is easily accepted that the 6-volt potential difference between the terminals is also established along and across the full length of the rods. State how the rods could extend across campus and someone far away could similarly light up a lamp. State how the resistance of the rods is very small compared to the resistance of the lamp filament. Compare the rods to a long lamp cord. Then to power lines from power plants to consumers. Take your time with these ideas, for they are central! (I show this in the screencast Battery Demo, a favorite!)_

Series Circuits
DEMONSTRATION CONTINUED: Attach two lamps in series via alligator clips. Before connecting the double lamp circuit to the rods, ask for a neighbor check about the relative brightness of light. [Since the resistance is doubled, the current is halved and the brightness diminished—brightness is "less than half" because most of the energy is going to heat and not light. The effects of heat can be discerned for low currents when no light is seen.] Point out that the voltage across each lamp is half the voltage across the battery terminals when connected in series. Repeat the process for three lamps in series, where three lamps share the 6 volts, and describe the reduced current in terms of Ohm's law. This is even more effective if you connect a lecture-size ammeter to your circuit.

Parallel Circuits
DEMONSTRATION CONTINUED: Now connect a pair of lamps in series. Before making the second connection, ask for a neighbor check about the relative brightnesses. It's easy to see that the voltage across each lamp is not reduced as with the series connection, but each is impressed with a full 6 volts. [Nearly a full 6 volts; line voltage diminishes with increased current through the battery—perhaps information overload at this stage of learning.] Repeat with three lamps after a neighbor check. Ask about the "equivalent resistance" of the circuit as more lamps are attached in parallel (or the equivalent resistance to people flow if more doors are introduced to the classroom). The lesser resistance is consistent with Ohm's law. An ammeter between one of the rods and the terminal shows line current, which is seen to increase as lamps are added. This is the simplest and most visually comprehensible demo of parallel circuits I have devised.

CHECK QUESTION: Consider two resistors to be connected in a circuit. Which will have more resistance, if they are connected in series or in parallel? [A series connection will have more resistance, regardless of the values of resistance; the equivalent resistance of a parallel connection will always be less than that of the smaller resistor.]

Home Circuits and Fuses

Discuss home lighting circuits. Draw a simple parallel circuit of lamps and appliances on the board. Estimate the current flowing through each device, and point out that it makes no difference how many of the other devices are turned on. Show on your diagram the currents in the branches and in the lead wires. Show where the fuse goes and describe its function. Then short your circuit and blow the fuse.

Overloading

Discuss the consequences of too many appliances operating on the same line, and why different sets of lines are directed to various parts of the home. Most home wiring is rated at 30 amperes maximum. A common air conditioner uses about 2400 watts, so if operating on 120 volts the current would be 20 amps. To start, the current is more. (Why the starting current is larger would be premature to explain here—if it comes up you can explain that every motor is also a generator, and the input electricity is met with a generated output that reduces the net current flow.) If other devices are drawing current on the same line, the fuse will blow when the air conditioner is turned on, so a 220-volt line is usually used for such heavy appliances. Point out that most of the world operates normally at 220-240 volts.

Answers and Solutions for Chapter 23

Reading Check Questions

1. Heat must have a difference in temperature. Flow of charge must have a difference in electrical potential.
2. Sustained flow of water in a pipe needs a difference in water pressure. Sustained flow of charge needs a difference in electric potential.
3. Electrons in metals are free to wander, whereas protons are imbedded in atomic nuclei, not free to roam.
4. An ampere is a unit of electric current, a flow of 1 coulomb per second.
5. One kind is a battery; another is a generator.
6. 12 joules of energy are supplied to each coulomb of charge that flows through a 12-volt battery.
7. Electric charge flows through a circuit. Voltage doesn't flow at all, but is impressed across a circuit.
8. Water flows more easily through a wide pipe, and similarly charge flows more easily through a thick wire.
9. Heating a metal wire increases molecular motion and therefore its electrical resistance.
10. The unit of electrical resistance is the ohm, symbol Ω.
11. When resistance doubles, current is halved.
12. When voltage is halved, current is halved.
13. Wetness lowers the body's electrical resistance.
14. The third prong is connected to the "ground," providing a route for unwanted charge. It prevents charge buildup on the appliance.
15. A battery produces dc. A generator normally produces ac.
16. Current oscillates 60 times per second at 60 hertz.
17. A diode passes current in one direction only.
18. A capacitor smoothes the pulses when a diode converts ac to dc.
19. The error is that no particle can travel at the speed of light.
20. Electrons collide with atoms transferring some of their energy to the atoms as increased vibrations, making the wire hotter.
21. Drift velocity is the net velocity of electrons that make up an electric current.
22. No. Electrons move with the electric field, which is established at about the speed of light in conductors. The domino analogy does fit sound, for their motion is due to molecules hitting molecules.
23. The error is that the source is the conducting wires themselves, not the power source.
24. You are billed for the energy consumed.
25. When you are shocked, your own body is the source of electrons, but not the source of energy imparted to them.
26. The relationship is given by the formula, power = current $\times$ voltage.
27. A watt and a kilowatt are units of power. A kilowatt-hour is a unit of energy.
28. Energy that goes to heat instead of light is wasted, so efficiency is less.
29. Current is 1 A everywhere in two lamps connected in series.
30. Voltages add, so if voltage in one lamp is 2 V, voltage in the other is 4 V to account for the 6 V impressed across both in series.
31. Both lamps have 6 volts across them when connected in parallel.
32. The sum of the currents in the branches add to the current in the voltage source.
33. The function of a fuse or a circuit breaker is to prevent overloading that may lead to fire.

Think and Do

34. This is a worthwhile activity.
35. A close-to-home activity!
36. This letter may dispel a widely-held misconception.

Plug and Chug

37. $I = \frac{V}{R} = \frac{120\ \text{V}}{15\ \Omega} = 8\ \text{A}$.

38. $I = \frac{V}{R} = \frac{6\ \text{V}}{1000\ \ \Omega} = 0.006\ \ \text{A}$.

39. $I = \frac{V}{R} = \frac{120\ \text{V}}{240\ \Omega} = 0.5\ \text{A}$.

40. $P = IV$ = (0.5 A)(120 V) = 60 W.

41. $P = IV$ = (10 A)(120 V) = 1200 W.

Think and Solve

42. From $I = V/R$, if both voltage and resistance are doubled, current remains unchanged. Likewise if both voltage and resistance are halved.

43. From "Power = current × voltage," 60 watts = current × 120 volts, current = $\frac{60\text{W}}{120\text{V}}$ = 0.5 A.

44. From current = $\frac{\text{voltage}}{\text{resistance}}$, resistance = $\frac{\text{voltage}}{\text{current}} = \frac{120\text{V}}{20\text{A}}$ = 6 Ω.

45. From power = current ´ voltage, current = $\frac{\text{power}}{\text{voltage}} = \frac{1200\text{W}}{120\text{V}}$ = 10 A.
From the formula derived above, resistance = $\frac{\text{voltage}}{\text{current}} = \frac{120\text{V}}{10\text{A}}$ = 12 Ω.

46. Two headlights draw 6 amps, so the 60 ampere-hour battery will last for about 10 hours.

47. \$2.52. First, 100 watts = 0.1 kilowatt. Second, there are 168 hours in one week (7 days × 24 hours/day = 168 hours). So 168 hours × 0.1 kilowatt = 16.8 kilowatt-hours, which at 15 cents per kWh comes to \$2.52.

48. (a) From power = current × voltage, current = power/voltage = 4W/120V = **1/30 A**.
(b) From current = voltage/resistance (Ohm's law), resistance = voltage/current = 120 V/(1/30 A) = 3600 W.
(c) First, 4 watts = 0.004 kilowatt. Second, there are 8760 hours in a year (24 hours/day × 365 days = 8760 hours). So 8760 hours × 0.004 kilowatt = 35.0 kWh.
(d) At the rate of 15 cents per kWh, the annual cost is 35.0 kWh × \$0.15/kWh = \$5.25.

49. The iron's power is $P = IV$ = (110 V)(9 A) = 990 W = 990 J/s. The heat energy generated in 1 minute is E = power × time = (990 J/s)(60 s) = 59,400 J.

50. Since current is charge per unit time, charge is current × time: $q = It$ = (9 A)(60 s) = (9 C/s)(60 s) = 540 C. (Charges of this magnitude on the move are commonplace, but this quantity of charge accumulated in one place would be incredibly large.)

51. The resistance of the toaster is $R = V/I$ = (120 V)/(10 A) = 12 Ω. So when 108 V is applied, the current is $I = V/R$ = (108 V)/(12 Ω) = 9.0 A and the power is $P = IV$ = (9.0 A)(108V) = 972 W, only 81 percent of the normal power. (Can you see the reason for 81 percent? Current and voltage are both decreased by 10 percent, and 0.9 × 0.9 = 0.81.)

Think and Rank

52. A = B = C
53. A = B = C
54. C, B, A
55. A, B, C
56. a. C, B, A b. A= B = C

Think and Explain

57. A sustained flow needs a sustained difference in potential across a conducting medium, due to a battery or generator.

58. Make the pipe wider and apply more pressure. Make the conducting wire thicker and apply more voltage (also you could use material with less resistance).

59. Six gallons per minute (10 – 4 = 6).

60. Six amperes (10 – 4 = 6).

61. The cooling system of an automobile is a better analogy to an electric circuit because like an electric circuit it is a closed system, and it contains a pump, analogous to the battery or other voltage source in a circuit. The water hose does not re-circulate the water as the auto cooling system does.

62. As the current in the filament of a lightbulb increases, the bulb glows brighter.

63. The circuit in the center is a complete circuit and will light the lamp.

64. Disagree, for the battery supplies the electric field in the circuit. The electrons already exist in the circuit.

65. Six joules of energy is given to each coulomb passing through a 6-volt battery.

66. Normally a current-carrying wire is not electrically charged because for every electron in the wire there is a proton.

67. Your tutor is wrong. An ampere measures current, and a volt measures electric potential (electric “pressure”). They are entirely different concepts; voltage produces amperes in a conductor.

68. Only circuit 5 is complete and will light the bulb. (Circuits 1 and 2 are “short circuits” and will quickly drain the cell of its energy. In circuit 3 both ends of the lamp filament are connected to the same terminal and are therefore at the same potential. Only one end of the lamp filament is connected to the cell in circuit 4.)

69. Current flows *through* electrical devices, just as water flows through a plumbing circuit of pipes. If a water pump produces water pressure, water flows through both the pump and the circuit. Likewise with electric current in an electric circuit. For example, in a simple circuit consisting of a battery and a lamp, the electric current produced in the lamp is the same electric current in the wires that connect the lamp and the same electric current flowing through the battery. Electric charge flows through these devices (the flow of charge being current).

70. Agree with the friend who says energy, not current, is used up.

71. Your friend is sharing voltage from his battery by connecting the two batteries in parallel.

72. Agree, for then the same appropriate voltage will power the circuit.

73. All other things being equal, a material with a short mean-free path offers more resistance to electron flow and has a higher electrical resistance. For all materials, the application of heat imposes more molecular chaos and shortens the path even more, increasing resistance in most materials. So to lengthen the path, simply cool the material. Conductivities are greatly increased in most materials when they are cooled to low temperatures.

74. Before it heats up, the filament is cooler and has less resistance.

75. Most of the energy, more than 90%, of the electrical energy in an incandescent lamp goes directly to heat. Thermal energy is the graveyard of electrical energy.

76. CFLs are more efficient because, relative to incandescents, more of the energy they transfer is light and less is heat.

77. Thick wires have less resistance and will more effectively carry currents without excessive heating.

78. Glow occurs where resistance is higher and therefore where most energy is being dissipated, in the filament.

79. The thick filament has less resistance and will draw (carry) more current than a thin wire connected across the same potential difference.

80. Electric shock *occurs* when current is produced in the body, which is *caused* by an impressed voltage. So the initial *cause* is the voltage, but it is the current that does the damage.

81. In the first case the current passes through your chest; in the second case current passes only through your arm. You can cut off your arm and survive, but you cannot survive without your heart.

82. Electric power in your home is likely supplied at 60 hertz and 110-120 volts via electrical outlets. This is ac. Battery terminals don't alternate, and current provided by them flows in one direction and is dc.

83. Auto headlights are wired in parallel. Then when one burns out, the other remains lit. If you've ever seen an automobile with one burned out headlight, you have evidence they're wired in parallel.

84. The more branches in both cases, the less the overall resistance.

85. (a) volt, (b) ampere, (c) joule.

86. Current remains the same in all the resistors in a series circuit.

87. Voltage across parallel branches, whatever the resistance, remains the same.

88. The amount of current through any conductor depends upon the voltage of the conducting device and its resistance. Also important is the amount of charge the device can deliver; a relatively large amount of charge at high voltage represents high energy (like that from a power line) while a small amount of charge at high voltage represents low energy (like discharging a balloon rubbed on your hair). The device being warned about is likely highly energized to a high voltage, and should be respected. It possesses no current to be warned about, but because of its high energy and high voltage, may produce a lethal current in anyone offering a conducting path from it to the ground.

89. The sign is a joke. High voltage may be dangerous, but high resistance is a property of all nonconductors.

90. No cause for concern. The label is intended as humor. It describes electrons, which are in all matter.

91. Damage generally occurs by excess heating when too much current is driven through an appliance. For the hairdryers, less damage is done plugging the 220-V one into 110 volts.

92. If the parallel wires are closer than the wing span of birds, a bird could short circuit the wires by contact with its wings, be killed in the process, and possibly interrupt the delivery of power.

93. Zero. Power companies do not sell electrons; they sell energy. Whatever number of electrons flow into a home, the same number flows out.

94. How quickly a lamp glows after an electrical switch is closed does not depend on the drift velocity of the conduction electrons, but depends on the speed at which the electric field propagates through the circuit—about the speed of light.

95. Electric energy is propagated through a circuit by electric fields moving at close to the speed of light, not by electron collisions. Sound, on the other hand, travels by molecular or atomic collisions—a much slower process.

96. Bulbs will glow brighter when connected in parallel, for the voltage of the battery is impressed across each bulb. When two identical bulbs are connected in series, half the voltage of the battery is impressed across each bulb. The battery will run down faster when the bulbs are in parallel.

97. Brightness remains the same.

98. Most of the electric energy in a lamp filament is transformed to heat. For low currents in the bulb, the heat that is produced may be enough to feel but not enough to make the filament glow white or even red hot.

99. Bulb C is the brightest because the voltage across it equals that of the battery. Bulbs A and B share the voltage of the parallel branch of the circuit and have half the current of bulb C (assuming

resistances are independent of voltages). If bulb A is unscrewed, the top branch is no longer part of the circuit and current ceases in both bulbs A and B. They no longer give light, while bulb C glows as before. If bulb C is instead unscrewed, then it goes out and bulbs A and B glow as before.

100. More bulbs in series means more resistance and less current. Bulbs glow dimmer. But when more bulbs are connected to the battery in parallel, the brightness of the bulbs doesn't change, for each bulb is connected directly to the battery. Each bulb has its own current path.

101. Line current decreases as more devices are connected in series. But line current increases as more devices are connected in parallel. This is because the circuit resistance is increased when devices are added in series, but decreased (more pathways) when devices are added in parallel.

102. What affects the other branches is the voltage impressed across them, and their own resistance—period. Opening or closing a branch doesn't alter either of these.

103. All are the same for identical resistors in series. If the resistors are not the same, the one of greater resistance will have less voltage across it and less power dissipated in it. Regardless of the resistances, however, the current through both will be the same.

104. All are the same for identical resistors in parallel. If the resistors are not the same, the one of greater resistance will have less current through it and less power dissipation in it. Regardless of the resistances, the voltage across both will be identical.

105. Yes, there will be a decrease in brightness if too many lamps are connected in parallel because of the increased current that flows through the battery. Internal voltage drop increases with current in the battery, which means reduced voltage supplied at its terminals to the circuit it powers. (If the parallel circuit is powered by a stronger source such as the power utility provides via common wall sockets, no dimming of bulbs will be seen as more and more parallel paths are added.)

106. All three are equivalent parallel circuits. Each branch is individually connected to the battery.

107. A fuse in series with any one of the appliances could be useful, for it would melt only if something went wrong with that particular appliance.

Think and Discuss

108. A lie detector circuit relies on the likelihood that the resistivity of your body changes when you tell a lie. Nervousness promotes perspiration, which lowers the body's electrical resistance, and increases whatever current flows. If a person is able to lie with no emotional change and no change in perspiration, then such a lie detector will not be effective. (Better lying indicators focus on the eyes.)

109. A resistor doesn't "attract" or "draw" current, just as a pipe in a plumbing circuit doesn't "draw" water; it instead "allows" or "provides for" the passage of current when an electrical pressure is established across it.

110. There is less resistance in the higher wattage lamp. Since power = current × voltage, more power for the same voltage means more current. And by Ohm's law, more current for the same voltage means less resistance. (Algebraic manipulation of the equations $P = IV$ and $I = V/R$ leads to $P = V^2/R$.)

111. The equivalent resistance of resistors in series is their sum, so connect a pair of resistors in series for more resistance.

112. The equivalent resistance of resistors in parallel is less than the smaller resistance of the two. So connect a pair of resistors in parallel for less resistance. (Interestingly, when in parallel more current also means more filament resistance, which doesn't change this answer.)

113. A lightbulb burns out when a break occurs in the filament or when the filament disintegrates or falls apart.

114. Agree, for resistances in series add.

115. Agree, because even for the smallest resistor, current has an alternative path(s), making for an overall smaller resistance.

116. Connect a pair of 40-ohm resistors in parallel.

117. Connect four 40-ohm resistors in parallel.

118. More current flows in the 100-watt bulb. We see this from the relationship "power = current × voltage." More current for the same voltage means less resistance. So a 100-watt bulb has less resistance than a 60-watt bulb. Less resistance for the same length of the same material means a thicker filament. The filaments of high wattage bulbs are thicker than those of lower-wattage bulbs. (It is important to note that both watts and volts are marked on a light bulb. A bulb that is labeled 100 W, 120 V, is 100 W *only* if there are 120 volts across it. If there are only 110 volts across it, and the resistance remains unchanged, then the power output would be only 84 watts!)

119. The 100-watt bulb has the thicker filament and lower resistance (as discussed in the previous answer) so in series where the current is the same in each bulb, less energy is dissipated in going through the lower resistance. This corresponds to lower voltage across the resistance—a lower voltage drop. So the greater voltage drop is across the 60-watt bulb in series. Interestingly, in series the 60-watt bulb is brighter than the 100-watt bulb! When connected in parallel, the voltage across each bulb is the same, and the current is greater in the lower resistance 100-watt bulb, which glows brighter than the 60-watt bulb.

120. (a) Equivalent resistance is 4 ohms. (b) $I = V/R$ = 24V/4ohm = 6 A. (c) $I = V/R$ =24V/12ohm = 2 A. So 2A flows through each branch.

121. (a) By Ohm's law, current in the 6-ohm resistor is V/R = 12 V/6 ohm = 2 A.
(b) The other two resistors, in series, add to 12 ohms, so the current in them is 12 V/12 ohm = 1 A.
(c) Current in the voltage source is the total current; 2A + 1A = 3 A.
(d) Two ways to find R_{eq}. (1) From $I_{total} = V/R_{eq}$, $R_{eq} = V/I_{total}$ = 12 V/3 A = 4 ohms.
(2) Since the circuit has 6 ohms in parallel with 12 ohms, the "product-over-sum rule" can be used to find the combined resistance:
$R = (R_1 \times R_2)/(R_1 + R_2) = (6 \times 12)/(6 + 12) = 4$ ohms.

24 Magnetism

Fred Myers, first photo in the chapter opener, has pioneered conceptual physics in the ninth grade since the late 1970s. He has instilled more love of physics in youngsters than any of my friends. Photo 2 is researcher and instructor Ken Ganezer of California State University at Dominquez Hills, a mutual friend of Charlie Spiegel (Figure 26.9) who was a contributor to Conceptual Physics before he died in 1995. Ken's passion for physics is evident in an e-mail to me in which he says, "Magnetism is the epitome of physics and of science in general—mysterious, beautiful, compelling, extremely practical, and a jumping off point for relativity (at least it was for Einstein) and an anomaly of our inertial frame." Not surprisingly, Ken has achieved numerous awards for dedicated teaching and improving undergraduate physics labs and curriculum, received NSF and NIH grants for research on neutrinos, grand unification, biomedical physics, and gravitational waves with LIGO. Photo 3 is Fred Cauthen, new to the CCSF physics faculty. Photo 4 is the son of friends Alan and Fe Davis. I first met Alan when visiting the island of Chuuk in Micronesia in the 1990s. They now live in the San Francisco Bay area.

The profile is on Nicola Tesla, an electric engineer rather than a physicist. What he did with physics was extraordinary and commendable.

This chapter, in the spirit of others, links the subject matter to the environment. It concludes with a bit of paleomagnetism, and the magnetic sensors in living organisms.

Direct measurements of the Earth's inner core recently suggest that it rotates faster than the bulk of the planet. Seismologists depended on the woodlike grain of the inner core, which alters the speed of seismic waves passing through it, and compiled 30 years of data to find a change of a few tenths of a second in wave travel times. Indications are that the inner core gains a full turn on the rest of the planet only every 400 years.

Magnetism is a major source of energy in galaxies, where twisting and turning of material creates a dynamo effect that amplifies the magnetic fields. The explosive release of magnetic energy from space storms that interact with Earth's magnetosphere can damage spacecraft, sicken astronauts and even disrupt power communication on the ground.

Bob Roemer reports his fascination with a compass on subways (*The Physics Teacher*, Feb. 1993). Rather than simply pointing north, the compass dances erratically in response to the strong dc that varies as the cars maneuver. Magnetic fields some 20 times larger than the Earth's are produced by dc in the wires, and the 600-V third rail that often carries currents in excess of 5000 A. Changes in field direction are noted when the cars brake by using motors as generators, supplying energy back into the third rail. If your

student rides subway or other electric cars, urge them to note the effects of the currents on small hand-held compasses!

A new radiation belt was discovered back in 1993, a toroid of anomalous cosmic rays making up a third radiation belt within the inner belt of protons. The outer belt is made up of electrons.

Make iron-filing permanent displays by spraying water on iron filings on a paper atop a magnet. The rust stains will leave a permanent impression of the magnetic field. (This idea is from Matt Keller.)

A long helically wound coil of insulated wire is called a *solenoid*.

The material in this chapter is prerequisite to the next chapter.

Practicing Physics Book:
• Magnetic Fundamentals.

Problem Solving Book:
There are ample problems on magnetism

Laboratory Manual:
• Seeing Magnetic Fields *Patterns of Attraction and Repulsion* (Activity)
• Electric Magnetism *Electric Currents and Magnetic Fields* (Activity)
• Motor Madness Simple DC Motors (Activity)

Next-Time Questions:
• Magnet and Tack
• Bar and Magnet
• Wire in Magnet

Hewitt-Drew-It! Screencast: •*Magnetism*

SUGGESTED LECTURE PRESENTATION

Magnetic Force: Begin by holding a magnet above some nails or paper clips on your lecture table. State that the nails or clips are flat on the table because every particle of matter in the whole world is gravitationally pulling them against the table. Then show that your magnet out pulls the whole world and lifts the nails or clips off the table.

> CHECK QUESTION: What is the net force on the magnetic needle of a compass? [Zero. When it's not aligned with the magnetic field, the net force is still zero although the net torque is not zero.]

Show that iron is not the only ferromagnetic substance. Certain Canadian nickels and quarters (1968 to 1981 which are pure nickel) are easily attracted to a magnet. The U.S. 5 cent piece is no longer pure nickel, is 75% copper, and won't respond to a magnet.

Magnetic Poles: Show how a bar magnet affects a large lecture compass and discuss magnetic poles. Similar to the fundamental rule of electricity, *like poles repel and opposite poles attract.*

Magnetic Fields: Show field configurations about bar magnets with the use of an overhead projector and iron filings. Simply lay a magnet on the glass surface of the projector and cover it with a sheet of plastic, and sprinkle iron filings over the plastic. Acknowledge the alignment of **magnetic domains** in the magnet material.

Magnetic Induction: Explain magnetic induction, and show how bringing a nonmagnetized nail near a magnet induces it to become a magnet and be attracted. Then contrast this with an aluminum rod—discuss unpaired electron spins and magnetic domains. Compare magnetic induction to the electric induction

shown in Figures 22.12 and 22.13 back in Chapter 22. Stress the similarities of electrically inducing charge polarization and magnetically inducing the alignment of magnetic domains.

Electric Currents and Magnetic Fields: Discuss the source of magnetism—the *motion* of charges. All magnetism starts with a moving electric charge: in the spin of the electron about its own axis (like a top), in the revolution about the nuclear axis, and as it drifts as part of an electric current.

> DEMONSTRATION: Place a compass near a wire and show the deflection of the compass needle when current is passed through the wire.

It should be enough to simply acknowledge that the magnetic field is a relativistic “side effect” or “distortion” in the electric field of a moving charge. (Unless you’ve already treated special relativity, the relativistic explanation may be too involved to be effective.)

Side point: When the magnetic field about a current-carrying wire is undesirable, double wires are used, with the return wire adjacent to the wire. Then the net current for the double wire is zero, and no magnetic field surrounds it. Wires are often braided to combat slight fields where the cancellation is not perfect.

Electromagnets:
Call attention to the circular shape of the magnetic field about a current-carrying wire (Figure 24.8 and the photos of field lines of Figure 24.9). It’s easy to see how the magnetic field is bunched up in a loop of current-carrying wire, and then in a coil of many loops. Then place a piece of iron in the coil and the added effect of aligned domains in the iron produces an electromagnet.

> DEMONSTRATION: Make a simple electromagnet in front of your class. Simply wind wire around a spike and pick up paper clips when you put a current through the wire. Mimic the operation of a junkyard magnet, where the clips are dropped when the current is turned off.

> DEMONSTRATION: Show your department’s goodies; electromagnets and superconducting electromagnets!

> DEMONSTRATION: Do as Wai Tsan Lee (Lillian’s dad) does in Figure 24.6 and show how nails or paper clips become induced magnets. This is more effective if done with an electromagnet. When the current is turned off, the nails or paper clips drop. What of those that don’t? [Residual magnetism!]

If you have an electromagnetic levitator, discuss the train application when you are fascinating your students with its demonstration. The idea of a **magnetically-levitated train** was described in 1909 by Robert Goddard, an American well known for inventing the liquid-fueled rocket. Japan was the first to demonstrate maglev trains during the 1964 Olympics held in Japan, transporting spectators at speeds up to 130 mph. Although Europe and Japan now have the lead in this field, the first modern design for a maglev train comes from Americans, nuclear-engineer James R. Powell, and particle-acceleration physicist Gordon T. Danby, who were awarded a patent for their design.

Whatever the present variations in design, once the train is levitated there is no mechanical friction to contend with, so only modest force is needed to accelerate it. Fixed electromagnets along the guideway alternately pull and push by switching polarity whenever one of the train’s propulsion magnets passes it. The phased switching is timed by computers under the control of the driver to accelerate or decelerate the train, or simply keep it moving. Various designs have the overall result of propelling the train like a surfboard riding a wave. Speculation by co-inventor Danby is that future travel in partially evacuated tubes will permit cross-country passage in about an hour. Maglev trains may play a large role in transportation in this century. Watch for new design features for this new technology. Also watch for Elon Musk’s Hyperloop. These are technologically exciting times!

Magnetic Force on Moving Charges:
Discuss the motion of a charged particle injected into a magnetic field perpendicularly, and explain how it will follow a circle. The perpendicular push is a centripetal force that acts along the radius of its path.

Briefly discuss cyclotrons and bevatrons, with radii that range from less than a meter to more than a kilometer.

The Hand Rules:
Sorry if in the textbook I don't feature the hand rules for magnetic field, current, and force. I joke about it in the Insight at the top of page 461. It has always seemed to me that a misquided purpose of these rules was to provide material for testing. To an engineer or physicist, the rules have practical use. But for the non-science student? Although the hand rules are a tiny part of what's important in electric-magnetic phenomena, in exams, unfortunately, they can dominate. However, in the lab activity *Electric Magnetism* students see how the magnetic field surrounding a current-carrying wire reverses when the direction of current reverses. These observations lead them to developing a right-hand rule (fingers around the wire) to describe the geometry. But in the textbook? Not there, and hopefully, not on any student exams.

Magnetic Force on Current-Carrying Wires:
Simple logic tells you that if forces act on electrons that move through a magnetic field, then forces act on electrons traveling through a wire in a magnetic field. Ask your class whether they see that what's happening in Figure 24.15 is a natural consequence of what's happening in Figure 24.13. This is one of the more straight-forward connections in nature, one thing following another.

> DEMONSTRATION: Show how a wire jumps out of (or into) a magnet when current is passed through the wire (Figure 24.15). Reverse current (or turn wire around) to show both cases.

If you have a large lecture galvanometer, show your class the coil of wire that is suspended in the magnetic field of the permanent magnet (Figure 24.17). The same is found in ammeters and voltmeters. Now you are ready to extend this idea to the electric motor.

> DEMONSTRATION: Show the operation of a dc demonstration motor.

Earth's Magnetic Field:
Discuss the field configuration about Earth and how cosmic rays are deflected by the magnetic field lines. In discussing pole reversals, state that the magnetic field of the Sun undergoes reversals about every eleven years.

Biomagnetism:
Acquaint yourself with the latest findings regarding magnetic field sensing by living things. Creatures such as bacteria, bees, and pigeons are mentioned briefly in the text. Recent findings show magnetic particles in the human brain. Insects sense the world in very different ways than humans, using things we can't perceive. Birds orient flight by sunset glow and star patterns as well as by the magnetic field—a combination of approaches.

Answers and Solutions for Chapter 24

Reading Check Questions

1. Hans Christian Oersted in a high-school classroom noted how a current affects a magnet, thus relating electricity and magnetism.
2. The force depends also on the velocity of the charge.
3. Moving electrons are the source of the magnetic force.
4. Yes, in each, likes repel likes; opposites attract.
5. Magnetic poles cannot be isolated; electric charges can.
6. The closer the field lines, the stronger the magnetic field.
7. The motion of electric charges produces a magnetic field.
8. Electrons exhibit spin motion and orbital motion.
9. A magnetic domain is a cluster of aligned atoms.
10. Iron atoms are mainly aligned in a magnetized material, and un-aligned in a non-magnetic material.
11. Iron has magnetic domains, wood does not.
12. Impact jostles domains out of alignment and weakens the magnet.
13. Magnetic field takes the form of concentric circles about a current-carrying wire.
14. When current reverses, magnetic field reverses direction.
15. Inside the loop lines are more concentrated.
16. The iron's domains align with the field and add to its strength.
17. Greater electron flow produces greater magnetic field strength.
18. True! If there's no motion, there's no magnetism.
19. Force is maximum when motion is perpendicular to the field; minimum when parallel.
20. Earth's magnetic field deflects incoming charged particles and lessens their impact on Earth's surface.
21. Force is maximum when current is perpendicular to the field.
22. Electric current in its coil is deflected by a permanent magnet.
23. When calibrated for current, it is an ammeter; when calibrated for voltage, a voltmeter.
24. Current is reversed with each half turn of the armature.
25. Yes, a motor is a sophisticated galvanometer.
26. Earth's intense heat prevents alignment of atoms.
27. Magnetic pole reversals are reversals of north and south poles, common throughout Earth's history.
28. The cause of the aurora borealis is impact of charged particles with atmospheric molecules.
29. Six creatures include bacteria, pigeons, bees, butterflies, sea turtles, and fish.
30. Cosmic rays are continually penetrating your body.

Think and Do

31. A worthwhile activity.

32. Make your own magnet!

Think Explain

33. Separation is easy with a magnet (try it and be amazed!)

34. All magnetism originates in moving electric charges. For an electron there is magnetism associated with its spin about its own axis, with its motion about the nucleus, and with its motion as part of an electric current. In this sense, all magnets are electromagnets.

35. How the charge moves dictates the direction of its magnetic field. (A magnetic field is a vector quantity.) Magnetic fields cancel, more in some materials than others.

36. Beating on the nail shakes up the domains, allowing them to realign themselves with the Earth's magnetic field. The result is a net alignment of domains along the length of the nail. (Note that if you hit an already magnetized piece of iron that is not aligned with the Earth's field, the result can be to weaken, not strengthen, the magnet.)

37. Attraction will occur because the magnet induces opposite polarity in a nearby piece of iron. North will induce south, and south will induce north. This is similar to charge induction, where a balloon will stick to a wall whether the balloon is negative or positive.

38. Yes, the poles, being of opposite polarity, attract each other. If the magnet is bent so that the poles get closer, the force between them increases.

39. The poles of the magnet attract each other and will cause the magnet to bend, even enough for the poles to touch if the material is flexible enough.

40. An electric field surrounds a stationary electric charge. An electric field and a magnetic field surround a moving electric charge. (And a gravitational field also surrounds both).

41. Refrigerator magnets have narrow strips of alternating north and south poles. These magnets are strong enough to hold sheets of paper against a refrigerator door, but have a very short range because the north and south poles cancel a short distance from the magnetic surface.

42. Apply a small magnet to the door. If it sticks, your friend is wrong because aluminum is not magnetic. If it doesn't stick, your friend might be right (but not necessarily—there are lots of nonmagnetic materials).

43. A magnet will induce the magnetic domains of a nail or paper clip into alignment. Opposite poles in the magnet and the iron object are then closest to each other and attraction results (this is similar to a charged comb attracting bits of electrically neutral paper—Figure 22.13). A wooden pencil, on the other hand, does not have magnetic domains that will interact with a magnet.

44. Over time, domains are knocked out of alignment.

45. Domains in the paper clip are induced into alignment in a manner similar to the electrical charge polarization in an insulator when a charged object is brought nearby. Either pole of a magnet will induce alignment of domains in the paper clip: Attraction results because the pole of the aligned domains closest to the magnet's pole is always the opposite pole, resulting in attraction.

46. The needle is not pulled toward the north side of the bowl because the south pole of the magnet is equally attracted southward. The net force on the needle is zero. (The net torque, on the other hand, will be zero only when the needle is aligned with the Earth's magnetic field.)

47. The mechanism of alignment involves two factors: First, each filing is turned into a tiny magnet by the magnetic field of the bar magnet, which induces domain alignment in the filing. Second, a pair of equal and opposite torques act on each filing whenever it is not parallel to the magnetic field lines. These torques rotate the filings into alignment with the field lines like little compass needles.

48. The north and south poles of a magnet are so named because they are "north-seeking" and "south-seeking." So magnetically speaking, Earth's pole in the Northern Hemisphere is a south pole. Earth's pole in the Southern Hemisphere is a north pole.

49. Yes, for the compass aligns with the Earth's magnetic field, which extends from the magnetic pole in the Southern Hemisphere to the magnetic pole in the Northern Hemisphere.

50. Rotation is not produced when the axis of the loop is aligned with the field.

51. Back to Newton's 3rd law! Both A and B are equally pulling on each other. If A pulls on B with 50 newtons, then B also pulls on A with 50 newtons. Period!

52. Yes, it does. Since the magnet exerts a force on the wire, the wire, according to Newton's third law, must exert a force on the magnet.

53. Newton's 3rd law again: Yes, the paper clip, as part of the interaction, certainly does exert a force on the magnet—just as much as the magnet pulls on it. The magnet and paper clip pull equally on each other to comprise the single interaction between them.

54. The needle points perpendicular to the wire (east or west). (See Figure 24.8.)

55. Both the vibrations in the coil and the speaker cone have identical frequencies at any instant.

56. Less power because of reduced electrical resistance means less heat loss.

57. Just as a nail is magnetized by beating on it, an iron ship is beat upon in its manufacture, making it a permanent magnet. Its initial magnetic field orientation, which is a factor in subsequent magnetic measurements, is in effect recorded on the brass plaque.

58. The beam must be traveling along or parallel to the magnetic field.

59. An electron must be moving across magnetic field lines in order to feel a magnetic force. So an electron at rest in a stationary magnetic field will feel no force to set it in motion. In an electric field, however, an electron will be accelerated whether or not it is already moving. (A combination of magnetic and electric fields is used in particle accelerators such as cyclotrons. The electric field accelerates the charged particle in its direction, and the magnetic field accelerates it perpendicular to its direction.)

60. The diameter decreases as the proton is pulled in a tighter circle.

61. If the particles enter the field moving in the same direction and are deflected in opposite directions (say one left and one right), the charges must be of opposite sign.

62. When we write *work* = *force* × *distance*, we really mean the component of force in the direction of motion multiplied by the distance moved (Chapter 7). Since the magnetic force that acts on a beam of electrons is always perpendicular to the beam, there is no component of magnetic force along the instantaneous direction of motion. Therefore a magnetic field can do no work on a charged particle. (Indirectly, however, a *time-varying magnetic field* can induce an electric field that *can* do work on a charged particle.)

63. If the field interacts with a stationary bar magnet it is magnetic; if with a stationary charge, it is electric. If an electric current is generated in a rotating loop of wire, the field is magnetic. If a force acts only on a moving charge, the field is magnetic. So any of the classes of experiments that deal with electric charge at rest and electric charge in motion could be used to determine the nature of the field in the room.

64. Charged particles moving through a magnetic field are deflected most when they move at right angles to the field lines, and least when they move parallel to the field lines. If we consider cosmic rays heading toward the Earth from all directions and from great distances, those descending toward northern Canada will be moving nearly parallel to the magnetic field lines of the Earth. They will not be deflected very much, and secondary particles they create high in the atmosphere will also stream downward with little deflection. Over regions closer to the equator like Mexico, the incoming cosmic rays move more nearly at right angles to the Earth's magnetic field, and many of them are deflected back out into space before they reach the atmosphere. The secondary particles they create are less intense at the Earth's surface. (This "latitude effect" provided the first evidence that cosmic rays from outer space consist of charged particles—mostly protons, as we now know.)

65. The Van Allen radiation belts are filled with swarms of high-energy charged particles that can damage living tissue. Astronauts, therefore, make an effort to keep below these belts.

66. Cosmic ray intensity at the Earth's surface would be greater when the Earth's magnetic field passed through a zero phase. Fossil evidence suggests the periods of no protective magnetic field may have been as effective in changing life forms as x-rays have been in the famous heredity studies of fruit flies.

67. Singly-charged ions traveling with the same speed through the same magnetic field will experience the same magnetic force. The extent of their deflections will then depend on their accelerations, which in turn depend on their respective masses. The least massive ions will be deflected the most and the most massive ions will be deflected least. (See Figure 34.14, further in the book, for a diagram of a mass spectrograph.)

68. A habitat in space could be shielded from cosmic radiation if a magnetic field were set up about the habitat, just as the magnetic field of the Earth shields us from much of the cosmic radiation that would otherwise strike the Earth. (As to the idea of a blanket, some have proposed that a thick layer of slag from mining operations on planets or asteroids could be placed around the habitat.)

69. To determine only by their interactions with each other which of two bars is a magnet, place the end of the bar #1 at the midpoint of bar #2 (like making a "T"). If there is an attraction, then bar #1 is the magnet. If there isn't, then bar #2 is the magnet.

70. Magnetic levitation will reduce surface friction to near zero. Then only air friction will remain. It can be made relatively small by aerodynamic design, but there is no way to eliminate it (short of sending vehicles through evacuated tunnels). Air friction gets rapidly larger as speed increases.

71. Yes, each will experience a force because each is in the magnetic field generated by the other. Interestingly, currents in the same direction attract, and currents in opposite directions repel.

72. The magnetic fields of each cancel at some distance from the wires.

73. Currents will be induced in metals by the changing magnetic field of the MRI device.

Think and Discuss

74. An electron always experiences a force in an electric field because that force depends on nothing more than the field strength and the charge. But the force an electron experiences in a magnetic field depends on an added factor: velocity. If there is no motion of the electron through the magnetic field in which it is located, no magnetic force acts. Furthermore, if motion is along the magnetic field direction, and not at some angle to it, then also no magnetic force acts. Magnetic force, unlike electric force, depends on the velocity of the charge. (Interestingly, due to electron spin it experiences a torque that tends to align its magnetic field with the external magnetic field.)

75. The dip needle will point most nearly vertically near the Earth's magnetic poles, where the field points toward or away from the poles (which are buried deep beneath the surface). It will point most nearly horizontally when near the equator (see Figure 24.20).

76. At the Earth's North magnetic pole the needle would point downward.

77. The net force on a compass needle is zero because its north and south poles are pulled in opposite directions with equal forces in the Earth's magnetic field. When the needle is not aligned with the magnetic field of the Earth, then a pair of torques (relative to the center of the compass) is produced (Figure 24.3). This pair of equal-strength torques, called a "couple," rotates the needle into alignment with the Earth's magnetic field.

78. Tell your first friend that the magnetic field of the Earth is continuous from pole to pole, and certainly doesn't make a turnaround at the Earth's equator; so a compass needle that is aligned with the Earth's field likewise does not turn around at the equator. Your other friend could correctly argue that compass needles point southward in the Southern Hemisphere (but the same pole points southward in the Northern Hemisphere). A compass does not turn around when crossing the equator.

79. The electric field in a cyclotron or any charged particle accelerator forces the particles to higher speeds, while the magnetic field forces the particles into curved paths. A magnetic force can only change the direction (not the speed) of a charged particle because the force is always perpendicular to the particle's instantaneous velocity. (Interestingly enough, in an accelerator called a betatron, the electric field is produced by a changing magnetic field.)

80. Speed or KE doesn't increase because the force is perpendicular to the velocity, doing no work on the particle.

81. Associated with every moving charged particle, electrons, protons, or whatever, is a magnetic field. Since a magnetic field is not unique to moving electrons, there is a magnetic field about moving protons as well. However, it differs in direction. The field lines about the proton beam circle in one way, the field lines about an electron beam in the opposite way. (Physicists use a "right-hand rule." If the right thumb points in the direction of motion of a positive particle, the curved fingers of that hand show the direction of the magnetic field. For negative particles, the left hand can be used.)

82. Each coil is magnetically attracted to its electromagnetic neighbor.

25 Electromagnetic Induction

Photo openers begin with Professor Jean Curtis who taught at the University of Hawaii at Hilo. She never smoked, yet recently died of lung cancer. Photo 3 shows Z. Tugba Kahyaoglu engaged with her students. illustrating that engagement with students is the key to good instruction. Photo 4 shows Sheron Snyder, an early pioneer of Conceptual Physics with very young students—8th graders—successfully! Also via student engagement. She has for years shown that properly engaged, the concepts of physics are indeed comprehensible to students.

A personality profile on Michael Faraday nicely opens this chapter.

This chapter focuses on the important features of electromagnetic induction, and avoids such complications as reactances, back emf, Lenz's law, and the left and right hand rules that normally serve to overwhelm your students. An important function of the chapter is to implant the idea of transferring energy from one place to another without means of physical contact. The chapter should be supported with various lecture demonstrations of electromagnetic induction, such as those in the figures of the chapter.

Magnetic strips of credit cards are common to all. Interestingly, there is now a new generation of "smart cards" that use *ferroelectric* memories, rather than ferromagnetic ones. Similar to the alignment of magnetic domains in ferromagnetic strips, the surfaces of ferroelectric crystals retain a charge polarization.

This chapter serves as a background for the study of light.

Practicing Physics Book:
• Faraday's Laws
• Transformers

Problem Solving Book:
Ample problems for both this and the preceding chapter

Laboratory Manual:
• Generator Activator Generators (Activity)

Next-Time Questions:
• Induction Coils
• Power Saw

Hewitt-Drew-It! Screencast: •*Electromagnetic Induction*

The suggested lecture will probably span two or three class periods.

SUGGESTED LECTURE PRESENTATION

This lecture is a series of demonstrations.

Electromagnetic Induction

Up to this point you have discussed how one can begin with electricity and produce magnetism. The question was raised in the first half of the 1800s; can it be the other way around—can one begin with magnetism and produce electricity? Indeed it can, enough to light entire cities with electric lighting! Now you produce your galvanometer, magnet, and wire loop—conspicuously well away from your previous electric power source.

> DEMONSTRATION: Plunge a magnet in and out of a single coil, as in Figures 25.1 and 25.3, and show with a galvanometer the current produced. This is nice with a large lecture demonstration galvanometer.

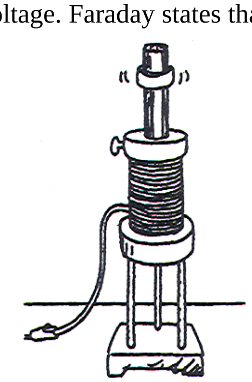
This need not be mysterious, for it follows from the deviations of electrons in a magnetic field, as in the previous chapter. Invoke the argument shown in Figure 25.7. [Electrons are moved across the magnetic field lines when you push the wire downward, and they experience a sideways force. That's because this time there *is* a path for them and they move along the wire. Point out that this is the same physics as Figure 25.7a.] Then repeat with the wire bent into two coils—twice the effect. Many coils (Figure 25.3), many times more current.

> DEMONSTRATION: (Comparing times of dropping a small bar magnet versus an unmagnetized piece of iron through a vertical conducting pipe.) First, drop a small unmagnetized piece of iron through a vertically held copper or aluminum pipe. It drops quickly. Then do the same with a small bar magnet. Aha, the dropping time is appreciably longer. The explanation is that as the magnet falls through the conducting pipe, the pipe's inner surface experiences a changing magnetic field, which induces a voltage and hence a flow of charge (a current). This current produces its own magnetic field, which interacts with the falling magnet. The interaction is repelling, for the direction of any induced field *opposes the change in the inducing field*. This is *Lenz's law* (not treated in the chapter to minimize information overload). Interestingly, if the induced field were to enhance the change in the inducing field, the falling magnet would be attracted rather than repelled and its acceleration would increase, meaning a gain in KE greater than its decrease in PE. A conservation of energy no-no! (Both Arbor Scientific and Pasco Scientific have kits that features this demonstration.)

Faraday's Law

We have seen that charges moving in a magnetic field experience forces. In the previous chapter, the force deviated the direction of electrons, both in a free beam and traveling along a wire, in which case the wire was deviated. Now we see that if we push electrons that are in a wire into a magnetic field, the deviating force will be along the direction of the wire and current is induced. Another way to look at this is to say that *voltage* is being induced in the wire. The current then, is a result of that voltage. Faraday states that the voltage induced in a closed loop equals the time rate of change of the magnetic field in that loop—another way of looking at induction. So rather than saying current is induced, Faraday says voltage is induced, which produces current.

> DEMONSTRATION: Show the assorted demonstrations with the classical Elihu Thompson Electromagnetic Demonstration Apparatus. With the power on, levitate an aluminum ring over the extended pole of the Elihu Thompson device, as is shown in the photo of the late Jean Curtis in the chapter opener.



> CHECK QUESTION: Do you know enough physics to state how much electromagnetic force supports this 1-newton aluminum ring (assuming the ring weighs 1 N)? [Answer: 1 N, not

particularly from a knowledge of electromagnetic forces, but from knowledge about forces in general that go back to Newton's laws. Since the ring is at rest and not accelerating, the upward electromagnetic force (in newtons!) must be equal to the downward force of gravity.]

DEMONSTRATION: With the power off, place the ring at the base of the extended pole. When you switch the power on, the current induced in the ring via electromagnetic induction converts the ring into an ac electromagnet. (By Lenz's law, the polarity of the induced magnet is always such to oppose the magnetic field imposed.)

CHECK QUESTION: Do you know enough physics to state whether or not the electromagnetic force that popped the ring was more than, equal to, or less than the magnetic force that produced levitation earlier? [Answer: More, because it accelerated upward, evidence the upward force was more than the weight. This is also understandable because the ring was lower where it intercepts more changing magnetic field lines.]

As interesting examples of electromagnetic induction, consider Think and Explains 53, 54, 55, and 56 (smart traffic lights, airport metal detectors, and earthquake detectors).

Emphasize the importance of this discovery by Faraday and Henry, and how its application transformed the world. In today's world it's difficult to imagine having no electric lights—to live in a time when illumination after the Sun goes down is by candles and whale-oil lamps. On a long scales this was not so long ago, really. In our older cities many buildings still have pre-electric light fixtures that once used gas or oil.

State that underlying all the things discussed and observed is something more basic than voltages and currents —the induction of *fields*, both electric and magnetic. And because this is true we can send signals without wires—radio and TV—and furthermore, energy reaches us from the Sun, sunlight.

Generators and Alternating Current
Point out that strictly speaking generators do not generate electricity—nor do batteries. What they do is pump a fluid composed of electrons. As stressed in the previous chapter, they don't make the electrons they pump. The electron fluid is in the conducting wires.

DEMONSTRATION: Return to the motor from the previous lecture and show that when you reverse the roles of input and output, and apply mechanical energy, it becomes a generator. Light a bulb with the hand-cranked generator and show how the turning is easier when the bulb is loosened and the load removed. Then allow students to try this themselves during or at the end of class.

Compare motor and generator—in principle the same. When electric energy is the input and mechanical energy is the output, the device is a motor. When mechanical energy is put in it and electrical energy is the output, the device is a generator. In fact, a motor acts also as a generator and creates a "back voltage" (back emf) and an opposing current. The net current in a motor is the input current minus the generated back current. An interesting example of this back current occurs in a motor that overheats. The net current in a power saw will not cause its overheating and damage to its motor windings—so long as it is running and generating a back current that keeps the net current low. But if you should jam the saw so that it can't spin, without the back current generated by the spinning armature, the net current is dangerously high and can burn out the motor.

It is interesting that electric motors are used in diesel-powered railroad engines. The combustion engine cannot bring a heavy load from rest, but an electric motor can. Why? Because when the armature is not turning, the current in the windings is huge, with a corresponding huge force. As both the train and the motor gain speed, the back current generated by the motor brings the net current in the motor down to nonoverheating levels.

Stress the fact that we don't get something for nothing with electromagnetic induction, and acknowledge Figure 25.4. This can be readily felt when lamps powered with a hand-cranked or a bicycle generator are switched on. Each student should experience this. The conservation of energy reigns!

Power Production

Continue with a historical theme: With the advent of the generator the task was to design methods of moving coils of wire past magnetic fields, or moving magnetic fields past coils of wire. Putting turbines beneath waterfalls, and boiling water to make steam to squirt against turbine blades and keep them turning—enter the industrial revolution.

Transformers

Explain the operation of a transformer. (I remember as a student being very confused about the seeming contradiction with Ohm's law—the idea that when voltage in the secondary was increased, current in the secondary was decreased.) Make clear that when the voltage increases in the coil of the secondary and the circuit it connects, the current in *that* circuit also increases. The decrease is with respect to the current that powers the *primary*—in the other coil—which is the reason why $P = IV$ does not contradict Ohm's law!

> DEMONSTRATION: With a step-down transfer, weld a pair of nails together. This is a spectacular demonstration when you first casually place your fingers between the nail ends before they make contact, and after removing your fingers bringing the points together allowing the sparks to fly while the nails quickly become red and white hot.

Cite the role of the transformer in stepping down voltages in toy electric trains, power calculators, and portable radios, and the role of stepping up voltages in various electrical devices, and both stepping up and stepping down voltages in power transmission.

> CHECK QUESTIONS: Consider feeding about 10 volts DC into a primary coil, turning it off and on so current fluctuations show on a galvanometer in the secondary circuit. When the coils are spread farther apart, a tiny current still shows on the galvanometer. Do as Henry A. Garon does and ask if induction will still occur if the coils are a mile away? A hundred miles away? If so, doesn't this suggest that the primary acts like a radio station, and the secondary as a radio receiver? Interestingly, receiver antennas in the early days of radio were in fact wound as large-diameter coils atop the receivers!

Field Induction

Point to the similarity of the field induction laws of Faraday and Maxwell—how a change in either field induces the other. This concept led Einstein to the development of his special theory of relativity. Einstein showed that a magnetic field appears when a purely electric field is seen by a moving observer, and an electric field appears when a purely magnetic field is seen from a moving vantage point.

Because of the electric and magnetic induction of fields in free space we can "telegraph" signals without wires—hence radio and TV—and furthermore, we shall see that because of field induction, there is light.
My screencast on *Electromagnetic Induction* focuses on this historical view.

Answers and Solutions for Chapter 25

Reading Check Questions

1. Independently, they both discovered electromagnetic induction.
2. For electromagnetic induction to occur there must be a change in magnetic field intensity in the coil.
3. The induced voltage in a coil is proportional to the number of loops, multiplied by the rate at which the magnetic field changes within those loops.
4. Move the loop near a magnet; move a magnet near a loop; change the current in a nearby loop.
5. Both frequencies are the same.
6. The basic differences are input and output, so whereas a motor converts electrical energy into mechanical energy, a generator does the reverse.
7. Current is ac because the induced voltage is ac.
8. Common frequency is 60 hertz.
9. Faraday and Henry made the discovery, Tesla put it to practical use.
10. An armature is an iron core wrapped with bundles of copper wire.
11. Steam commonly supplies energy to a turbine.
12. No, a generator simply transforms energy from one form to another.
13. A MHD generator has no moving parts.
14. Yes, the flow of electric charged particles through a magnetic field induces voltage.
15. Power is the rate that energy is transferred.
16. No, a transformer boosts voltage, or reduces it, but not energy. That's a conservation of energy no-no!
17. A transformer changes voltage and current, but not energy and power.
18. Power input and output are the same.
19. A step-down transformer steps down voltage.
20. Output current is increased.
21. Operation depends on change, hence alternating current ac.
22. The advantage of ac is efficient voltage stepping up or down.
23. Yes, this is called self-induction.
24. High voltage means less current for a given amount of power, which means less wasteful heating of wires.
25. No wires are needed. Personal electronic devices attest to this.
26. James Clerk Maxwell extended Faraday's law.
27. An alternating electric field is induced.
28. An alternating magnetic field is induced.
29. No wires needed!
30. Light!

Think and Do

31. Open-ended.

32. Open-ended.

33. Cans contain iron. Domains in the can tend to line up with Earth's magnetic field. When the cans are left stationary for several days, the cans become magnetized by induction, aligning with Earth's magnetic field.

34. When dropping the magnet through the copper pipe, its motion induces a circular current in the pipe, which is accompanied by a magnetic field. This induced field opposes the field that produced it and the magnet is considerably slowed as it falls through. Yum!

Plug and Chug

35. $\dfrac{120\ \text{V}}{10\ \text{turns}} = \dfrac{x\ \text{V}}{100\ \text{turns}}$, where x = (100 turns) $\times \dfrac{120\ \text{V}}{10\ \text{turns}}$ = 1200 V.

36. $\dfrac{120\ \text{V}}{100\ \text{turns}} = \dfrac{x\ \text{V}}{10\ \text{turns}}$, where x = (10 turns) $\times \dfrac{120\ \text{V}}{100\ \text{turns}}$ = 12 V.

Think and Solve

37. $\dfrac{120\ \text{V}}{500\ \text{turns}} = \dfrac{6\ \text{V}}{x\ \text{turns}}$, x turns $= 500$ turns $\times \dfrac{6\ \text{V}}{120\ \text{V}} = 25$ turns.

38. $\dfrac{120\ \text{V}}{360\ \text{turns}} = \dfrac{6\ \text{V}}{x\ \text{turns}}$, x turns $= 360$ turns $\times \dfrac{6\ \text{V}}{120\ \text{V}} = 18$ turns.

39. From the transformer relationship,
$\dfrac{\text{primary voltage}}{\text{number of primary turns}} = \dfrac{\text{secondary voltage}}{\text{number of secondary turns}} = \dfrac{120\ \text{V}}{24\ \text{V}} = \dfrac{5}{1}$. So there are

5 times as many primary turns as secondary turns.

40. Since power in both the primary and secondary is the same, $IV_{prim} = IV_{sec}$, a 5 times greater voltage in the primary means 1/5 as much current as in the secondary. That's 1/5 $\times$ 1.8 A = 0.36 A. Then (120V)(0.36A) = (24 V)(1.8 A).

41. The transformer steps up voltage by a factor 36/6 = 6. Therefore a 12-V input will be stepped up to 6 $\times$ 12 V = 72 V.

42. (a) From the transformer relationship, $\dfrac{\text{prim voltage}}{\text{number of prim turns}} = \dfrac{\text{sec voltage}}{\text{number of sec turns}}$,

$$\text{sec voltage} = \frac{\text{prim voltage} \times \text{number of sec turns}}{\text{number of prim turns}} = \frac{12\ \text{V} \times 250\ \text{turns}}{50\ \text{turns}} = 60\ \text{V}$$

(b) From Ohm's law, current $= \dfrac{V}{R} = \dfrac{60\ \text{V}}{10\ \text{W}} = 6\ \text{A}$.

(c) Power supplied to the primary is the same as the power delivered by the secondary;
Power = current $\times$ voltage = 6 A $\times$ 60 V = 360 W.

43. The voltage step up is (12,000V)/(120V) = 100. So there should be 100 times as many turns on the secondary as compared with the primary.

44. (a) Since $P = IV$, the current supplied to the users is

$$I = \frac{P}{V} = \frac{100,000\ \text{W}}{12,000\ \text{V}} = 8.3\ \text{A}.$$

(b) Voltage in each wire = current $\times$ resistance of the wire = (8.3 A)(10 Ω) = 83 V.
(c) In each line, power = current $\times$ voltage = (8.3 A)(83 V) = 689 W. The total power wasted as heat is twice this, 1.38 kW.
(d) The 1.38 kW wasted as heat is a small and tolerable loss. If the transmission voltage were ten times less, the losses to heat in the wires would be 100 times more! Then more energy would go into heat in the wires than into useful applications for the customers. That would not be tolerable, which is why high-voltage transmission is so important.

Think and Rank

45. B, C, A
46. (a) B, C, A (b) A, C, B (c) A=B=C

Think and Explain

47. E & M induction requires change; of the intensity of a magnetic field, or of motion in a magnetic field.

48. Magnetic induction will not occur in nylon, since it has no magnetic domains. That's why electric guitars use steel strings.

49. The magnetic domains that become aligned in the iron core contribute to the overall magnetic field of the coil and therefore increase its magnetic induction.

50. The magnetic field of the iron core adds to the magnetic field of the coil, as stated in the previous answer. Greater magnetic field means greater torque on the armature.

51. Work must be done to move a current-carrying conductor in a magnetic field. This is true whether or not the current is externally produced or produced as a result of the induction that accompanies the motion of the wire in the field. It's also a matter of energy conservation. There has to be more energy input if there is more energy output.

52. While the armature of a motor spins, converting electrical energy to mechanical energy, electric current (in the opposite direction) is induced. Then a motor acts as a generator.

53. A cyclist will coast farther if the lamp is disconnected from the generator. The energy that goes into lighting the lamp is taken from the bike's kinetic energy, so the bike slows down. The work saved by not lighting the lamp will be the extra "force $\times$ distance" that lets the bike coast farther.

54. Part of the Earth's magnetic field is enclosed in the wide loop of wire imbedded in the road. If this enclosed field is somehow changed, then in accord with the law of electromagnetic induction, a pulse of current will be produced in the loop. Such a change is produced when the iron parts of a car pass over it, momentarily increasing the strength of the field. A practical application is triggering automobile traffic lights. (When small ac voltages are used in such loops, small "eddy currents" are induced in metal of any kind that passes over the loop. The magnetic fields so induced are then detected by the circuit.)

55. As in the previous answer, eddy currents induced in the metal change the magnetic field, which in turn changes the ac current in the coils and sets off an alarm.

56. The changing magnetic field of the moving tape induces a voltage in the coil. A practical application is the early models of the tape recorder.

57. In both cases the direction of the magnetic force is perpendicular to the magnetic field and the motion of charges—but with different results. In the motor effect, the magnetic force pushes the wire upward. In the generator effect, the wire is pushed downward and the magnetic force pushes electrons in a direction along the wire to produce a current.

58. Voltage is induced.

59. Agree with your friend. Any coil of wire spinning in a magnetic field that cuts through magnetic field lines is a generator.

60. In accord with Faraday's law of induction, the greater the rate of change of magnetic field in a coil or armature, the greater the induced voltage. So voltage output increases when the generator spins faster.

61. In accord with electromagnetic induction, if the magnetic field alternates in the hole of the ring, an alternating voltage will be induced in the ring. Because the ring is metal, its relatively low resistance will result in a correspondingly high alternating current. This current is evident in the heating of the ring.

62. The changing magnetic field produced when the current starts to flow induces a current in the aluminum ring. This current, in turn, generates a magnetic field that opposes the field produced by the magnet under the table. The aluminum ring becomes, momentarily, a magnet that is repelled by the hidden magnet. It is repelled, just as the aluminum ring levitates in the photo opener with Jean Curtis.

63. The electromagnet is ac, which means a continually changing magnetic field in the copper ring. This induces a current in the ring, which then becomes its own electromagnet, which is continually repelled by the large electromagnet. The force of repulsion equals the weight of the ring, producing mechanical equilibrium.

64. If the light bulb is connected to a wire loop that intercepts changing magnetic field lines from an electromagnet, voltage will be induced which can illuminate the bulb. Change is the key, so to stay lit the electromagnet should be powered with ac.

65. Since all the electric resistance in this case is merely that of the wire itself (no other external load), twice the wire length means twice the resistance. So although twice the number of loops means twice the voltage, twice-as-much resistance results in the same current.

66. Induction occurs only for a *change* in the intercepted magnetic field.
(a) The galvanometer displays a pulse when the switch in the first circuit is closed, as the current in the coil increases from zero.
(b) When the current in the first coil is steady, no current is induced in the secondary and the galvanometer reads zero.
(c) The galvanometer needle will swing in the opposite direction when the switch is opened and current falls to zero.

67. The iron core increases the magnetic field of the primary coil, as stated in the answer to question 49. The greater field means a greater magnetic field change in the primary, and a greater voltage induced in the secondary. The iron core in the secondary further increases the changing magnetic field through the secondary and further increases the secondary voltage. Furthermore, the core guides more magnetic field lines from the primary to the secondary. The effect of an iron core in the coils is the induction of appreciably more voltage in the secondary.

68. A transformer requires alternating voltage because the magnetic field in the primary winding must change if it is to induce voltage in the secondary. No change, no induction.

69. When the secondary voltage is twice the primary voltage and the secondary acts as a source of voltage for a resistive "load," the secondary current is half the value of current in the primary. This is in accord with energy conservation, or since the time intervals are the same, "power conservation." Power input = power output; or $(\text{current} \times \text{voltage})_{\text{primary}} = (\text{current} \times \text{voltage})_{\text{secondary}}$: with numerical values, $(1 \times \text{V})_{\text{primary}} = (1/2 \times 2\text{V})_{\text{secondary}}$. (The simple rule power = current × voltage is strictly valid only for dc circuits and ac circuits where current and voltage oscillate in phase. When voltage and current are out of phase, which can occur in a transformer, the net power is less than the product current × voltage. Voltage and current are then not "working together." When the secondary of a transformer is open, for example, connected to nothing, current and voltage in both the primary and the secondary are completely out of phase—that is, one is maximum when the other is zero—and no net power is delivered even though neither voltage nor current is zero.)

70. A transformer is analogous to a mechanical lever in that work is transferred from one part to another. What is multiplied in a mechanical lever is *force*, and in an electrical lever, *voltage*. In both cases, energy and power are conserved, so what is not multiplied is energy, a conservation of energy no-no!

71. A step-up transformer multiplies voltage in the secondary by having more turns in the secondary coil than in the primary coil; a step-down transformer does the opposite—less turns in the secondary, which decreases voltage in the secondary.

72. The hum heard when a transformer is operating on a 60 hertz ac line is a 60 hertz forced vibration of the iron slabs in the transformer core as their magnetic polarities alternate. The hum is greater if any other mechanical parts are set into vibration.

73. The name of the game with E&M is *change*. No change, no induction. Alternating current changes direction, normally at 60 Hz.

74. High efficiency requires that the maximum number of magnetic field lines produced in the primary are intercepted by the secondary. The core guides the lines from the primary through the secondary. Otherwise some of the magnetic field generated by the primary would go into heating metal parts of the transformer instead of powering the secondary circuit.

75. A physical space is between the two. They are linked, however, by changing magnetic fields—the same in each coil.

76. The voltage impressed across the lamp is 120 V and the current through it is 0.1 A. We see that the first transformer steps the voltage down to 12 V and the second one steps it back up to 120 V. The current in the secondary of the second transformer, which is the same as the current in the bulb, is one-tenth of the current in the primary, or 0.1 A.

77. Oops! This is a dc circuit. Unless there is a changing current in the primary, no induction takes place. No voltage and no current are induced in the meter.

78. By symmetry, the voltage and current for both primary and secondary are the same. So 12 V is impressed on the meter, with a current of 1 A ac.

79. No, no, no, a thousand times no! No device can step up energy. This principle is at the heart of physics. Energy cannot be created or destroyed.

80. The moving magnet will induce a current in the loop. This current produces a field that tends to repel the magnet as it approaches and attract it as it leaves, slowing it in its flight. From an energy point of view, the energy that the coil transfers to the resistor is equal to the loss of kinetic energy of the magnet.

81. The source of an electromagnetic wave is an oscillating electric charge.

82. Waving it changes the "flux" of the Earth's magnetic field in the coil, which induces voltage and hence current. You can think of the flux as the number of field lines that thread through the coil. This depends on the orientation of the coil, even in a constant field.

83. The incident radio wave causes conduction electrons in the antenna to oscillate. This oscillating charge (an oscillating current) provides the signal that feeds the radio.

84. The frequencies are the same.

85. Agree with your friend, for light is electromagnetic radiation having a frequency that matches the frequency to which our eyes are sensitive.

86. Electromagnetic waves depend on mutual field regeneration. If the induced electric fields did not in turn induce magnetic fields and pass energy to them, the energy would be localized rather than "waved" into space. Electromagnetic waves would not exist.

Think and Discuss

87. Copper wires were not insulated in Henry's time. A coil of non-insulated wires touching one another would comprise a short circuit. Silk was used to insulate the wires so current would flow along the wires in the coil rather than across the loops touching one another.

88. When the ground shakes, inertia of the suspended massive magnet tends to resist such shaking. But the coils of wire are fixed to the Earth and shake relative to the magnet. Motion of the magnet within conducting loops induces a current, which depends on the strength of the earthquake. So the law of inertia and the law of electromagnetic induction underlie the operation of this device.

89. Two things occur in the windings of the electric motor driving a saw. Current input causes them to turn and you have a motor. But motion of windings in the magnetic field of the motor also make them a generator. The net current in the motor is the input current minus the generated output current, which is opposite in direction to the input current. You pay the power company for the net current. When the motor jams, the net current is increased because of the absence of generated current. This can burn the windings of the saw!

90. In a power line, the high voltage is between one wire and another, not from one end of a given wire to the other end. The voltage difference between one end of the wire and the other is actually small, corresponding to the small current in the wire. The voltage difference *between the wires* multiplied by the current gives the power transmitted to the load. The voltage difference *between one end of a wire and the other* multiplied by the current gives the (much smaller) power dissipated in the wire. So, in applying Ohm's law, it's important that the voltage and current are applied to the same part of the circuit.

91. As the magnet falls, it induces current that circles in the conducting pipe and is accompanied by its own magnetic field. The moving magnet is slowed by interaction with this induced field.

92. Slowness of fall is due to interaction of the magnetic field of the falling magnet with the field induced in the conducting tube. No conduction, as with a cardboard tube, means no induced field and no slowness of fall.

93. Motion of conducting sheets through a magnetic field induces swirling currents (eddy currents) with fields that interact with the magnet and slow motion. Such doesn't occur in non-conducting cardboard.

94. Induced currents in the bar are accompanied by their own magnetic fields, which interact with the magnet and slow motion.

95. A voltage difference is induced across the wings of a moving airplane. This produces a momentary current and charge builds up on the wing tips to create a voltage difference that counteracts the induced voltage difference. So charge is pulled equally in both directions and doesn't move.

96. Such a scheme violates both the 1st and 2nd laws of thermodynamics. Because of inherent inefficiencies, the generator will produce less electricity than is used by the adjoining motor to power the generator. A transformer will step up voltage at the expense of current, or current at the expense of voltage, but it will not step up both simultaneously—that is, a transformer cannot step up energy or power. Like all practical systems, more energy is put in than is supplied for useful purposes.

26 Properties of Light

The opening photo for Part Six is Lillian's nephew, Christopher Lee, who has been helpful in our development of screencasts. Thank you Christopher!

For chapter photo openers, how lucky I was to come across this photo from space of a solar eclipse! An astronaut's view of a solar eclipse. With pride the second photo is my daughter and her husband Bob, with physics instructor friend Dave Wall. And how nice that a partial solar eclipse in 2012 was caught by lab manual author Dean Baird outside his classroom. The sunballs just before the eclipse beautifully transform to crescents as the Moon passes in front of the Sun. Exploratorium physicist and senior staff scientist Paul Doherty traveled to Nevada to catch the totality, and a rare annular eclipse, nicely caught in the fifth photo.

The personal profile is James Clerk Maxwell, who among so many other things showed how electricity and magnetism connect to become light.

Some instructors begin their course in physics with light, a topic that has greater appeal to many students than mechanics. Your course could begin with this chapter and continue through the following chapters of Part 6, or you could first integrate chapters on vibrations, waves, and sound from Part 4 in your sequence. Since the chapters are nearly self-contained allows you flexibility. If you're doing Parts 4 and 6 together, the reason for jumping in at this chapter may be to avoid the more technical nature of Chapter 19. This sequence, Chapters 26, 27, 19-21, 28, and 30, is a gradual entrance to the study of physics. If this chapter is used as a launch point, you need only introduce the definitions of speed and frequency. In addition, give a demonstration of resonance with a pair of tuning forks—a foundation for explanations of the interaction of light and matter.

Note that the "depth of the plow" in the treatment of light is respectably deep. The aim is not to separate and name categories such as transmission, reflection, and absorption, but to promote good physics comprehension. Your students will experience some good physics in this chapter—and understand it. Understanding more than they may expect, and discovering more than they thought they could, is the real joy of learning. So this should be an enjoyable chapter—why some teachers opt to begin here.

Of particular interest to your students is the box on Fractal Antenna and mobile phones on page 490. The box is a jumping off place if you wish to further discuss fractals—fascinating information!

Figure 26.4 features Bruce Novak, whose many suggestions for this edition I am grateful for. For one thing, I've used his photo of the color spectrum in three of my screencast backgrounds.

In reference to the optical illusions of Figure 26.23: The slanted line is not broken, as can be seen looking at the book at a grazing angle. The dashes are all the same length, as a ruler will show. For a bit of humor, the vertical lines are *not* parallel. And a look at the page at a grazing angle will confirm that the tiles are not crooked. The width of the hat is the same as its height, the "fork" and "rectangular" piece could not be made in the shop, and there are two THEs in the PARIS IN THE THE SPRING.

How nice eyeglasses are light sensitive and become sunglasses when UV light hits them. My sister complains that they "don't work" when driving. A nice physics anecdote! Of course they don't work in an automobile because the glass windows shield the UV necessary to activate their darkness. Share that info with your class.

One page 2 of **Practicing Physics** is a fascinating exercise on the pinhole image of the Sun. One of my very favorites! Its early placement is to provide a first measuring activity to accompany Chapter 1. If you haven't done it there, consider it here, although you should call attention to the box on page 535 of the next chapter that describes the pinhole camera. Interestingly, most people don't notice the circles or ellipses of sunlight that are cast beneath trees due to the openings between leaves. Many artists who paint splotches of light in the shade of trees paint irregular shapes because they expect the shapes should be as irregular as the openings in the leaves above. Renoir, as Chapter 1 indicated, saw what was there and painted it accordingly (back on page 7). This exercise puts you in a beautiful role: being the person to point out the niceties in the world that ordinarily might be missed. That's one of the niceties of being a physics instructor!

Practicing Physics:
• Pinhole Image of the Sun

Next-Time Questions:
• Radio and Sound Waves
• Faster than *c*

Hewitt Drew It! Screencast: •*Speed of Light*

SUGGESTED LECTURE PRESENTATION

If this chapter follows E&M, and your students have just finished Chapter 25, then begin your lecture with **Begin 1** that follows. If you're beginning your course with light without having covered E&M, then jump ahead to **Begin 2**.

Begin 1: **Electromagnetic Waves**: Usually I begin my lecture by asking the class to recall my recent demonstration of charging a rubber rod with cat's fur and how when I brought it near a charged pith ball, I produced *action at a distance*. When I moved the charged rod, the charged ball moved also. If I gently oscillate the rod, the ball in turn oscillates. State that one can think of this behavior as either action-at-a-distance or the interaction of the ball with the space immediately around it—the electric field of the charged rod. For low frequencies, the ball will swing in rhythm with the shaking rod. But the inertia of the ball and its pendulum configuration makes response poor for any vigorous shaking of the rod (that's why it's best not to actually show this, but to only describe it and go through the motions as if the equipment were present—you avoid the "that's the way it should behave" situation). You can easily establish in your students' minds the reasonableness of the ball shaking to-and-fro in response to the shaking electric field about the shaking rod. Carry this further by considering the ball to be simply a point charge with negligible mass. Now it will respond in synchronous rhythm with the shaking rod. Increase the frequency of the shaking rod and state that not only is there a shaking electric field about the rod, but because of its changing, there is a different kind of field.

> CHECK QUESTIONS: What kind of field is induced by the charged shaking rod? What kind of field in turn, does this induced field induce? And further in turn, what kind of field does this further induced field induce? And so on.

Develop the idea of the optimum speed of the field emanation, that is consistent with energy conservation, discussed in the section *Electromagnetic Wave Velocity*. This is treated in the *Speed of Light* screencast.

Begin 2: **Electromagnetic waves**: Begin by stating that everybody knows that if you place the end of a stick in a pond and shake the stick back-and-forth, you'll generate waves across the water surface. But what everybody doesn't know is that if you shake a charged rod back-and-forth in free space, you'll generate

waves also. Not waves of water, or even waves of the medium in which the stick exists, but waves of electric and magnetic fields. You'll generate *electromagnetic waves*. Shaking the rod at low frequencies generates radio waves. Shaking at a million billion times per second generates waves one could see in the dark. For those waves would be seen as light.

Electromagnetic Wave Velocity

If you've just covered E&M, go into some detail on the mutual induction of electric and magnetic fields, and how the critical speed of light is determined by the conservation of energy (in the section *Electromagnetic Wave Velocity*). But if you're jumping into light without having done E&M, tell your students that this section should be treated lightly, and to move onward. A small price for jumping into the middle of a book!

> CHECK QUESTION: So the speed of light is finite; does this mean your image in the mirror is always a bit younger or a bit older than you? [Younger, but of course not by very much!]

Electromagnetic Spectrum

Continue by stating that, strictly speaking, light is the only thing we see. And to understand what light is, we will first try to understand how it behaves. Call attention to the rainbow of colors that are dispersed by a prism or by raindrops in the sunlight, evidence that white light can be spread into a spectrum of colors. Ask your students to consider the world view of little creatures who could only see a tiny portion of the spectrum, who would be color blind to all the other parts. Their world view would be very limited. Then state that we are like those little creatures, in that the spectrum of colors we can see are a tiny portion of the *electromagnetic spectrum* (Figure 26.3)—less than a tenth of one percent! We are color blind to the other parts. The instruments of science have extended our view of the other parts. These instruments are not microscopes and telescopes, for they enable closer viewing of the part of the spectrum we are familiar with. It is the infrared detecting devices, microwave and radio receivers, that allow us to explore the lower-frequency end of the spectrum, and ultraviolet, x-ray, and gamma-ray detectors that let us "see" the higher-frequency end. What we see without unaided eyes is a tiny part of what's out there!

Buckminster Fuller put it well when he stated that ninety-nine percent of all that is going to affect our tomorrows is being developed by humans using instruments that work in ranges of reality that are nonhumanly sensible.

> CHECK QUESTION: Where does sound fit in the electromagnetic spectrum? [It doesn't!]

> CHECK QUESTION: A photographer wishes to photograph a lightning bolt, and comes up with the idea of having the camera triggered by the sound of thunder. A good idea or a poor idea? [Very poor, for light travels about a million times faster than sound. By the time the sound of thunder arrives, the lightning bolt is long gone!]

A sunburn is easier to get at the beach because the UV reflects from both water and to a lesser extent, sand. You're lit not just from above, but from beside and below. And for the record, you can get sunburned through a wet T-shirt.

Transparent Materials

Recall your earlier demonstration of sound resonance (or if you haven't done this, demonstrate now the resonance of a pair of tuning forks mounted on sounding boxes (Figure 26.6). The tuning fork demo provides important experience for your students in understanding the interaction of light and matter. In some cases light strikes a material and rebounds—reflection (Chapter 28). In cases where light continues through the material, we say the material is transparent.

> DEMONSTRATION: Show the swinging balls apparatus (Newton's cradle) that is usually used to illustrate momentum and energy conservation. Here you are showing that the energy that cascades through the system of balls is analogous to light energy cascading through transparent matter. Just as the incident ball is not the same ball that emerges, the incident "photon" of light

upon glass is not the same photon that emerges through the other side. Although too difficult to see, slight interaction times between balls produces a slight time delay between incidence and emergence of balls. Likewise for light.

Note that the text does not mention photons in the light-through-glass explanation. Photons aren't introduced until Chapter 30 (although this treatment of light passing through glass does invoke photon in my screencast *Speed of Light*).

CHECK QUESTION: Compared to the speed of light in a vacuum, why is the speed of light less in transparent materials such as water or glass? [Answer: According to the model treated in the text, there is a time delay between the absorption of light and its re-emission. This time delay serves to decrease the average speed of light in a transparent material.]

Another analogy for light traveling through glass is the average speed of a basketball moving down a court. It may fly through the air from player to player at one constant speed, but its average speed down the court depends on the holding time of the players. Carrying the analogy further, different materials have different players, and although the instantaneous speed of light is always the same, the average speed depends on the number of players encountered, and the holding time of each player.

Why light travels in a straight line is not evident at this point. Later in Chapter 29, Huygens' principle provides an explanation (Figure 29.4).

On the subject of glass, it's interesting to note that we see through it for the same reasons we see through water. Despite the appearance of glass, it is really a highly viscous liquid rather than a solid. Its internal structure is not the regular crystalline latticework of most solids, but is essentially random like that of liquids. Whereas conventional liquids have a freezing point at which they become solid, liquid glass gets stiffer as it cools. At room temperature its rate of flow is so slow that it takes centuries for it to appreciably ooze out of shape. Because of the downward flow due to gravity, windowpanes only several decades old show a lens effect at their bottoms due to the increased thickness there (most cases of window glass being thicker at the bottom, however, is due to installers favoring the thicker part for the bottom).

Opaque Materials
State that light generally has three possible fates when incident upon a material: (1) reflects, (2) is transmitted through the material, or (3) is absorbed by the material. Usually a combination of all three fates occurs. When absorption occurs, the vibrations given to electrons by incident light are often great enough to last for a relatively long time, during which the vibratory energy is shared by collisions with neighboring atoms. The absorbed energy warms the material.

CHECK QUESTION: Why is a black tar road hotter to the touch when in sunlight than a pane of window glass? [Sunlight is absorbed and transformed into internal energy in the road surface, but transmitted through the glass to somewhere else.]

For the record, we say that ultraviolet light cannot penetrate glass. Hence you cannot get a sunburn through glass. But *some* ultraviolet light does pass through glass—long wavelength ultraviolet light, which has insufficient energy to cause a sunburn. Most sunlamps *aren't* made of ordinary glass—they're made of quartz or special UV-transparent glass.

Shadows
Illustrate the different shadows cast by small and large sources of light. Ask why there appears no definite shadow of students' hands when held above their desks, and relate this to the multiple sources and diffused light in the room.

Eclipses
Explain and distinguish solar and lunar eclipses.

CHECK QUESTION: Does the Earth cast a shadow in space whenever a lunar or solar eclipse occurs? [Yes, but not only when these events occur—the Earth, like all objects illuminated by light from a small source, casts a shadow. Evidence of this perpetual shadow is seen at these special times.]

CHECK QUESTION: Why do you not cast a shadow on the ground on an overcast day? [A relatively small light source such as the Sun casts a relatively sharp shadow. On an overcast day the primary Sun is blocked and the whole sky, the secondary light source, illuminates you. The source is now so big that no shadow is seen.]

Point out that light from a point source follows the inverse-square law (first treated in Chapter 9, and again for Coloumb's law in Chapter 22). A camera flash is a point source, obeys the inverse-square law, something that is not understood by people who attempt to take pictures of far-away nighttime scenes with flash cameras—like snapping long-distance shots at a nighttime concert, or a night view of a distant city. Cite how light from the flash spreads out on both the outgoing and return trip to the camera, consequently delivering very little light to the camera.

Seeing Light—The Eye

An interesting tidbit not in the chapter is the explanation for the seemingly luminous eyes of nocturnal animals such as cats and owls at night. It turns out there are reflective membranes located in back of the rods in the animals' eyes, which provide a "second chance" for the animal to perceive light that initially misses the rods. This arrangement, common in night predators, gives excellent night vision. Hence also the reflection from their eyes when light is shone on them.

Discuss the function of the rods and three types of cones in the retina of the eye, and how color cannot be perceived in dim light, and how the colored stars appear white to us whereas they show up clearly colored with camera time exposures. (I show a colored slide that I took of the stars, and discuss the curved lines encircling the North Star, and get into a discussion of how long the camera shutter was held open.)

In discussing color vision, point out that in a bullfight, the bull is angry not at the redness of the cape that is flaunted before him, but because of the darts that have been stuck into him! Whereas a frog is "wired" to see only motion, so it is also on the periphery of our vision. Discuss the fact that we see only motion and no color at the periphery of our vision.

DEMONSTRATION: Figure 26.19; stand at a corner of the room and shake brightly colored cards, first turned backward so the color is hidden and students can adjust the position of their heads (somewhat facing the opposite corner of the room). When they barely see the moving cards, turn them over so the color shows. They'll see the cards, but not their colors! Try with different colors. This goes over well, and is surprising to most students.

Pupilometrics (Figure 26.20) is prone to misunderstanding. If you lecture on this topic, it is important to dispel misconceptions your students may associate with pupil size. It would not be well for people who normally have small pupils to feel self-conscious about this and mistakenly believe that small pupils display a slight negativity. Also, pupil size decreases with age. It would not be well for young people to mistakenly feel that their older peers were "emotionally down" in general. It is the *change* in pupil size, not the pupil size itself, that pupilometrics is about. For more on this, Google *pupilometrics* on the Internet.

Figure 26.21 on lateral inhibition is just one more reminder to your students that they should be careful about believing firmly in what appears to be true. By obstructing the edge between the rectangles, a whole different picture is presented. Our eyes do indeed deceive us from time to time. We should always be open to new ways to look at what we consider is real.

The tiles illusion in Figure 26.23 is nicely employed in the public restrooms in the San Francisco Exploratorium. The shape of grey caulking between tiles makes a big difference. Quite impressive!

Answers and Solutions for Chapter 26

Reading Check Questions

1. A changing magnetic field induces a changing electric field.
2. A changing electric field induces a changing magnetic field.
3. An electromagnetic wave is produced by vibrating electric and magnetic fields.
4. If the wave slowed, regeneration of waves would decrease, and lose energy. Therefore this doesn't occur.
5. If the wave sped up, there would be greater regeneration of waves and energy would increase. Therefore this doesn't occur.
6. Electric and magnetic fields contain and transport energy.
7. The principle difference between radio, light, and X-rays is frequency.
8. Light occupies about one millionth of 1% of the measured spectrum.
9. Red for lowest frequencies, violet for highest visible frequencies.
10. The frequencies of vibrating electrons are transferred to the waves, so the frequencies of both are the same.
11. Higher frequencies of light have shorter wavelengths.
12. The wavelength is 300,000 km long.
13. Outer space is filled with electromagnetic waves, for one thing.
14. Light encountering a transparent material causes atoms in the material to vibrate.
15. The resonant frequency of glass is in the ultraviolet region.
16. The energy of ultraviolet light becomes thermal energy.
17. The energy of visible light transmits through the glass and passes out the other side.
18. The energy of infrared light becomes thermal energy.
19. The frequencies match.
20. The average speed of light in glass is less than its speed in a vacuum.
21. The incident and emerging speed of light are the same.
22. Infrared waves cause whole atoms and molecules to vibrate.
23. Light is absorbed and turns to thermal energy.
24. Metals are shiny because their free electrons easily vibrate to incoming light.
25. Multiple reflections absorb light and the light emerging is weaker.
26. Umbra is the totally dark part of a shadow; a partial shadow is a penumbra.
27. All object in sunshine cast shadows, so yes, Earth and Moon always cast shadows. When the Sun or Moon passes within the other's shadow, we have an eclipse.
28. Rods in the eye see brightness but not color; cones are sensitive to color.
29. Object on the periphery is best seen when moving.
30. The pupil widens with emotional interest.

Think and Do

31. You may be surprised to find that the size of the Moon in the sky is that same whether low or high in the sky, even though a casual look finds it larger nearer the horizon. The explanation is physiological.
32. Open ended and interesting!

Think and Solve

33. Speed $= \dfrac{300,\,000,\,000 \text{ km}}{1300 \text{ s}}$ = 231,000 km/s. This value is 77% the modern value.

34. Round trip is 30 km, so from *d* = *ct, t* = *d/c* = 30 km/300,000 km/s = 0.0001 second.

35. From $v = \dfrac{d}{t}$, $t = \dfrac{d}{v} = \dfrac{d}{c} = \dfrac{1.5 \times 10^{11}\,\text{m}}{3 \times 10^{8}\,\text{m/s}} = 500\ \text{s}$ (which equals 8.3 min).
    The time to cross the diameter of the Earth's orbit is twice this, or **1000 s**, as estimated fairly closely by Roemer (question 33).

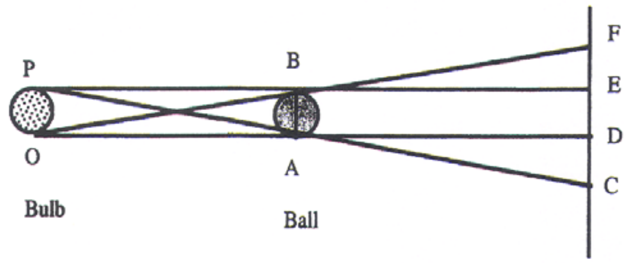
36. Earth-Moon distance is 3.8×10^8 m, so the round-trip distance is 7.6×10^8 m. As in the previous problem, $t = \dfrac{d}{v} = \dfrac{d}{c} = \dfrac{7.6 \times 10^{8}\,\text{m}}{3 \times 10^{8}\,\text{m/s}} = 2.5\ \text{s}$.

37. As in the previous problem, $t = \frac{d}{v} = \frac{d}{c} = \frac{4.2 \times 10^{16}\ \text{m}}{3 \times 10^{8}\ \text{m/s}} = 1.4 \times 10^{8}\ \text{s}$.

Converting to years by dimensional analysis,

$$1.4 \times 10^8\ \text{s} \times \frac{1\ \text{h}}{3600\ \text{s}} \times \frac{1\ \text{day}}{24\ \text{h}} \times \frac{1\ \text{yr}}{365\ \text{day}} = 4.4\ \text{yr}.$$

38.



The lines OAD and PBE are parallel, so the umbra, between D and E, has the same diameter as the ball. The triangles OAB and ODF are similar, with sides in the ratio of 2 to 1, so the distance DF is twice the distance AB. This means that the distances CD, DE, and EF are the same, so the penumbra, between C and F, has three times the diameter of the ball.

39. (a) Frequency = speed/wavelength = $(3 \times 10^8\ \text{m/s})/(0.03\ \text{m}) = 1.0 \times 10^{10}$ Hz = 10 GHz.
(b) Distance = speed × time, so time = distance/speed = $(10{,}000\ \text{m})/(3 \times 10^8\ \text{m/s}) = 3.3 \times 10^{-5}$ s. (Note the importance of consistent SI units to get the right numerical answers.)

40. Light in water travels at 0.75*c*. $\lambda = \frac{c}{f}$ for light in a vacuum (or air), and $\lambda = \frac{0.75c}{f}$ for light in water.
The ratio of λ_{water} to λ_{air} is therefore 0.75, the same for all frequencies.
So the wavelength of light in water is $^3/4$ its value in air. Wavelength changes while frequency remains the same. In water, the wavelength of this orange light is (0.75)(600) = 450 nm.
In Plexiglas, its wavelength is (0.67)(600) = 400 nm.

Think and Explain

41. Your friend is correct. Also in a profound tone, your friend could say that sound is the only thing we hear!

42. Your friend is again correct. Light is the oscillation of electric and magnetic fields that continually regenerate each other.

43. The fundamental source of electromagnetic radiation is oscillating electric charges, which emit oscillating electric and magnetic fields.

44. The wavelengths of radio waves are longer than those of light waves, which are longer than the wavelengths of X-rays.

45. Ultraviolet has shorter wavelengths than infrared. Correspondingly, ultraviolet also has the higher frequencies.

46. Use film or a photosensitive element that is sensitive to the infra-red part of the spectrum, for things in the environment emit infrared waves, whether they are in darkness or in light.

47. What waves in a light wave are the electric and magnetic fields. Their oscillation frequency is the frequency of the wave.

48. Frequency; a gamma ray has a higher frequency (and therefore more energy per photon) than an infrared ray.

49. Speed is *c*, the speed of light.

50. Both travel at the same speed *c*.

51. Agree. They are both electromagnetic waves.

52. Agree, for a radio wave is an E&M wave while sound is a mechanical wave.

53. Agree. Electromagnetic wave are everywhere.

54. Both are much longer because their frequencies are much lower than the frequencies of visible light.

55. The faster wave has the longer wavelength—light, in accord with the rule $\lambda = v/f$.

56. Sound requires a physical medium in which to travel. Light does not.

57. Radio waves are electromagnetic waves and travel at the speed of light. (Don't confuse sound waves with radio waves!)

58. Radio waves and light are both electromagnetic, transverse, move at the speed of light, and are created and absorbed by oscillating charge. They differ in their frequency and wavelength and in the type of oscillating charge that creates and absorbs them.

59. The shorter wavelength corresponds to a higher frequency, so the frequency of the blue-green light from the argon laser has higher frequency than the red light from the helium-neon laser.

60. The average speed of light will be less where it interacts with absorbing and re-emitting particles of matter, such as in the atmosphere. The greater the number of interactions along the light's path, the less the average speed.

61. Glass is opaque to frequencies of light that match its own natural frequencies. This is because the electrons in the absorbing medium are driven to oscillations of much larger amplitudes than occurs for non-resonant frequencies. These large amplitudes result in energy transfer to neighboring atoms and an increase in internal energy rather than a re-emission of light.

62. The greater number of interactions per distance tends to slow the light and result is a smaller average speed.

63. Transparency or opaqueness is determined by the match between incident light frequencies and the resonant frequency of the material. A substance that is transparent to a range of light frequencies will be opaque to those frequencies that match its own resonant frequency.

64. Clouds are transparent to ultraviolet light, which is why clouds offer very little protection from sunburn. Glass, however, is opaque to ultraviolet light, and will therefore shield you from sunburn.

65. The sunglasses will be warmer in sunlight than regular reading glasses because the reading glasses transmit most of the light energy that is incident upon them, whereas the sunglasses absorb more light energy, increasing their internal energy.

66. Any shadow cast by a faraway object such as a high-flying plane is filled in mainly by light tapering in from the Sun, which is not a point source. This tapering is responsible for the umbra and penumbra of solar eclipses (Figure 26.14). If the plane is low to the ground, however, the tapering of light around the airplane may be insufficient to fill in the shadow, part of which can be seen. This idea is shown in Figure 26.12.

67. Rods, not cones, will respond to weak light, so you want to focus low-intensity light on a part of the retina that is composed of rods. That would be off to the side of the fovea. If you're looking at a dim star, look a bit off to the side of where you expect to see it. Then its image will fall on a part of your eye where rods may pick it up.

68. The light reflected by objects in the moonlight is most often too dim to stimulate the color-perceiving cones in the eye. So we see these objects primarily with our rods, which explains their lack of color.

69. We see no color at the periphery of our vision simply because there are no cones located on the outermost regions of the retina.

70. Unless light reaching her eyes has increased in intensity, her contracting pupils imply that she is displeased with what she sees, hears, tastes, smells, or how she feels. In short, she may be displeased with you!

71. The blind spot is located on the side of the fovea away from your nose.

72. We cannot infer that people with large pupils are generally happier than people with small pupils. The size of a person's pupils has to do with the sensitivity of the retina to light intensity. Your pupils tend to become smaller with age as well. It is the *change* in pupil size that suggests one's psychological disposition.

73. In accord with the inverse-square law, brightness is less than 1/25 that seen from Earth.

74. No, for the brightest star may simply be the closest star.

75. You're seeing the galaxy as it "was" when light left it, long, long ago.

76. You see your hand in the past! How much? To find out, simply divide the distance between your hands and your eyes by the speed of light. (At 30 cm, this is about a billionth of a second.)

77. From the Conversion Factors table on the inside back cover, note that 1 ft = 0.3048 m. So 20 feet is 20 $\times$ 0.3048 m = 6.096 m. So rounded off, in the metric system you could hope for 6/6 vision.

Think and Discuss

78. The terms are misleading in that they imply that ultraviolet and infrared are forms of visible light. More correctly, they are forms of electromagnetic radiation. So in the sense used, "light" is used to mean "electromagnetic radiation." This usage stems from the fact that the ultraviolet and infrared regions of the spectrum are adjacent to visible light. The terms "radio light" and "x-ray light" are uncommon, for one likely reason, that radio x-ray parts of the spectrum are far removed from the visible part.

79. We can see the Sun and stars.

80. Radio waves are electromagnetic waves, not to be confused with sound, which is a mechanical wave entirely different than any electromagnetic wave. Neither is visible.

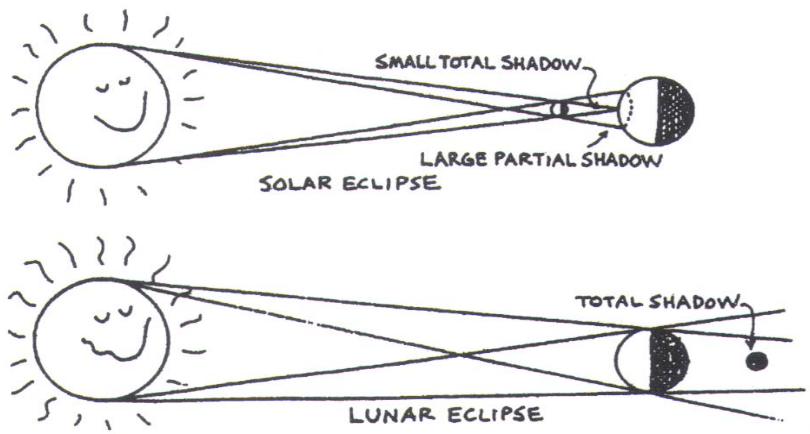
81. The fact that the different parts of the electromagnetic spectrum emitted in the explosion are received simultaneously is evidence for the frequency independence of the speed of light. If wave speed depended on frequency, different frequencies would be received at different times.

82. The instantaneous speed of the bullet after penetrating the board is less than its incident speed, but not so with light. The instantaneous speed of light before meeting the glass, while passing through it, and when emerging is a constant, *c*. The fundamental difference between a bullet fired through a board and light passing through glass is that the *same* bullet strikes and later emerges. Not so for light. The "bullet of light" (photon) that is incident upon glass is absorbed by its interaction with an atom or molecule. The atom or molecule in turn then emits, with some time delay, a new "bullet of light" in the same direction. This process cascades through the glass with the result being that the "bullet of light" emerging is not the same "bullet" that was first incident. In the space between the atoms in matter the instantaneous speed of light is *c*. Because of the time delay of the interactions, only its average speed is less than *c*. The light that emerges has speed *c*.

83. Walking across a room and pausing to greet others is analogous to the transmission-of-light model in that there is a pause with each interaction. However, the same person that begins the walk ends the walk, whereas in light transmission there is a "death-birth" sequence of events as light is absorbed and "new light" is emitted in its place. The light to first strike the glass is not the same light that finally emerges. (Another analogy is a relay race, where the runner to begin the race is not the runner to cross the finish line.)

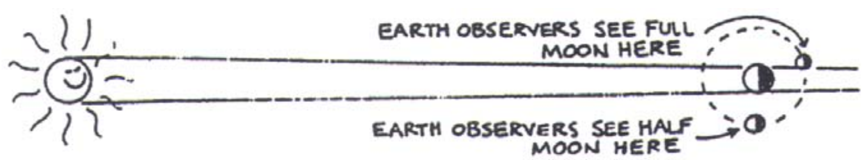
84. A solar eclipse is a shadow of the Moon that reaches a relatively small part of the Earth, and only those people in the shadow or partial shadow experience it. But a lunar eclipse is the Earth's shadow

upon the Moon, which is visible to all who can see the Moon. So everyone who can see the Sun won't see its eclipse unless they're in its shadow, but everyone who can see the Moon will see its eclipse where there is one.



85. Yes. Evidence is a lunar eclipse, when the Moon passes in the Earth's shadow.

86. A lunar eclipse occurs when the Earth, Sun, and Moon all fall on a straight line, with the Earth between the Sun and the Moon. During perfect alignment the Earth's shadow falls on the Moon. Not-quite-perfect alignment gives Earth observers a full view of the Moon. Moonlight is brightest and the Moon is always fullest when the alignment is closest to perfect—on the night of a lunar eclipse. At the time of a half moon, however, lines from Earth to Moon and from Earth to Sun are at right angles to each other. This is as non-aligned as the Earth, Moon, and Sun can be, with the Moon nowhere near the Earth's shadow—no eclipse is possible. Similarly for the non-aligned times of a crescent moon.



87. During a partial eclipse where crescents of the Sun are cast, the Moon is partly in front of the Sun.

88. The solid angle from each opening in the leaves to the circles cast on Dean is the same solid angle between the leaves and the Sun. So just as 100 circles, each the size of the solar image, fit between Dean and the tree opening, 100 Suns would fit between the tree and its position from Earth, a distance of 150,000,000 km.

89. The Moon is farther away from its average distance from Earth, so is smaller in the sky. If it were closer, the Moon would appear bigger and the Sun would be entirely blocked when the Moon, Sun, and Earth align.

90. No eclipse occurred because no shadow was cast on any other body.

91. (a) Moon observers would see the Earth in the path of the sunlight and see a solar eclipse. (b) Moon observers would see a small shadow of the Moon slowly move across the full Earth. The shadow would consist of a dark spot (the umbra) surrounded by a not-as-dark circle (the penumbra).

92. Energy is spread out and diluted, but not "lost." We distinguish between something being diluted and something being annihilated. In accord with the inverse-square law, light intensity gets weaker with distance, but the total amount of light over a spherical surface is the same at all distances from the source.

93. Light from the flash spreads via the inverse-square law to the ground below, and what little returns to the airplane spreads further. The passenger will find that the flash makes no difference at all. Taking pictures at great distances, whether from an airplane or the football stands, with the flash intentionally turned on is rather foolish.

94. Some airplanes bounce radar waves to and from the ground below, measuring the round trip time for determining distance to the ground, much as a ship bounces sonic waves from the ocean floor to measure water depth. Far above the ground an altimeter is fine for determining the airplane's height above sea level, but close to the ground the pilot wants to know the airplane's distance from local ground.

27 Color

Carlos Vasquez colorfully opens this chapter with the three-lamp demo. Carlos's dad is John Vasquez, one of the five Vasquez brothers who took my class in consecutive years back in the 70s and 80s. All are now educators. Some twenty years ago I boasted that Suzanne Lyons Lange was the best of my editors with Addison-Wesley. Since then she advanced through the ranks and I'm presently delighted to have her as a co-author to my physical science books! She is shown here with her children, Tristan and Simone. Photo five is of Jeff Wetherhold who brings color not only to his classroom, but to canvas. Jeff's passion for physics is evident in his website (www.parklandsd.org/web/wetherhold/). Between the Vasquez and Lange family, and Jeff Wetherhold, what a great group of people!

The brief profile is of Isaac Newton and his investigations of color.

In this chapter we introduce a model of the atom in which electrons behave as tiny oscillators that resonate or are forced into vibration by external influences. If you haven't preceded light with a study of sound, and if you haven't demonstrated resonance with a pair of tuning forks, do it now, for the tuning fork model is used in the text to account for selective reflection and transmission of light.

We continue to refer to color primarily by frequency rather than wavelength, in effort to reduce the number of terms students must learn to understand concepts. Wavelength is now measured in nanometers for the color spectrum, probably because there seems to be evidence that the color sensitive elements of the retina-optic-nerve-brain system are more reasonably a function of wavelength than frequency due to velocity variation. There is a trend to terahertz (THz) in place of exponential notation for visible light frequencies.

Titanium dioxide makes up white pigments used for nearly all things that are white.

The conure shown in Figure 27.13, for what it's worth, is the pet bird of my wife Lillian.

Be sure to mount three floodlights on your lecture table, red, green, and blue, of shades such that all three overlapping produce white on a white screen, as shown in the chapter opener photograph of Carlos Vasquez. Then stand in front of the lamps, illuminated one at a time and show the interesting colors of the shadows, as shown by the shadows of the golf ball in Figure 27.10 (photographed, by the way, by Carlos's Uncle David Vasquez). Impressive!

Do as Lew Slack does at Christmas time and shine three lights on your white door—red, green, and blue. Guests who come to the door are quite impressed with the colored shadows!

Arbor Scientific has a 3-lamp apparatus (P2-9700) that lets you project colored circles on a screen or wall. You can adjust the intensity of each spotlight. Their Light Box and Optical Set (P2-9561) is also impressive.

After the suggested lecture below, I'm including a special lecture that is appropriate not only for your class, but for a general audience. If you're ever asked to do a science demonstration for a general audience, they'll be thrilled by this one. Go for it! To do it you'll need the three colored lamps and rheostats to vary their brightness.

This interesting chapter is not a prerequisite to chapters that follow.

Practicing Physics Book:
• Color Addition (overlapping primary colors producing shadows)

Next-Time Questions:
• Colored Shadows

Hewitt Drew It! Screencasts: •*Color* •*Why the Sky is Blue*

SUGGESTED LECTURE PRESENTATION

Selected Reflection
Discuss the oscillator model of the atom, and the ideas of forced vibration and resonance as they relate to color, as you display different colored objects. A red object, for example, reflects red. It absorbs the other colors. Resonance is *not* occurring for red, by the way, for the resonant frequencies are being *absorbed*. (I was confused about this point for years!) Recall the absorption of resonant frequencies in the treatment of transparency in Chapter 26.

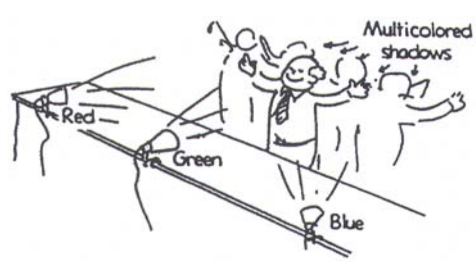
Selective Transmission
Similarly for colored glass—the resonant frequencies are absorbed and becomes the internal energy of the transparent material. The frequencies to pass through the glass are those away from the resonant frequencies. Frequencies close to resonance undergo more interactions with the molecules and take longer to travel than frequencies far from resonance. Hence different colors have different speeds in transparent materials. (If not, then no rainbows, as we shall see!)

Mixing Colored Light
The colors in the rainbow combine to white, but red, green, and blue do the same. You can show that in a variety of ways. The Arbor Scientific 3-lamp apparatus described earlier is one.

DEMONSTRATION: Show the overlapping of the primary colors with a 3-lamp demo. Show complementary colors, and discuss the rule of color mixing.

DEMONSTRATION: If you haven't shown your class the black hole that appears in a box with white interior, back in the heat chapter (Chapter 16 opener photos) do it now. It nicely illustrates the "color" black.

DEMONSTRATION: This is a must! Show the overlapping of light from three lamps on your lecture table aimed at a white screen behind you. The variety of colors in the shadows of you are very impressive. And their explanation by showing only the black shadow from one lamp, then two lamps where the black shadow is now the color of the second lamp, and then three lamps with explanation, is quite satisfying. (A complete narration to accompany this demonstration, suitable for general audiences, is at the back of this suggested lecture.) Carlos Vasquez shows this in the photo that opens this chapter.



DEMONSTRATION: Do as Chris Chiaverina does and attach to an electric drill three chemical tubes that glow red, green, and blue when activated. When spun they combine to a white light. When a piece of tape covers a part of each, in turn, the complementary color is seen. Quite impressive in a darkened room.

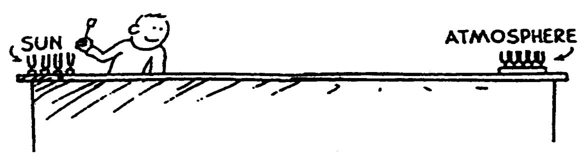
Why Water is Greenish Blue

Water absorbs infrared. It also absorbs visible light up into the red end of the color spectrum. Take away red from white light and you are left with the complementary color—cyan. A piece of white paper deep in the water looks cyan. There is no red left in the sunlight to make it white. A red crab and a black crab have the same appearance on the ocean floor.

Why the Sky is Blue

Compare the molecules in the atmosphere to tiny bells, that when struck, ring with high frequencies. They ring mostly at violet, and next at blue. We're better at hearing blue, so we hear a blue sky. On the other hand, bumblebees and other creatures that are good at seeing violet see a violet sky.

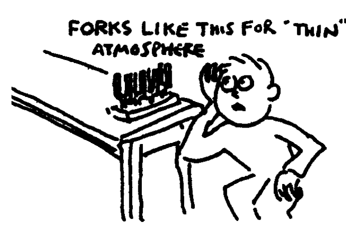
LECTURE SKIT—PART 1; Blue sky: (You can see this on my video *Why the Sky is Blue.*) Put a variety of six tuning forks at one end of your lecture table—a "red" one, "orange" one, "yellow" one, etc., to a "violet" one. Ask what "color" sound they would hear if you struck all the tuning forks in unison. Your class should answer, "White." Then suppose you have a mirror device around the forks so that when you "strike" them again, a beam of sound travels down the length of your lecture table. Ask what color they will hear. Several might say "White" again, but state that if there is no medium to scatter the beam that they will hear nothing (unless, of course, the beam is directed toward them). Now place a tray of tuning forks at the opposite end of your lecture table (the tray I use is simply a 2 by 4 piece of wood, about a third meter long, with about a dozen holes drilled in it to hold a dozen tuning forks of various sizes). Ask your class to pretend that the ends of your lecture table are 150 million km apart, the distance between the Earth and the Sun.



State that your tray of assorted tuning forks represents the Earth's atmosphere—point to the tuning forks, calling out their colors; a blue one, a violet one, a blue one, a blue one, a red one, a blue one, a violet one, a blue one, a green one, a blue one, a violet one, and so forth emphasizing the preponderance of blue and violet forks. Your tray of forks is perpendicular to the imaginary beam from the Sun (to simulate a noonish thin atmosphere). Walk to the Sun end of the table and again pretend to strike the forks and show how the beam travels down the table and intercepts and scatters from the atmospheric tuning forks in all directions. Ask what color the class hears. And you have a blue sky, especially if they're a bit deficient in hearing violet.

Why Sunsets are Red

PART 2; Red sunset: Sketch a rendition of Figure 27.18 on the board and show that at sunset the sunlight must travel through many kilometers of air to reach an observer—that blue light is scattered all along these kilometers. What frequencies survive, you ponder. Then back to your Sun and Earth forks on the lecture table. It is important to rotate the tray of forks 90° to represent the Earth's thicker atmosphere at sunset. Select a student (a cooperative one, of course) from the class to sit beside the tray of Earth forks. State to the class that your volunteer represents an Earth observer at sunset. Go back to the Sun forks which you pretend to strike. Down the table comes the beam, which you follow. Whap, into the



> Earth's atmosphere where most of it scatters throughout the classroom. Again, ask the class what color they "hear." "Blue" is the answer. Correct. Now you ask your volunteer what color he or she heard. "Orange," is the answer! Your demonstration has been a success. For humor, by "experiment" you have proved your point. Your student volunteer has simply heard a composite of the lower-frequency leftover colors after the class received most all the higher-frequency blues. So those nice colors at sunset are what? Leftover colors.

Put another way, you can say the orange of the sunset is the complementary color of the blue-violet sky.

> DEMONSTRATION: Back to the three-lamps demo. With the three lamps fully illuminated to produce white on the screen, gradually turn down the blue and the screen turns yellow, and then turn the green lamp down a bit to produce an orange—the color of the sunset. Very impressive! Don't turn the green all the way down—save this for the red color of the eclipsed Moon.

Why the Moon is Red During a Lunar Eclipse
This is featured as a Chapter 28 Next-Time Question in the NTQ book. Return to your three-lamps demo. Begin with all lamps fully illuminated to produce white. Then turn down the blue and green lamps, gradually, until all that's left on the screen is red. This is what occurs when all the higher frequencies (green as well as blue) are scattered, leaving only the red to refract through the "lens" of the Earth's atmosphere to shine on the eclipsed Moon. Again, most impressive!

Why Clouds Are White
Small particles scatter high frequencies. Larger molecules and particles also scatter lower frequencies (like larger bells ring at lower frequencies). Very large ones ring in the reds. In a cloud there are a wide assortment of particles—all sizes. They ring with all colors. Ask your class if they have any idea why clouds are white! (Cumulus clouds, composed of droplets, are white because of the multitude of particle sizes, but higher-altitude cirrus clouds are composed of ice crystals, which like snow, reflect all frequencies.)

> DEMONSTRATION: (An alternate to the above sequence.) Shine a beam of white light through a colloidal suspension of a very small quantity of instant nonfat dry milk in water, to show the scattering of blue and transmission of orange. (Dean Baird does this at the bottom of page 513.)

Discuss the blueness of distant dark mountains and the yellowness of distant snow-covered mountains (as discussed in the Check Yourself questions in the text).

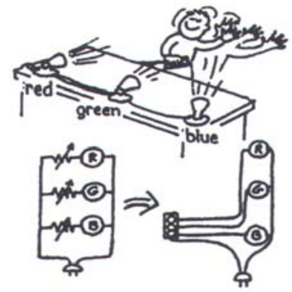
Mixing Colored Pigments
Now we address color mixing as it relates to early finger painting experience (blue + yellow = green; red + yellow = orange; red + blue = purple). This was likely the only color mixing information encountered by your students prior to this chapter. (I have never lectured about this material in detail, and have left it to the students' reading.)

Pass a magnifying glass around and look at the cyan, magenta, and yellow dots that make up the colors of photos in the book.

Retina fatigue
Looking for a long time at a strong color causes cone fatigue. If the eye then looks at a white surface, there is a strong afterimage of the complementary color. Surgeons stare intently for long periods of time at scenes that appear bright (blood) red under bright lights. The red photoreceptors in the eye thus become fatigued. If the surgeon looked at assistants in white suits, disturbing afterimages would occur. This effect is counteracted by blue, green, or cyan scrub uniforms, that result in an unnoticeable afterimage.

Special Lecture/Demo on Color Light Addition

This narration with three colored lamps, red, green, and blue, each a meter or so apart in front of a white surface, is great for a general audience. The narrator holds dimmer switches for each lamp and has an assistant stand between the lamps and screen. The narrator can stand in the light, but if it's a classroom, students like to see "one of their own" in the light for a change. Although dichro-color flood lights are quite vivid, any red, green, or blue flood lamps, or even colored gels in front of white lamps, works fine. Common wall-switch dimmers vary brightness. [*Wiring diagram is as shown.*]



White light from the Sun or an incandescent lamp is composed of the spectral colors. The reds are the lowest frequencies, the greens the middle, and the blue and violet the highest. Color vision is the result of three types of cones sensitive to the three colors, red, green, and blue. Color television uses combinations of only these three primary colors to produce the color spectrum. Note the white light where the red, green, and blue lamps overlap.

[Project all three lamps at once on the screen to show white.]

Let's look at these colors one at a time.

[Project red on screen; then green.]

Note that red and green overlap to produce yellow. Is that surprising? What is the average of red + green? What's between red and green in the spectrum? Yellow! So red light and green light produce yellow light.

[Project blue atop red and green.]

And all three produce white light.

[Person walks into the crossed beams.]

Note that she is illuminated just as if white light was shining upon her. You can't tell the difference—except for the shadows! Where the colors overlap, different colors are produced. Can these colors be understood? Yes they can, if we look at their role one at a time.

[Shine only red light and step into beam.]

Note that both the person and the screen is red. But the shadow is black. Black, strictly speaking, isn't a color. It's the absence of light. And the shadow region is a region with no light—so it's dark. No mystery here. But watch the color of the black shadow when I turn on the green light.

[Turn on green light, so red and green are on.]

Note that the black shadow is now green. That makes sense. Green light is falling on the formerly dark area. And note that the green light casts a shadow. If the red light weren't here, what color would it be?

[Turn off the red light so black shadow from green lamp appears.]

[Turn back the green so red and green shine.]

No color! Black. So we see the shadow from the green lamp is red because red light shines on it.

No mystery here. And look at the background—yellow. As we expect from the average of red + green. Now let's focus our attention to one of these shadows, say the red one when I turn on the blue.

[Turn on the blue, so all three are shining.]

We see the red shadow turns a different color—the average of red + blue—**magenta**—bluish **red**—the color of Bougainvillea blossoms! And look at the former green shadow. With blue added, it's now a bluish green—**cyan**—the color of tropical seas. And we see a third shadow, the one cast by the blue lamp. It's not black because there are two colors shining on it. We see the color is **yellow**. Why is the color of this shadow yellow? In other words, what are the colors that shine on the shadow produced by the blue lamp? Check your neighbor!

We've seen that red, green, and blue overlap to produce white light. We call these three colors the **additive primary colors**. The three types of cones in our retinas are sensitive to these colors.
Question time: Is it possible for *two* colors to produce white?

Will red + green = white? No, we've seen that red + green = yellow.
Will green + blue = white? No, we've seen that green + blue = cyan.
Will red + blue = white? No, we've seen that red + blue = magenta.
Is there some other color that when combined with red = white? Check your neighbor!

The answer is cyan. And why not, for cyan, after all, is the combination of green + blue. So cyan + red = white. Colors are logical.

We call any two colors that add to produce white, **complementary colors**. We say red and cyan are complementary colors. Put this algebraically: red + cyan = white.
Question: By the same algebra, what is white-red? Check your neighbor! Let's try it.

[Turn down the red light from the overlapping three, and leave cyan.]

This brings us to some interesting physics. Water is a strong absorber of infrared radiation—that's light with a lower frequency than red. Different materials absorb different frequencies of light, which is why we see so many different colors around us. It turns out that water not only absorbs infrared, but also absorbs visible red. Not a lot, which is why a glass of water appears without color. But the red absorbed by a larger body of water, like the ocean, means that when white light from the Sun shines on it and is reflected, some of that white light isn't there anymore. The red is absorbed, which is why the ocean is cyan. A white piece of paper near the surface of water still looks white because only a little bit of red is absorbed by the time it reaches the paper. But if the white paper is deeper, it looks greenish blue. If it's very deep, it's a vivid greenish blue—cyan. Sunlight that reaches the bottom of the sea has no more red in it. A lobster that looks red at the surface, looks black at the bottom, for there is no red light to show its redness. At the bottom of the sea, a red-painted object and a black-painted object look alike.

We have a nearly white Sun because it emits all the visible frequencies. The distribution of frequencies is not even, however, and since more red is emitted than violet, the Sun is a yellowish white. But the sky is blue. Why is the sky blue? Well this is another story; let's discuss the short version.

When sunlight hits the molecules in the Earth's atmosphere, light is **scattered**. Have you ever seen the demonstration where sound is scattered off a tuning fork? When you hit one fork and the sound travels across the room and interacts with another tuning fork of the same frequency, what happens? The answer is, the second fork is set into vibration. In a sense, it *scatters*, the sound from the first fork. The same demonstration can be done with bells. Tuning forks and bells scatter sound. Molecules similarly scatter light waves—at select frequencies. Everything has its own natural frequency. Consider two bells—a large one and a small one.

If we strike the large one it goes “bong.” If we strike the small one it goes “ting.” We all know, that large bells ring with low frequencies, and tiny bells ring with high frequencies. Similarly with light waves. Small molecules, or small particles, scatter high frequencies; large particles scatter low frequencies. So what is the atmosphere composed of? Tiny molecules. And what color of sunlight do these tiny particles scatter? High-frequency; blue! So we have a blue sky.

We look at the clouds and they are white. What does this indicate about the size of particles making up a cloud? Check your neighbor! The answer is, an assortment of particle sizes. Different particle sizes scatter different colors, so the whiteness of a cloud is evidence of a wide variety of particle sizes. If white light falls on a cloud, it looks white. If the particles grow so that they absorb rather than reflect light, then the cloud is dark—and we have a rain cloud.

Now at sunset, or sunrise, clouds are not white. Even the Sun is not white. The Sun is reddish yellow—orange—low frequency light. Why is the Sun this color? Watch what happens when I subtract the higher frequencies from white light.

[From the three shining lamps, turn down the blue lamp.]

All the blue is gone. The white light has turned yellow. If the atmosphere is thick enough, some of the greens are scattered as well.

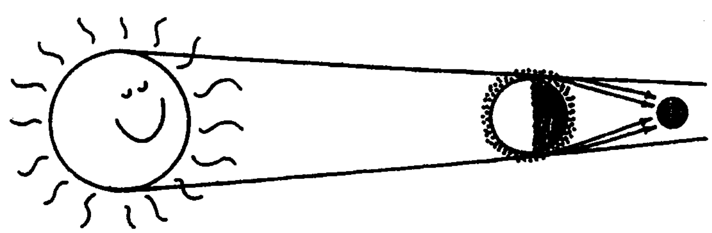
[Turn down the green lamp, but not all the way.]

And we have a yellowish red—the color of sunsets. The passage through the atmosphere at sunset is not long enough to scatter all the mid-frequencies, so we don’t normally see the Sun as a deep red. But there is an event where only a deep red survives atmospheric scattering. And that happens during the **eclipse of the Moon**.

Exactly what is happening during a lunar eclipse? The Earth casts a shadow on the Moon. [Show via overhead projector or chalkboard (if you have either) how Earth is between Sun and Moon, and show the lens effect of the Earth’s atmosphere—how rays of light refract through the Earth’s atmosphere and cast upon the Moon. So the Moon is not completely dark. The small amount of light that falls on it has traveled through twice as much air as one sees at sunset, so all the blues and greens are scattered. The result? A deep red!]

[Turn the green lamp off, leaving only red on the screen.]

So poetically enough, the redness of the Moon is the refracted light from all the sunups and sunsets that completely circle the Earth!



Solutions to Chapter 27 Exercises

Reading Check Questions

1. Blue light has a higher frequency than red light.
2. The electrons are forced into vibration.
3. When light falls on a material with a matching natural frequency it is absorbed.
4. When light falls on a material with a natural frequency above or below the frequency of incoming light it is reemitted.
5. Red light is transmitter through red glass.
6. A pigment selectively absorbs light.
7. A colored piece of glass absorbs light and warms more quickly.
8. Light passing through a prism is separated into all the colors of the rainbow, and when recombined produce white light.
9. Peak frequency of sunlight is yellow-green.
10. Our eyes are most sensitive to yellow-green.
11. A radiation curve is a plot of brightness vs frequency for light.
12. Red, green, and blue occupy the full range of frequencies visible to the eye.
13. These three of equal brightness add together to produce white.
14. The resulting color is yellow.
15. Red and cyan add to produce white.
16. Cyan is the color most absorbed by red paint.
17. The three subtractive primaries are cyan, yellow, and magenta (CYM).
18. The colors are magenta, yellow, and cyan.
19. Small bells better interact with high-frequency sounds.
20. Small particles better interact with high-frequency light.
21. The sky normally appears blue because the blue end of the spectrum is scattered most by sunlight.
22. Light of lower frequencies is scattered by particles larger than oxygen and nitrogen molecules are in the atmosphere, producing a whitish sky.
23. Scattering of high-frequency blue light occurs all along the path of sunlight, so the long path at sunrise or sunset finds much blue missing. What remains is light of lower frequencies, which accounts for the reddish color of the Sun at these times. At noon the path through the atmosphere is shorter and less scattering occurs.
24. The colors vary because the atmospheric particle in the atmosphere vary.
25. A cloud is white because it reflects all the colors of sunlight equally.
26. Large droplets absorb light and the cloud becomes darker.
27. Infrared light is most absorbed by water.
28. Red light is mostly absorbed.
29. When red is subtracted, the result is cyan.
30. Water appears cyan because red light has been absorbed by the water.

Think and Do

31. Try this with the American flag!
32. Try this with youngsters!
33. This will be fascinating to skeptics!
34. Can you convince her that knowledge adds, not subtracts, from nature appreciation?

Think and Explain

35. Red has the longest wavelength; violet has the shortest wavelength.

36. Black is the absence of light. White can be formed by the combination of all spectral colors of light.

37. The interior coating absorbs rather than reflects light, and therefore appears black. A black interior in an optical instrument will absorb any stray light rather than reflecting it and passing it around the interior of the instrument to interfere with the optical image.

38. They are most likely to be noticed if they are yellow-green. That is where the eye is most sensitive. (See Figure 27.7.)

39. Tennis balls are yellow green to be more visible, where they match the color to which we are most sensitive.

40. Red cloth appears red in sunlight, and red by the illumination of the red light from a neon tube. But because the red cloth absorbs cyan light, it appears black when illuminated by cyan light.

41. A piece of paper that appears white in sunlight has the property of reflecting any color that is incident upon it.

42. The color that will emerge from a lamp coated to absorb yellow is blue, the complementary color. (White - yellow = blue.)

43. If the yellow clothes of stage performers are illuminated with a complementary blue light, they will appear black.

44. Color television employs color addition. White is the mixture of red, blue, and green, and black is an absence of light (actually the color of the blank screen). Yellow is produced by illumination of green and red dots, while magenta is produced by illumination of red and blue dots.

45. Red and green produce yellow; red and blue produce magenta; red, blue, and green produce white.

46. The colors used are cyan, yellow, and magenta. Black is also used. Colors are formed by color subtraction.

47. The orange-yellow is complementary to blue, which combine to black. Cars would be difficult to see under such light.

48. Blue illumination produces black. A yellow banana reflects yellow and the adjacent colors, orange and green, so when illuminated with any of these colors it reflects that color and appears that color. A banana does not reflect blue, which is too far from yellow in the spectrum, so when illuminated with blue it appears black.

49. Purple is seen. See Figure 27.12.

50. The red is absorbed by the water, enough to make a visible difference with slightly reddened feet. Try it and see.

51. Deep in water red is no longer present in light, so blood looks black. But there is plenty of red in a camera flash, so the blood looks red when so illuminated.

52. Yellow light + blue light = *white* light.
    Green light + *magenta* light = white light.
    Magenta light + yellow light + cyan light = *white* light.

53. Green + blue = cyan = white - *red*.

54. Agree, for the "light mathematics" is correct.

55. The reflected color is white minus red, or cyan.

56. Ultraviolet light is reflected by the sand, so although you are not in direct light, you are in indirect light, including ultraviolet. Also, just as visible light is scattered by particles that make up the atmosphere, ultraviolet radiation is scattered even more. So you can get a sunburn in the shade—by both reflection and scattering. (Years ago the author was quite sunburned while sitting in the shade of a mangrove tree at a sandy beach brainstorming exercises for this book! I learned this one the hard way.)

57. Such glasses eliminate the distraction provided by the more strongly scattered blue and violet light yet let the pilot see in a frequency range where the eye is sensitive. (Glasses that transmit predominantly red would also get rid of the scattered blue and violet light but would provide light to which the eye is not very sensitive.)

58. Light travels faster through the upper atmosphere where the density is less and there are fewer interactions with molecules in the air.

59. Agree.

60. Particles in the smoke scatter predominantly blue light, so against a dark background you see the smoke as blue. What you see is predominantly light scattered by the smoke. But against the bright sky what you see is predominantly the sky minus the light that the smoke scatters from it. You see yellow.

61. The statement is true. A more positive tone would omit the word "just," for the sunset is not *just* the leftover colors, but *is* those colors that weren't scattered in other directions.

62. An orange sky indicates preferred scattering of low frequencies. At sunset when the scattering path is longer, very little low-frequency light would get to an observer. The less-scattered high frequencies would produce a bluish sunset.

63. Through the volcanic emissions, the Moon appears cyan, the complementary color of red.

64. When reflection is dominant in clouds, sunlight is reflected evenly by color and the clouds are white. When absorption is dominant, the clouds are dark.

65. The foam is composed of tiny bits of liquid that scatter light as a cloud does.

66. Rain clouds are composed of relatively big particles that absorb much of the incident light. If the rain clouds were composed only of absorbing particles, then the cloud would appear black. But its mixture of particles includes tiny high-frequency scattering particles, so the cloud is not completely absorbing, and is simply dark instead of black.

67. If the atmosphere were several times thicker, the sunlight reaching the Earth would be predominantly low frequencies because most of the blue light would be scattered away. Snow would likely appear orange at noon, and a deep red when the Sun is not directly overhead.

68. If Jupiter had a semi-transparent atmosphere, the sun would not appear white. Molecules in the atmosphere would absorb some colors more strongly than others, producing a colored sun. In fact, there is a thick cloud cover in Jupiter's atmosphere that blocks all sunlight from reaching its "surface." And it doesn't have a solid surface!

69. Sunset follows the activities of humans and other life that put dust and other particles in the air. So the composition of the sky is more varied at sunset.

70. The water is broken up into a multitude of different size droplets when the wave breaks, and like the droplets in clouds overhead, light of many visible frequencies is scattered to produce the white color.

Think and Discuss

71. The customer is being reasonable in requesting to see the colors in the daylight. Under fluorescent lighting, with its predominant higher frequencies, the bluer colors rather than the redder colors will be accented. Colors will appear quite different in sunlight.

72. Red paint is red because it reflects the red component of white light, while absorbing the other components, particularly red's compliment cyan.

73. The red petals of a red rose will reflect red light while the green leaves absorb red light. The energy absorbed by the leaves tends to increase their temperature. White material reflects radiation and is therefore worn by those who do not wish to be warmed by absorbing radiant energy.

74. Either a white or green garment will reflect incident green light and be cooler. The complementary color, magenta, will absorb green light and be the best garment color to wear when the absorption of energy is desired.

75. We see not only yellow green, but also red and blue. All together, they mix to produce the white light we see. And due to atmospheric scattering the Sun is yellowish.

76. If only blue light gets through the blue filter, and only yellow gets through the yellow filter, the overlapping beams will produce white light. When the two panes of glass are overlapped and placed

in front of a single flashlight, however, little or no light will be transmitted, or some green depending on the range of colors getting through the filters.

77. Agree, for the “light mathematics” is correct.

78. The red shirt in the photo is seen as cyan in the photographic negative, and the green shirt appears magenta—both complementary colors. When white light shines through the photo negative, red is transmitted where cyan is absorbed. Likewise, green is transmitted where magenta is absorbed.

79. You see the complementary colors due to retina fatigue. The blue will appear yellow, the red cyan, and the white black. Try it and see!

80. We cannot see stars in the daytime because their dim light is overwhelmed by the brighter skylight, which is sunlight scattered by the atmosphere. However, a rare supernova (exploding star) is bright enough to be seen in a daytime sky.

81. At higher altitudes, there are fewer molecules above you and therefore less scattering of sunlight. This results in a darker sky. The extreme, no molecules at all, results in a black sky, as on the Moon.

82. The daytime sky is black, as it is on the nighttime sky there.

83. As seen from the surface of the Moon, both the Sun and the stars are clearly visible. This is because there is no skylight (scattered sunlight) to overwhelm the starlight.

84. The color of the Sun is yellow-white at all times on the Moon.

28 Reflection and Refraction

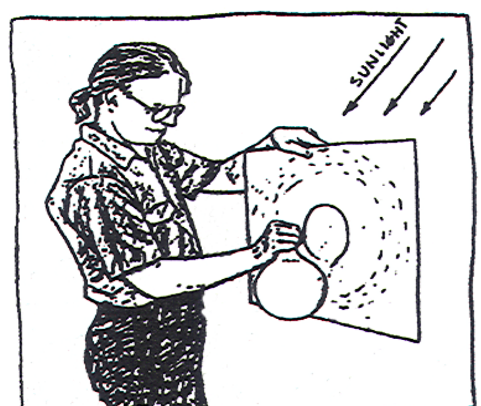
The first of the chapter opening photos shows Peter Hopkinson of Vancouver Community College in Canada performing one of his many classroom antics. The duck on the rock, second photo, shows that the reflected view is not identical to the right-side-up view, because the viewing angles differ. The duck's feet do not show in the reflection. Photo three is Fred Myers and his daughter McKenzie posing between a pair of parallel mirrors. Karen Jo Matsler goes further with three mirrors in the fourth photo, all of which show interesting reflections.

The personal profile for this chapter is Pierre de Fermat.

Reflection and refraction are introduced via Fermat's Principle of Least Time, a la Feynman. The treatment of reflection is brief, with only scant application to convex and concave mirrors. The treatment of refraction is supported by many examples. You may wish to further support the cases of atmospheric refraction by discussing the analogous case of sound refraction in a region where the temperature of air at the ground is appreciably higher or lower than the air temperature above as was treated in Chapter 20.

For a very brief treatment on light, this chapter may be covered in place of the regular sequence of Part 6. In this case, the behavior rather than the nature of light would be emphasized (which most introductory texts stress anyway).

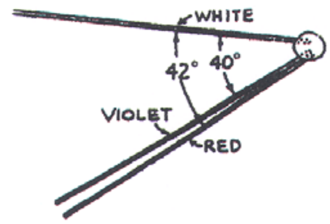
Paul Doherty makes rainbows that his students can study first hand at the Exploratorium. You can too. Your giant water drop is a glass sphere filled with water. Cut a hole that's slightly larger than your sphere in a piece of white cardboard. Shine a bright beam of light from a slide projector or the Sun through the hole so that the beam illuminates the entire water drop. The drop will project a colored circle of light onto the cardboard screen around the hole you have cut. If at first you don't see a circle of light, move the screen closer to the drop, as Paul shows to the right! (See his article on rainbows back in the Exploratorium quarterly, *Exploring* (Summer 1992). Thanx Paul!



Courtesy Exploratorium

I owe the conical treatment of the rainbow in the text to one of Cecil Adams's syndicated newspaper columns, *The Straight Dope*.

An explanation of why a rainbow is bow-shaped is aided with this simple easy-to-construct apparatus: Stick three colored dowels into a sphere of clay, Styrofoam, wood, or whatever that represents a raindrop. One dowel is white, one violet, and the other red, to represent incident white light and refracted red and violet. The angles between dowels are shown in the sketch. A student volunteer crouching in front of your chalkboard shows the class how the only drops that cast light to him or her originate in drops along a bow-shaped region. (More on this in a lecture video and in the lecture below.)



A plastic viewing tank designed by Dean Baird is available from Arbor Scientific. Laser beam refraction and reflection and diffraction are nicely seen in a tank that is lightweight and easy to store. It's 18 inches × 6 inches × 1 inch, skinny, so it weighs only about 3 pounds with water (P2-7690). A photo of Dean with his tank is on page 513 of the previous chapter.

Nanoparticles of zinc oxide or titanium in sunscreen are totally transparent to ordinary visible light, because of their size, but are highly reflecting to UV.

Black fabrics normally absorb about 90 percent of the Sun's heat. An exception is black fabrics that have been chemically treated to reflect about 80 percent of Sun's rays, nearly as much as white fabrics. Watch for them in winter wear.

The first telescope is credited to a Dutch spectacle maker, Hans Lippershey, in 1608. Galileo was the first to be reported as using it to observe the nighttime sky.

The half-size mirror problem, as well as Think and Rank 43 and Think and Explains 47 - 50, nicely illustrate one of the valuable things about your course—that the richness in life is not only seeing the world with wide open eyes, but in knowing what to look for. Concepts in this chapter provide a lot of guidance in this respect.

Not covered in the text or ancillaries is the green flash, the momentary flash of green light that is sometimes seen when the Sun sets. A simple explanation is that the atmosphere acts as a prism, but upside down, so that white light of the Sun is dispersed with blue on top, green near the top, and red on the bottom. At the moment the Sun sets, the red is cut off by the Earth, the blue is removed by scattering, and green survives to give the famous green flash.

Animals with 360° vision without turning their heads include rabbits and hares because of their big protruding eyes on the sides of their heads. But they have depth perception only where the view from each eye overlaps a bit in front of their heads and behind them.

Practicing Physics Book:
• Pool Room Optics
• Reflection
• Reflected Views
• More Reflection
• Refraction
• More Refraction
• Lenses

Problem Solving Book:
Problems on reflection and refraction

Laboratory Manual:
• Mirror rorriiM *The Geometry of Plane Mirror Images* (Activity)
• Mirror Experiences *Images in Spherical Mirrors* (Activity)
• Diversion into Refraction *The Nature of Refraction* (Activity)
• Coin Under the Cup *The Magic of Reflection* (Activity)
• Diversion into Dispersion *Turning White Light into a Full Spectrum* (Activity)

• Trapping the Light Fantastic *Total Internal Reflection* (Activity)
• A Sweet Mirage *Gradual Refraction* (Activity)
• Lenses Positive and Negative *The Geometry of the Focal Point* (Activity)
• Lens Experience *Images in a Fresnel Lens* (Activity)

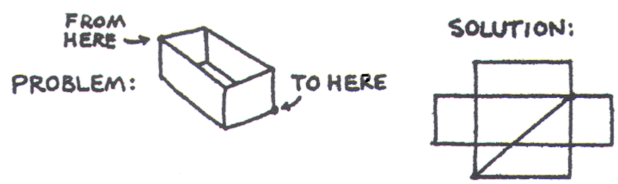
Next-Time Questions:
• Shortest Distance
• Refraction
• View in Full-Length Mirror
• View in Pocket Mirror
• View in Hand-held Mirror
• Bridge Reflection
• Light Column on Water
• Red Sunset
• Photographing a Rainbow
• Spearing a Fish
• Submerged Coin
• Laser Beam
• Underwater Viewing
• Red Lunar Eclipse
• Corner Refractor

Hewitt-Drew-It! Screencasts: •*Reflection* •*Refraction* •*The Rainbow* •*Pinhole Images* •*Lenses*

The following suggested lecture will probably take at least two class periods.

SUGGESTION LECTURE PRESENTATION

Principle of Least Time
You can lead into Fermat's principle of least time for reflection by posing to your class the following: Consider a rectangular box, like a shoe box, with an ant inside at one of its corners, say an upper corner. Question: What would be the path of least distance along the inside surface of the box to the diagonally opposite corner? (Most will likely answer "straight down to the lower corner, then diagonally across the floor.") Then after a "talk to your neighbor" routine, provide this hint: Flatten the box out and consider the shortest distance.



Law of Reflection
Now you're ready to discuss Figures 28.2 through 28.5, and cap it off with Figure 28.6, the law of reflection.

Plane Mirror
Sketch Figure 28.7 on the board and carefully show how image and object distance are the same. Call attention to the curved mirrors of Figure 28.9 and stress that the law reigns in whatever small region a light ray strikes. Likewise with diffuse reflection. Discuss Think and Discuss 93, about the diffuse dry road becoming a "plane mirror" when wet, and hence the difficulty of seeing the road in a car on a rainy night.

> CHECK QUESTION: If a camera shot on TV or in the movies shows a person and a mirror in which we see the person's reflection, what does the person see when looking at the mirror? [The camera!] (This is the crux of Think and Discuss 96.)

There is common confusion about just what a mirror reverses. Left and right aren't reversed. What *is* reversed is front and back. I hope the diagram next to the photo of my sister in Figure 28.8 helps clear this.

Half-Size Mirror
Answers to the question about the minimum size mirror needed to view a full-size image will elicit much class interest. My screencast on *Reflection* featuring "Blinky Bill" treats this. You can expect spirited discussions of Think and Rank 43, Think and Explains 60 – 64. I regret to report, that seldom do I find half of my class answering these questions correctly—particularly when I first emphasize that the results will be

surprising, and that if they are careful they will learn something about their image in a mirror that has likely escaped them all their lives (that the size of the mirror is independent of their distance from it). Most correctly get the first part, the half-size answer, but miss the part about distance from the mirror being irrelevant. That's where I ask them to mark the mirror where they see the top of their head and bottom of their chin, and then to step back and look carefully for the effect of distance. Perhaps like the visual illusion of Think and Do 31 on page 177 at the end of Chapter 9 (judging hand sizes), their belief in their uninvestigated answer is so strong that they will not see what is there unless it is explicitly pointed out to them. Are your students more perceptive than mine? In any event, when you discuss the answers to the minimim-size mirror questions, bring into class a full-length mirror or pass a few small mirrors among your students. It's worth the extra effort.

Refraction
Discuss Fermat's principle for refraction, via the lifeguard analogy presented in the text. Contrast the path the lifeguard would take compared to the path a seal would take. Point out that the bend you draw on the board when illustrating these "refractions" depends on the relative speeds on the sand and in the water. Continue with the examples in the text, that light takes a longer path but shorter distance, time wise when incident obliquely on glass; likewise through a prism, and through a lens, above the atmosphere during sunsets, and close to the ground when a mirage is produced. Consider relating the refraction of light during a mirage to the reaction of sound as treated in Chapter 20. Then to the mechanics of how light follows these incredible paths.

Cause of Refraction
Refraction hinges on the slowing of light in a transparent medium. This was established in Chapter 26. The analogy of the wheels rolling onto the grass lawn (Figure 28.23) shows that bending of path is the result of this change of speed. This is reinforced in the *Practicing Physics Book*. So we see that the bending is the result of light changing speed, rather than the result of light "waning" to reach a place in the least time. It is important to underscore this distinction. Here a straightforward physics explanation is much simpler than the mystical explanation. How many other mystical explanations fall in this category?

Index of Refraction
New to the 12th edition is Snell's Law, not in a footnote as in previous editions, but as a text section, *Index of Refraction*. The math is light and involves, a bit of trigonometry, which can either be amplified or glossed over, depending on the class time you want to allot to quantitative coverage.

When the speed of light in a transparent object is the same as the speed of light in a fluid in which it is immersed (or in physics lingo, when the index of refraction is the same for each), then the object won't be seen. Putting glass items in some vegetable oils will demonstrate this, as shown by my niece Stephanie in Think and Explain 91.

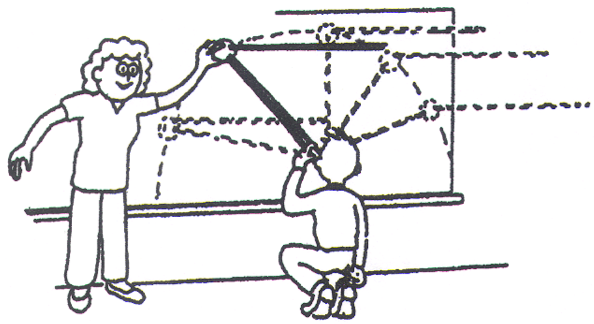
Dispersion
Now that you've established refraction as a result of changes in light speed, it follows that different speeds of different frequencies of light in transparent materials refract at different angles. This is dispersion, nicely illustrated with a prism.

Rainbows
Amplify the section on rainbows, and liken them to viewing a cone held with its apex to the eye. The deeper the misty region, the more intense the rainbow appears. The cone bit explains why the rainbow is round. Another is via the ball-and-sticks demonstration.

> DEMONSTRATION: Show the rainbow-sticks apparatus described and compare it to the rainbow schematic drawing of Figures 28.30 and 28.31. The white stick represents incoming white light, and the red and violet sticks represent the refracted rays. Have a student volunteer crouch in front of the board as shown in the sketch. Place the ball near the chalkboard so the white dowel is perpendicular to the board (from the Sun at the horizon for simplicity). Position the free end of the violet dowel so that it nearly meets the volunteer's eye. State that a drop at this location refracts violet light to the eye. The question follows: Are there other locations that will also refract violet

> light to the eye? Move the “drop” to other locations along the board while keeping the white dowel perpendicular to the board. It is easy to see that refracted violet coming from drops farther away miss the eye altogether. The only locations that send violet light to the eye are along a bow—which you trace with violet or blue chalk. This is easy to do if the student holds the end of the violet dowel near the eye while you scribe the arc in compass fashion.

Enlist a second volunteer to crouch in front of the board at a different position. Show how this volunteer must look to different drops in the sky to see a rainbow. Ask the class if the two volunteers see the same rainbow. [No, each sees his or her own personal rainbow!]



> CHECK QUESTION: With the ball and dowels positioned at the top of the bow, ask where the volunteer must look to see red—above the violet, or below? [Above (2° to be exact).] Show this by moving the “drop” up, whereupon the red dowel lines up with the eye. Complete your demo by sweeping this wider bow with red chalk.

Rainbows cannot be seen when the Sun is more than 42 degrees in the sky because the bow is below the horizon where no water drops are to be seen. Hence rainbows are normally seen early and late in the day. So we don’t see rainbows in midday in summer in most parts of the world (except from an airplane, where they are seen in full circles).

Point out a significant yet commonly unnoticed feature about the rainbow—that the disk segment bounded by the bow is appreciably brighter than the rest of the sky. Refracted light overlaps in this region. Only at the edges, the rainbow, does it not overlap. The rainbow is similar to the chromatic aberration around a bright spot of projected white light. Notice this in Figure 28.34 (taken from my former bedroom window in Hilo, HI).

Show Paul Doherty’s rainbow from a sphere of water (described on page 291, four pages back).

Extend rainbows to the similar phenomenon of the halo around the Moon. Explain how the halo is produced by refraction of moonlight through ice crystals in the atmosphere. Note the important difference: Whereas both refraction and internal reflection produce rainbows, only refraction produces halos. And whereas the observer is between the Sun and the drops for seeing a rainbow, the ice crystals that produce halos are between the observer and the Moon. Moonlight is refracted through ice crystals high in the atmosphere—evidence of the coldness up there even on a hot summer night.

Total Internal Reflection

> DEMONSTRATION: Show examples of reflection, refraction and total internal reflection with the usual apparatus—light source (laser), prisms, and a tank of water with the addition of a bit of fluorescence dye.

(You may notice that at the critical angle, some light skims the surface of the water. This is because your beam is slightly divergent, so where the central axis of the beam may be at the critical angle and reflect back into the medium, part of the beam is slightly beyond the critical angle and refracts.)

Ask your class to imagine how the sky would look from a lake bottom. For humor, whereas above water we must turn our heads through 180 degrees to see from horizon to horizon, a fish needs only scan twice the 48 degree critical angle to see from horizon to horizon—which is why fish have no necks!

Fiber Optics
Show some examples of light pipes. Discuss some of the many applications of these fibers, or "light pipes," particularly in telephone communications. The principle underlying fiber optics is similar to a boy scout signaling Morse code by flashlight to a distant friend. In fiber optics, computers fire lasers that turn on and off rapidly in digital code. Current lasers send about 1.7 billion pulses per second to optical detects that receive and interpret the information.

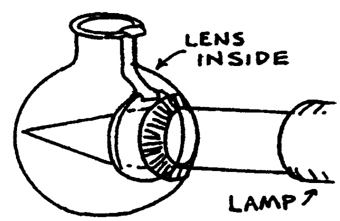
Today glass fibers as thin as a human hair carry thousands of simultaneous telephone conversations, compared to the only 24 that can be carried per conventional copper cable. Signals in copper cables must be boosted every 4 to 6 kilometers, whereas re-amplification in light-wave systems occurs every 10 to 50 kilometers. For infrared optical fibers, the distance between regenerators may be hundreds or perhaps thousands of kilometers. Fibers are indeed very transparent!

Lenses
The explanation of lenses follows from your demo of light deviating through a prism. Whereas a study of lenses is properly a laboratory activity, all the ray diagrams, in the world are of little value unless paired with a hands-on experience with lenses. So if a laboratory experience is not part of your course, I would recommend lenses be treated very briefly if at all in lecture.

State the difference between a virtual and a real image: A virtual image is formed by light rays that only appear to intersect. A real image is formed where light rays do intersect at a single point.

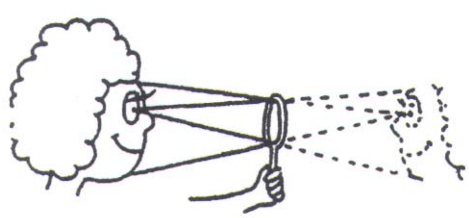
DEMONSTRATION: Show examples of converging a diverging lenses. A white light source will do, but a neat source of light is a laser beam that is widened by lenses and then directed through a mask of parallel slits. Then parallel rays of light are incident upon your lenses.

DEMONSTRATION: Simulate the human eye with a spherical flask filled with a bit of fluorescence dye. Paint an "iris" on the flask and position appropriate lenses in back of the iris for normal, farsighted and nearsighted vision. Then show how corrective lenses placed in front of the eye put the light in focus on the retina.



Think and Discuss 107 about sheets of lenses that supposedly direct more solar energy into a swimming pool makes a good discussion topic.

NEXT-TIME QUESTION: Refer to the minimum size mirror and respective distances questions, and tie them to Think and Rank 43. This activity is also a Next-Time Question, and a concluding question in my screencast on *Reflection*.



Answers and Solutions for Chapter 28

Reading Check Questions

1. Incident light sets electrons into vibration.
2. Vibrating electrons emit electromagnetic waves.
3. Fermat's principle of least time states that light will take the path of least time when going from one point to another.
4. The angle of incidence equals the angle of reflection.
5. Image distance and object distance are the same.
6. About 4% of incident light is reflected from the first surface.
7. Yes, a surface may be polished for short-wavelength waves and not for longer ones. The mesh on a parabolic dish is rough for short waves, but not for long waves.
8. Both angles are the same for window glass.
9. When the faces of the glass are not parallel, as with a prism.
10. Light travels faster in thin air. This produces atmospheric refraction, which lengthens the daylight hours.
11. Yes, the law of reflection holds locally at each tiny part of the curved surface, but not for the curved mirror as a whole.
12. A mirage is a result of atmospheric refraction.
13. Interaction of light with transparent material lowers the speed of light in the material.
14. The angle is always 90°.
15. Light speed slows when refracted in a medium.
16. High index glass means more bending and thinner lenses.
17. Refraction makes the pool bottom appear shallower.
18. Violet light travels more slowly in glass than red light.
19. Each drop disperses a spectrum of colors.
20. A viewer only sees a small segment of colors, a single color, dispersed from a far-away drop
21. A secondary bow is dimmer due to an additional internal reflection.
22. Critical angle is the minimum angle of incidence inside a medium at which a light ray is totally reflected.
23. Inside glass light is totally reflected at about 43°, depending on the type of glass; in a diamond, 24.5°.
24. It bends by a succession of internal reflections, following the contour of the fiber.
25. A converging lens is thickest in the middle, causing parallel rays to come together at a point. A diverging lens is thickest at the edges.
26. The focal length of a lens is the distance between the center of the lens and the point where parallel light rays intersect.
27. A real image can be cast on a screen; a virtual image cannot.
28. Only a converging lens can produce a real image; both converging and diverging lenses can produce a virtual image.
29. Small pupils mean small opening, which means less overlapping of out-of-focus rays.
30. Astigmatism is a defect in which there is more curvature of the lens in one direction than the other. The remedy is eyeglasses with cylindrical lenses that curve more in one direction than in another.

Think and Do

31. Many Grandmas do not realize that only a half-size mirror gives a full view of oneself.
32. This is an intriguing activity.
33. This is an intriguing activity.
34. This is an intriguing activity.
35. This is an intriguing activity.
36. Experiment will show that about 100 coins will fit between the coin-sized image of the Sun and the hole in the paper. And incredibly, that's the same number of Suns that would fit between Earth and the position of the Sun!

Think and Solve

37. 4 m/s. You and your image are both walking at 2 m/s.

38. When a mirror is rotated, its normal rotates also. Since the angle that the incident ray makes with the normal is the same angle that the reflected ray makes, the total deviation is twice. In the sample diagram, if the mirror is rotated by 10°, then the normal is rotated by 10° also, which results in a 20° total deviation of the reflected ray. This is one reason that mirrors are used to detect delicate movements in instruments such as galvanometers. The more important reason is the amplification of displacement by having the beam arrive at a scale some distance away.

39. The butterfly's image is 20 cm in back of the mirror, so the distance from the image to your eye is 70 cm.

40. If 96% is transmitted through the first face, and 96% of 96% is transmitted through the second face, 92% is transmitted through both faces of the glass.

41. The amount of light transmitted through two sheets of glass is about 85%. To see this, consider an incident intensity of 100 units. Then 92 units are transmitted through the first pane. 92% of this amount is transmitted through the second pane (0.92 of 92 = 84.6).

42. Use ratios: (1440 min)/(360 deg) = (unknown time)/(0.53 deg). So the unknown time is 0.53 x 1440/360 = 2.1 minutes. So the Sun moves a solar diameter across the sky every 2.1 minutes. At sunset, time is somewhat extended, depending on the extent of refraction. Then the disk of the setting Sun disappears over the horizon in a little longer than 2.1 minutes (the Sun's path also varies with latitude and day of the year).

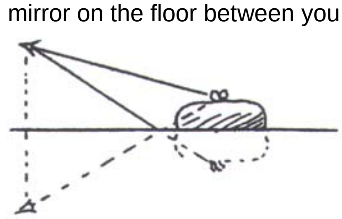
Think and Rank

43. A=B=C (all same)
44. B, C, A
45. B, C, A
46. C, B, A

Think and Explain

47. Peter's left foot is firmly planted on the table, behind the mirror between his legs.

48. First of all, the reflected view of a scene is different than an inverted view of the scene because the reflected view is seen from lower down. Just as a view of a bridge may not show its underside where the reflection does, so it is with the bird. The view reflected in water is the inverted view you would see if your eye were positioned as far beneath the water level as your eye is above it (and there were no refraction). Then your line of sight would intersect the water surface where reflection occurs. Put a mirror on the floor between you and a distant table. If you are standing, your view of the table is of the top. But the reflected view shows the table's bottom. Clearly, the two views are not simply inversions of each other. Take notice of this whenever you look at reflections (and of paintings of reflections—it's surprising how many artists are not aware of this).



49. e are between two parallel mirrors. The reflection from one mirror is incident on the other, and

50. Only three plane mirrors produce the multiple images of Karen Jo, who shows a large kaleidoscope.

51. Fermat's principle for refraction is of least time, but for reflection it could be of least distance as well. This is because light does not change mediums for reflection so no change in speed occurs and least-time paths and least-distance paths are equivalent. But for refraction, light goes from a medium where it has a certain speed to another medium where its speed is different. When this happens the least-distance straight-line paths take a longer time to travel than the nonstraight-line least-time paths. See, for example, the difference in the least-distance and least-time paths in Figure 28.13.

52. Only light from card number 2 reaches her eye.

53. Cowboy Joe should simply aim at the mirrored image of his assailant, for the ricocheting bullet will follow the same changes in direction when its momentum changes (angle of incidence = angle of rebound) that light follows when reflecting from a plane surface.

54. Such lettering is seen in proper form in the rearview mirrors of cars ahead.

55. Light that takes a path from point A to point B will take the same reverse path in going from point B to point A, even if reflection or refraction is involved. So if you can't see the driver, the driver can't see you. (This independence of direction along light's path is the "principle of reciprocity.")

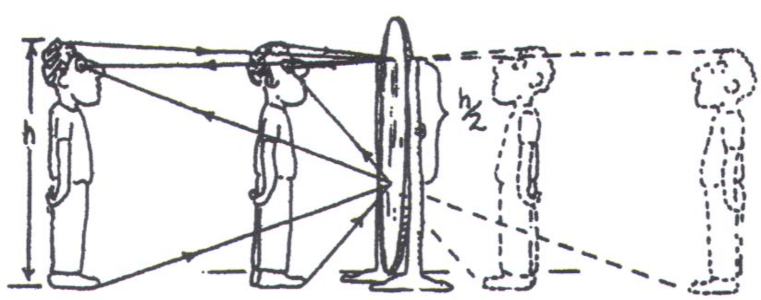
56. When you wave your right hand, image of the waving hand is still on your right, just as your head is still up and your feet still down. Neither left and right nor up and down are inverted by the mirror—but *front and back* are, as the author's sister Marjorie illustrates in Figure 28.8. (Consider three axes at right angles to each other, the standard coordinate system; horizontal *x*, vertical *y*, and perpendicular-to-the-mirror *z*. The only axis to be inverted is *z*, where the image is *-z*.)

57. Two surfaces of the mirror reflect light. The front surface reflects about 4% of incident light, and the silvered surface reflects most of the rest. When the mirror is tilted in the "daytime" position, the driver sees light reflecting from the silvered surface. In the "nighttime" position, with the mirror tilted upward, light reflecting from the silvered surface is directed above the driver's view and the driver sees light reflected from the front surface of the mirror. That 4% of rearview light is adequate for night driving.

58. A window both transmits and reflects light. Window glass typically transmits about 92% of incident light, and the two surfaces reflect about 8%. Percentage is one thing, total amount is another. The person outside in the daylight who looks at the window of a room that is dark inside sees 8% of the outside light reflected back and 92% of the inside light transmitted out. But 8% of the bright outside light might be more intense than 92% of the dim inside light, making it difficult or impossible for the outside person to see in. The person inside the dark room, on the other hand, receiving 92% of the bright outside light and 8% of the dim inside light, reflected, easily sees out. (You can see how the reverse argument would be applied to a lighted room at night. Then the person inside may not be able to see out while the person outside easily sees in.)

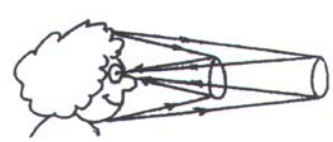
59. Rough pages provide diffuse reflection, which can be viewed from any angle. If the page were smooth it could only be viewed well at certain angles.

60. The minimum length of a vertical mirror must be half your height in order for you to see a full-length view of yourself. The part of the mirror above and below your line of sight to your image isn't needed, as the sketch shows.



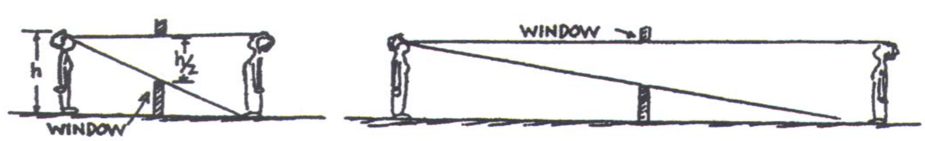
61. The half-height mirror works at any distance, as shown in the sketch above. This is because if you move closer, your image moves closer as well. If you move farther away, your image does the same. Many people must actually try this before they believe it. Distinguish this from looking at a tall building in a pocket mirror and looking at *yourself* in the pocket mirror!

62. Note in your pocket mirror that the amount of your face you can see is twice the size of the mirror—whether you hold it close or at arm's length. (You can win bets on this question!)



63. The wiped area will be half as tall as your face.

64. The smallest window will be half the height of the person or her twin. Note that this does not depend on distance, providing both subjects are the same distance from the wall. This illustrates the preceding questions on mirror height.



65. The person is farsighted.

66. A lens of higher index of refraction will allow thinner lenses.

67. Agree, as inspection of Figure 28.24 shows. Note wavefronts are closer together in water as compared with in air above.

68.

69. Red light travels faster through glass and will exit first.

70. During a lunar eclipse the Moon is not totally dark, even though it is in Earth's shadow. This is because the atmosphere of Earth acts as a converging lens that refracts light into Earth's shadow. It is the low frequencies that pass more easily through the long grazing path through Earth's atmosphere to be refracted finally onto the Moon. Hence its reddish color—the refraction of the whole world's sunrises and sunsets.

71. The "non-wetting" leg of the water strider depresses and curves the surface of the water, which effectively produces a lens that directs light away from its path to form the extended shadow region. (Close observation shows a bright ring around the darker region. Interestingly, the overall brightness of the shadow and the bright ring average the same brightness—"conservation of light.")

72. We cannot see a rainbow "off to the side," for a rainbow is not a tangible thing "out there." Colors are refracted in infinite directions and fill the sky. The only colors we see that aren't washed out by others are those that are along the conical angles between 40° and 42° to the Sun-anti-Sun axis. To understand this, consider a paper-cone cup with a hole cut at the bottom. You can view the circular rim of the cone as an ellipse when you look at it from a near side view. But if you view the rim only with your eye at the apex of the cone, through the hole, you can see it only as a circle. That's the way we view a rainbow. Our eye is at the apex of a cone, the axis of which is the Sun-anti-Sun axis, and the "rim" of which is the bow. From every vantage point, the bow forms part (or all) of a circle.

73. Normal sight depends on the amount of refraction that occurs for light traveling from air to the eye. The speed change ensures normal vision. But if the speed change is from water to eye, then light will be refracted less and an unclear image will result. A swimmer uses goggles to make sure that the light travels from air to eye, even if underwater.

74. What is true of the swimmer in the previous exercise is true for the fish above water. Normal vision for the fish is for light going from water to the eye. This condition is met if the fish wears goggles filled with water.

75. The diamond sparkles less because there are smaller angles of refraction between the water and the diamond. Light is already slowed when it meets the diamond so the amount of further slowing, and refraction, is reduced.

76. Cover half the lens and you cut out half the illumination of the light. But you don't cut out half the image, as is commonly and mistakenly thought. (This incorrect thinking, unfortunately, may be fostered by ray diagrams, which are useful for locating image positions, but not for defining image formation.)

77. The image will be a bit dimmer with original colors, but otherwise unaffected.

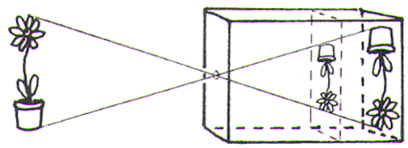
78. A lens that refracts sound waves is a sphere of gas that transmits sound at a slower speed. Like a glass lens redirects waves of light, the sound lens redirects waves of sound.

79. If light had the same average speed in glass lenses that it has in air, no refraction of light would occur in lenses, and no magnification would occur. Magnification depends on refraction, which in turn depends on speed changes.

80. A magnifying glass will magnify less under water. Under water there is less difference in speeds between water and the lens, than in air.

81. A pinhole image is one of sharpness.

82. Rays do not converge as with a glass lens, so a pinhole image is sharp in all positions.



83. The image produced by a pinhole is sharp, but very dim—a serious liability for a spy camera. A spy camera needs all the light it can get because the image is highly enlarged, so the light is spread way out. Hence, a large aperture is advantageous.

84. The circular spots are images of the Sun cast through "pinholes" in the spaces between leaves above. (See other such images in the photo openers of Chapter 26.)

85. For very distant objects, effectively at "infinity," light comes to focus at the focal plane of the lens. So the photosensitive surface is one focal length in back of the lens for very distant shots. For shorter distances, it is farther from the lens.

86. Real images—those that can be projected on a screen—are always inverted. Therefore, your slides should be upside down so that the image will be right-side-up.

87. Yes, the images are indeed upside down! The brain re-inverts them.

88. Yes! The images are indeed upside down! You view them as you wish, right-side up or upside down.

89. Moon maps are upside-down views of the Moon to coincide with the upside-down image that Moon watchers see in an astronomical telescope.

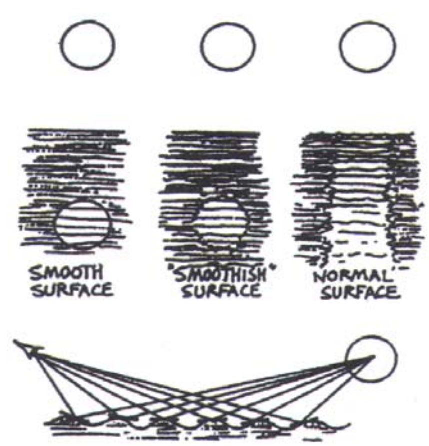
90. The near point of vision recedes with advancing age because the lenses in peoples eyes get less flexible with age. When you have to hold a book at arm's length to see it clearly, you're really ready for glasses (or other corrective options).

91. The speed of light in the glass rod and the oil is the same. Said another way, both have the same index of refraction. You'd only see the submerged transparent rod if light underwent a change in speed as it passes from oil to glass and back to oil again. No change in light speed means no visual evidence of its presence.

Think and Discuss

92. When the source of glare is somewhat above the horizon, a vertical window will reflect it to people in front of the window. By tipping the window inward at the bottom, glare is reflected downward rather than into the eyes of passersby.

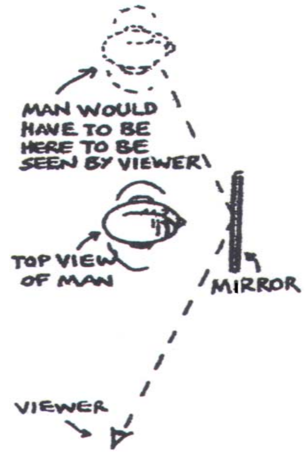
93. The pebbly uneven surface is easier to see. Light reflected back from your headlights is what lets you see the road. The mirror-smooth surface might reflect more light, but it would reflect it forward, not backward, so it wouldn't help you see. Whereas diffuse reflection from a rough road allows a motorist to see the road illuminated by headlights on a dry night, on a rainy night the road is covered with water and acts like a plane mirror. Very little of the illumination from the headlights returns to the driver, and is instead reflected ahead (causing glare for oncoming motorists).



94. If the water were perfectly smooth, you would see a mirror image of the round Sun or Moon, an ellipse on the surface of the water. If the water were slightly rough, the image would be wavy. If the

water were a bit more rough, little glimmers of portions of the Sun or Moon would be seen above and below the main image. This is because the water waves act like tiny parallel mirrors. For small waves only light near the main image reaches you. But as the water becomes choppier, there is a greater variety of mirror facets that are oriented to reflect sunlight or moonlight into your eye. The facets do not radically depart from an average flatness with the otherwise smooth water surface, so the reflected Sun or Moon is smeared into a long vertical streak. For still rougher water there are facets off to the side of the vertical streak that are tilted enough for Sun or moonlight to be reflected to you, and the vertical streak is wider.

95. You are seeing skylight refracted upward near the road surface.



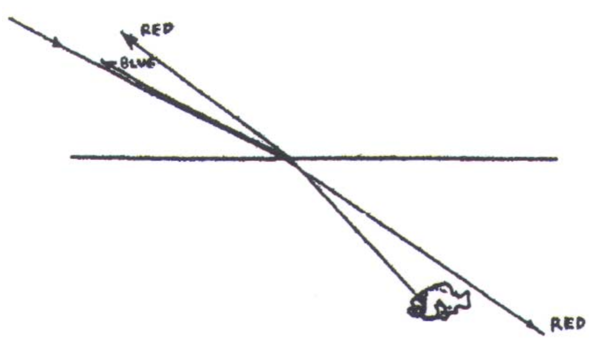
96. We would not see an image of the man in the mirror as shown. If he is viewing himself, then we wouldn't also be able to see his image unless we were in back (or in front) of him. If we are to stand to the side of the man and see him *and* an image of him in the mirror, then the mirror cannot be exactly in front of him. The mirror would have to be located to the man's right, as shown in the sketch. The man's view would miss the mirror completely. Such arrangements are made when staging an actor who is supposed to be viewing himself in a mirror. Actually, however, the actor pretends to be looking at himself. If he really were, his image in the mirror wouldn't be shared by the audience. That's Hollywood!

97. The two pictures do not contradict each other. In both cases light is bent away from the normal upon emerging from the water. That's why the corner of the immersed square appears to be shallower. Notice that it's easy to confuse the beam of the left-hand picture with the edge of the immersed square in the right-hand picture. Light travels *from* the edge, not *along* the edge of the square.

98. The speed of light increases in going from water into the air above.

99. Throw the spear below the apparent position of the fish because refraction makes the fish appear closer to the surface than it really is. But in zapping a fish with a laser, make no corrections and simply aim directly at the fish. This is because the light from the fish you see has been refracted in getting to you, and the laser light will refract along the same path in getting to the fish. A slight correction may be necessary, depending on the colors of the laser beam and the fish—see the next exercise.

100. The angle of refraction for blue light is greater than for red, so if you fired your red beam along the line of sight for blue, the beam would pass above the fish. So you should aim slightly below the sighted fish.



101. A fish sees the sky (as well as some reflection from the bottom) when it looks upward at 45°, for the critical angle is 48° for water. If it looks at and beyond 48° it sees only a reflection of the bottom.

102. Total internal reflection occurs only for light rays that would gain speed in crossing the boundary they encounter. For light in air encountering a water surface, there is no total reflection. You can see this by sketching rays that go from water to air, and noting that light can travel in the other direction along all of these rays.

103. In sending a laser beam to a space station, make no corrections and simply aim at the station you see. This is like zapping the fish while standing on the shore of question 99. The path of refraction is the same in either direction.

104. The fact that two observers standing apart from one another do not see the same rainbow can be understood by exaggerating the circumstance: Suppose the two observers are several kilometers apart. Obviously they are looking at different drops in the sky. Although they may both see a rainbow, they are looking at different rainbows. Likewise if they are closer together. Only if their eyes are at the very same location will they see exactly the same rainbow.

105. When the Sun is high in the sky and people on the airplane are looking down toward a cloud opposite to the direction of the Sun, they may see a rainbow that makes a complete circle. The shadow of the airplane will appear in the center of the circular bow. This is because the airplane is directly between the Sun and the drops or rain cloud producing the bow.

106. Moon halos and rainbows are similar in that both are produced by light refracting from water. Ice crystals can disperse moonlight into two halos, much as water droplets disperse light into two rainbows. For both, the outer bow is much fainter than the inner one. Halos and rainbows are different in that a halo and Moon are seen in the same part of the sky, with the Moon in the middle of the halo—whereas a rainbow is seen in the part of the sky opposite to the Sun (your shadow, if it can be seen, is in the middle of the rainbow). Another difference is that for rainbows reflection as well as refraction is important, whereas for halos only refraction is important. Yet another difference is that whereas a rainbow involves liquid water droplets, a halo involves frozen water crystals.

107. A magnifying lens used as a “burning glass” does nothing more than gather a certain amount of energy and concentrate it at some focal point. The important point is that the lens is considerably larger than the area over which the light is concentrated. But the solar heat sheet is not larger than the surface area of the swimming pool, and doesn’t collect any more solar energy than the pool receives anyway. The sheet may help warm the pool by preventing evaporation, as would be the case with any cover, but in no way do the lenses direct additional solar energy to the water beneath. This fraudulent advertising plays on the ignorance of the public.

108. The average intensity of sunlight at the bottom is the same whether the water is moving or is still. Light that misses one part of the bottom of the pool reaches another part. Every dark region is balanced by a bright region—”conservation of light.”

109. The bending is less because the light is already slowed down in water, and slows only slightly more in your cornea. That’s why nearsighted eyes see clearer in water than in air. The index of refraction of your cornea is closer to that of water than of air.

110. The speed of light decreases as it passes from the water into your cornea, but not as much as from air to your cornea.

111. The two rays are a sample of many many rays needed to produce a sharp image. The pair of rays merely locate image distance from the lens. The two rays are hardly enough to produce an image.

29 Light Waves

The first photo opener is Bob Greenler blowing a large soap bubble. A good read is Bob's *Chasing the Rainbow: Recurrences in the Life of a Scientist*, Cambridge University Press, 2000. Photo 2 shows Richard Feynman with Helen Yan and Marshall Ellenstein, a gem. Photo 3 is Jennie McKelvie, teaching physics at Massey University, Palmerston North, in New Zealand. Photo 4 is Janie Head, who has been eliciting a love of conceptual physics to her students in Texas for many years. All these photos are of physics educators who enjoy the challenge of getting students to appreciate that physics is an enjoyable part of their world.

The profile for this chapter features one of these outstanding teachers, Marshall Ellenstein.

In your treatment of light waves, emphasize that light does not travel in little sine-wave lines as some diagrams of light suggest. More than one student has asked me if light wiggles as it travels. The wavy lines represent a graph of the changes in the intensity of the E&M fields of which light is composed.

The text mentions how diffraction blurs images in microscopes. Diffraction also tricked Galileo into mismeasuring distances to the stars. This occurred some 200 years before wave optics was understood. Read more on this in Christopher Graney's article "Objects in Telescopes Are Farther Than They Appear" in the Sept. 2009 issue of The Physics Teacher.

If you put some care into the two demonstrations of interference with music suggested here, you'll impress your students with the beauty of physics that should be among the high points of your course.

Practicing Physics Book:
• Diffraction and Interference
• Polarization

Laboratory Manual:
• The Fringe of Optics *Two Slit Interference Equation Simulation* (Tech Lab)
• Light Rules *Turn an mm into a μ to find λ* (Demonstration)
• Diffraction in Action *Diffraction of Light* (Activity)
• Laser Tree *The Geometry of Diffraction Maxima* (Activity)
• Pole-Arier *The Polarization of Mechanical Waves* (Demonstration)
• Blackout *The Polarization of Light Waves* (Demonstration)

Next-Time Questions:
• Three Polaroids
• Soap Bubble
• Polaroid Glasses

Hewitt-Drew-It! Screencasts: •*Diffraction* •*Interference of Light* •*Interference Colors* •*Polarization of Light*

SUGGESTED LECTURE PRESENTATION

Huygens' Principle

A model for understanding the propagation of light is presented in Huygens' principle. Careful investigation of Figure 29.5 illustrates *why* the angle of reflection equals the angle of incidence. The figure also shows another view of refraction. Going further, one can see why light travels in straight lines when passing through a transparent medium. Recall the "photon" cascading in a straight-line fashion back in Figure 26.8. Why the cascade is along a straight-line path is unclear, especially if considered from a *ray* point of view. But for many photons, wavefronts cancel one another in random directions and reinforce along the path that makes up the straight line of the ray. The overlapping wavelets of Huygens is a useful model.

Diffraction

Discuss examples of diffraction as in Figures 29.7 – 29.11.

> DEMONSTRATION: After discussing diffraction, pass some index cards with razor slits in them throughout the class. Show a vertical show-case lamp or fluorescent lamp separated into three segments by colored plastic; red, clear, and blue. Have your students view the diffraction of these three segments through the slit, or through a slit provided by their own fingers. Note the different fringe spacings of different colors.

Diffraction is accounted for in the small holes in the door of a microwave oven. The holes allow you to see the food cooking inside, and they're too small for the 12-cm wavelength microwaves to penetrate.

Interference

Sketch the overlapping of water waves on the board, like that shown in Figure 29.12 on the board. Point out that interference is a property of light waves, sound waves, and ALL kinds of waves.

Prepare your class for your laser demonstration by holding a piece of glass with an irregular surface (shower door glass, sugar bowl cover, crystal glassware) against a laser and show the interference pattern on a screen. Be sure to hold the glass steady so the pattern is fixed. Then make a sketch similar to Figure 29.15 on the board to explain the fringes (a dark area is the result of waves meeting out of phase; a bright area where waves meet in phase).

> DEMONSTRATION: This is a great one! With the lights out, shine laser light through the same irregular piece of glass while making slight movements of the glass and display beautiful interference patterns on the wall. I do this in rhythm with music (Bach's Suite Three in D). Your students will not forget this demonstration!

The Practice Page that treats Figure 29.18 should be helpful at this point. Pass around diffraction gratings if available. (Arbor Scientific 33-0980, or the *Elements, Mixtures and Molecules* spectrum viewer Web: www.hermograph.com/spectrumviewers.)

Interference Colors by Reflection from Thin Films

Bubble time! Your class will be delighted if you show a display of giant bubbles (made with a wide hoop in a wide tray of bubble solution—a mixture of equal amounts of Joy or Dawn dishwashing liquid, glycerin, and water). Point out that the film of the soap bubble is the thinnest thing seen by the unaided eye—5000 times thinner than a human hair or cigarette paper. The smallness of light waves is sensed here also. Emphasize the need for two reflecting surfaces for interference colors.

Go through the text explanation of interference colors seen from splotches of gasoline on a wet street (Figure 29.26). Shown is a single wave of blue light that reflects from the upper surface and travels to the eye. The eye would see blue light if this wave were alone reflecting from a single surface. This would be the case with no gasoline film on a water surface. Ask how many students have ever seen gasoline films illuminated with blue light. None. But sunlight, yes. Reflection of blue from the second surface of water produces cancellation of the blue light. (This wave is drawn in black, only to distinguish the two waves, the

other of which is blue in color.) And when sunlight is incident blue light is canceled. The complementary color of blue, yellow, is what is seen.

> CHECK QUESTION: Why are interference colors not seen from gasoline spilled on a dry surface? [Only one plane reflecting surface is present.]

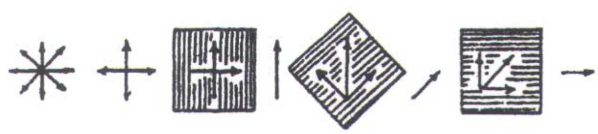
The example of the bluish tint of coated lenses nicely illustrates interference. The predominant yellow of most light is cancelled.

> DEMONSTRATION: Do the experiment "Light Rules" with your class! You'll measure the wavelength of laser light using a ruler with raised grooves as a diffraction grating. Doing so in your class makes a wonderful demonstration. It is the only one I've done at CCSF that elicited a class ovation! I've also done it several times for general talks at physics meetings. Very impressive!

Polarization
Distinguish between polarized and non-polarized light.

> DEMONSTRATION: Tie a rubber tube to a distant firm support and pass it through a grating (as from a refrigerator or oven shelf, as Janie Head shows in the chapter opening photo). Have a student hold the grating while you shake the free end and produce transverse waves. Show that when the grating "axis" and the plane of "polarization" are aligned, the wave passes. And when they are at right angles, the wave is blocked.

Crossed Polaroids with another sandwiched between, as shown by my daughter-in-law in Figure 29.34, is an intriguing demonstration. Second only to the sailboat sailing into the wind, it is my favorite illustration of vectors. The explanation for the passage of light through the system of three Polaroids is not given in the chapter, but is indicated in Figure D.6, Appendix D (repeated here more quantitatively).



[For an ideal polarizer, 50% of nonpolarized incident light is transmitted. That is why a Polaroid passes so little light compared to a sheet of window pane. The transmitted light is polarized. So in the above diagram, only the electric vector aligned with the polarization axis is transmitted; this is 50% of the incident light transmitted by the first sheet. The magnitude of this vector through the second sheet is 50% cos ø, where ø is the angle between the polarization axes of both sheets, and (50% cos ø) cos ß of the original vector gets through the third sheet, where ß is the angle between the polarization axes of the second and third sheet. The intensity of light is proportional to the square of the emerging vector (not treated in the textbook). In any event, the polarizers are less than ideal, so less than this actually gets through the three-sheet system.]

After explaining how the light that reflects from nonmetallic surfaces is polarized in a plane parallel to the surface (by drawing an analogy of skipping flat rocks off a water surface only when the plane of the rock is parallel to the water surface), draw a couple of pair of sunglasses on the board with the polarization axes as shown in the Check Yourself question in the text and ask which are the best for reducing road glare. If you want to discuss the viewing of three-dimensional slides and movies, you'll have a transition to such by the third choice of sunglasses with Polaroids at right angles to each other.

3-Dimensional Viewing
Not everybody can flex their eyes to see the depth of Figures 29.36, 29.37, and 29.39, although with practice most students can do it. Stereograms are easy to construct. Figure 29.39 was easily done on a typewriter with simple line displacement, or such can be drawn by hand. The snowflake stereogram of Figure 29.37 was made by John Dennis, editor of the magazine, *Stereo World*. Make your own by placing

cutouts of snowflakes on a photocopier for one view, then horizontally displace some a bit for a second view. By good old trial and error, students can easily construct their own stereograms.

Stereo buff Marshall Ellenstein contributed the computer generated stereogram shown in Figure 29.41—which reads, "$E = mc^2$."

> DEMONSTRATION: The vivid colors that emerge from cellophane between crossed Polaroids makes a spectacular demonstration. Have students make up some 2 by 2 inch slides of cut and crinkled cellophane mounted on Polaroid material (which can be obtained inexpensively from Arbor Scientific.). If you have a slide projector, insert a slide of crinkled cellophane and rotate a sheet of Polaroid in front of the projecting lens so that a changing montage of colors is displayed on the screen. Also include a showing of color slides of the interference colors seen in the everyday environment, as well as of microscopic crystals. This is more effective with two projectors with hand dissolving from image to image on the screen. Do this in rhythm to some music and you'll have an unforgettable lecture demonstration! [My students report that this is the best part of my course—to which I have mixed feelings. I would prefer that some of my *explanations* were the highlight of my course.]

Holograms

To understand the hologram, view the spectral lines of a gas discharge tube through a diffraction grating and emphasize that there are really no physical lines where they appear to be—that the lines are virtual images of the glowing tube (just as they would be images of slits if a slit were being used). With a fairly good idea of how these images are produced by the diffraction grating, show the class a really sophisticated diffraction grating—not of vertical parallel lines in one dimension, but of microscopic swirls of lines in two dimensions—a hologram, illuminated with a laser.

Interestingly enough, holography does not require a laser. As the text states, Dennis Gabor created the first hologram using light from a sodium vapor lamp. Holography requires monochromatic light from a point source. Gabor simply passed sodium light through a pinhole, which reduced intensity and required long exposures and sensitive film. The advantage of the laser for holograms is that a laser emits all its light in a point-source form. Lasers make holography much easier to do.

Although some layered holograms can be viewed with ordinary white light, like those on credit cards, they are nevertheless made with the coherent light of the laser.

Answers and Solutions for Chapter 29

Reading Check Questions

1. Every point on a wavefront behaves as a source of new wavelets which combine to form new wavefronts.
2. Plane waves through a small opening will fan out on the other side.
3. Diffraction is more pronounced through small openings.
4. Diffraction is more pronounced for longer wavelengths.
5. Longer wavelength waves diffract more than shorter waves, so the longer waves of AM diffract more.
6. Interference is a property of all types of waves.
7. Thomas Young demonstrated the wave nature of light.
8. Light bands are regions of constructive interference; dark bands of destructive interference.
9. An optically flat surface is one where interference fringes are uniform in shape.
10. Interference of light is the cause of Newton's rings.
11. Iridescence is produced by light interference.
12. These are interference colors, a result of different thicknesses of gasoline on a water surface. On a dry street there is no underlying reflective surface as water provides.
13. These colors are interference colors, resulting from double reflection from two surfaces.
14. The colors that make up interference colors are the result of cancellation of primary colors each of which is a single frequency.
15. Polarization distinguishes between longitudinal and transverse waves.
16. The directions match for both light and the vibrating electron producing it.
17. When aligned, what gets through one gets through the other. When at right angles, what gets through the first is absorbed by the second.
18. An ideal Polaroid will transmit 50% of incident ordinary light.
19. The reflected light is polarized in the direction of the plane surface of reflection.
20. Parallax is evident when you view something with both eyes, but is not evident when viewed with one eye.
21. Yes, the phenomenon of parallax does underlie depth perception.
22. No, each image must have been created when viewed somewhat apart from each other.
23. Polarization filters at right angles to each other project a pair of images that merge on a screen. These images can reach separate eyes when the screen is viewed through polarization filters at the same right angles to each other.
24. A hologram shows three-dimensional images, whereas a photograph does not.

Think and Do

25. Diffraction is nicely evident.
26. The rays to each viewer are slightly displaced, and therefore different, producing different interference colors.
27. This activity reveals polarization in the sky.
28. This activity is even more dramatic if the colors are projected on a screen.

Think and Explain

29. Earth intercepts such a tiny fraction of the expanding spherical wave from the Sun that it can be approximated as a plane wave (just as a small portion of the spherical surface of the Earth can be approximated as flat). The spherical waves from a nearby lamp have noticeable curvature (see Figures 29.3 and 29.4).

30. Diffraction around ordinary-sized objects is most pronounced for waves with a wavelength as long or longer than the objects. The wavelength of sound waves is relatively long, and for light, extremely short. Hence the diffraction of sound is more evident in our everyday environment.
31. The wavelengths of AM radio waves are hundreds of meters, much larger than the size of buildings, so they are easily diffracted around buildings. FM wavelengths are a few meters, borderline for diffraction around buildings. Light, with wavelengths a tiny fraction of a centimeter, show no appreciable diffraction around buildings.

32. Both interference fringes of light and the varying intensities of sound are the result of the superposition of waves that interfere constructively and destructively.

33. By a half wavelength, or an odd number of half-wavelengths.

34. The fringes will be spaced farther apart if the pattern is made of longer-wavelength yellow light. The shorter wavelength green light will produce closer fringes.

35. Blue light will produce narrower-spaced fringes.

36. Constructive interference.

37. Destructive interference.

38. You'll photograph what you see through the lens—a spectrum of colors on either side of the streetlights. We'll see in the following chapter that the colors diffracted correlate with the illuminating gas in the streetlights.

39. Fringes become closer together as the slits are moved farther apart. (Note this in the photos of Figure 29.14.)

40. Young's interference experiment produces a clearer fringe pattern with slits than with pinholes because the pattern is of parallel straight-line-shaped fringes rather than the fringes of overlapping circles. Circles overlap in relatively smaller segments than the broader overlap of parallel straight lines. Also, the slits allow more light to get through; the pattern with pinholes is dimmer.

41. Refraction: rainbow. Selective reflection: flower petals. Thin-film interference: soap bubbles.

42. Diffraction is the principle by which peacocks and hummingbirds display their colors. The ridges in the surface layers of the feathers act as diffraction gratings.

43. Interference colors result from double reflections from the upper and lower surfaces of the thin transparent coating on the butterfly wings. Some other butterfly wings produce colors by diffraction, where ridges in the surface act as diffraction gratings.

44. The optical paths of light from upper and lower reflecting surfaces change with different viewing positions. Thus, a change in color can be seen by tilting the shell at different angles.

45. Interference of light from the upper and lower surfaces of the soap or detergent film is occurring.

46. A necessary condition for interference is that the out-of-phase parts of the wave coincide. If the film is thick, the part of the wave that reflects from one surface will be displaced from the part that reflects from the other surface. No interaction, no cancellation, no interference colors. For thin films, the two parts of the wave coincide as they recombine.

47. Light from a pair of stars will not produce an interference pattern because the waves of light from the two separate sources are incoherent; when combined they smudge. Interference occurs when light from a single source divides and recombines.

48. Each colored ring represents a particular thickness of oil film, just as the lines on a surveyor's contour map represent equal elevations.

49. Blue, the complementary color. The blue is white minus the yellow light that is seen above. (Note this exercise goes back to information in Chapter 27.)

50. Ultraviolet, due to its shorter wavelengths.

51. Polarization is a property of transverse waves. Unlike light, sound is a longitudinal wave and can't be polarized. Whether a wave can be polarized or not, in fact, is one of the tests to distinguish transverse waves from longitudinal waves.

52. To say that a Polaroid is ideal is to say that it will transmit 100% of the components of light that are parallel to its polarization axis, and absorb 100% of all components perpendicular to its polarization axis. Nonpolarized light has as many components along the polarization axis as it has perpendicular to that axis. That's 50% along the axis, and 50% perpendicular to the axis. A perfect Polaroid transmits the 50% that is parallel to its polarization axis.

53. If the sheet is aligned with the polarization of the light, all the light gets through. If it is aligned perpendicular to the polarization of the light, none gets through. At any other angle, some of the light gets through because the polarized light can be "resolved" (like a vector) into components parallel and perpendicular to the alignment of the sheet.

54. With polarization axes aligned, a pair of Polaroids will transmit all components of light along the axes. That's 50%, as explained in the preceding answer. Half of the light gets through the first Polaroid, and all of that gets through the second. With axes at right angles, no light will be transmitted.

55. You can determine the polarization axis for a single sheet of Polaroid by viewing the glare from a flat surface, as in Figure 29.34. The glare is most intense when the polarization axis is parallel to the flat surface.

56. Glare is composed largely of polarized light in the plane of the reflecting surface. Most glaring surfaces are horizontal (roadways, water, etc.), so sunglasses with vertical polarization axes filter the glare of horizontally polarized light. Conventional nonpolarizing sunglasses simply cut down on overall light transmission either by reflecting or absorbing incident light.

57. The axis of the filter should be vertical, not allowing the passage of the glare, which is parallel to the plane of the floor—horizontal.

58. Since most glare is due to reflection from horizontal surfaces, the polarization axes of common Polaroid sunglasses are vertical.

59. You can determine that the sky is partially polarized by rotating a single sheet of Polaroid in front of your eye while viewing the sky. You'll notice the sky darken when the axis of the Polaroid is perpendicular to the polarization axis of the skylight.

60. Making holograms requires coherent light, exactly what a laser provides. Hence practical holography followed the advent of the laser. (Interestingly enough, the first holograms were made before the advent of the laser, and were crude by today's standards. They were made with monochromatic light from a sodium vapor lamp, through a tiny pinhole to provide a close approximation of coherent light, and required very long exposures.)

61. Interference is central to holography.

Think and Discuss

62. Larger wavelengths diffract more (since the ratio of wavelength to slit size is greater), so red diffracts the most and blue the least.

63. Longer wavelength red light.

64. Wider fringes in air, for in water the wavelengths would be compressed (go back to Figure 28.24), with closer-together fringes.

65. The spot will be bright due to constructive interference.

66. Longer wavelength red light produces wider fringes.

67. The problem is serious, for depending on the orientation of the polarization axes of the display and the glasses, no display may be seen.

68. Call the three Polaroids 1, 2, and 3. The first one acts as a polarizer of the unpolarized light, ideally letting half of it through with a specific polarization direction that is perpendicular to the axis of Number 3. So when only 1 and 3 are present, no light gets through. But Number 2, when placed between 1 and 3, is illuminated by light aligned at 45° to its axis, so it lets half of the light through. The light striking Number 3 is now aligned at 45° to the axis of Number 3. So Number 3 transmits half of the light that strikes it. (The amount that gets through is one-eighth of the original intensity.)

30 Light Emission

Photo openers show three physics-educator friends, George Curtis, University of Hawaii at Hilo, Neil de Grasse Tyson, Hayden Planetarium in New York, and Evan Jones, Sierra College in California. Evan is a big advocate of LEDs for home and industrial lighting, and contributed to their treatment in this chapter. The laser show is by friends at Lund University in Sweden.

The profile is Neil de Grasse Tyson, who wonderfully brings good science to the public.

This chapter begins by treating the Bohr model of the atom with simplified energy levels to explain light emission, whether by a gas discharge tube, incandescent or fluorescent lamp, phosphorescent mineral, or a laser.

Excitation between the various simplified energy levels of the Bohr model of the atom is used in this chapter to explain the emission of light. Note that this is quite a different model of light emission compared to the oscillator model we introduced in Chapters 26 and 27. Subtle oscillations of the electron shells underscore light being reflected or transmitted. Excitation is not subtle, and is a different process—electrons make transitions from one electron shell to another. There are two different models of behavior here. One suits the processes of reflection and transmission of light, and the other suits the way light is emitted from a light source to begin with. Neither of the two atomic models presented is intended to convey a picture of what atoms are "really like," but instead are simplified representations that are useful for conceptualizing how atoms behave. You may comment on the nature of a model in physics here; namely that a model is not "right" or "wrong," but "useful" or "nonuseful." No scientific models are carved in stone.

Arbor Scientific has a Spectrum Analysis kit composed of a power supply and gas tube holder, with seven gas spectrum tubes about 26 cm long. Power supply (P2-9500), analysis set (P2-9501), and discharge tubes (P2-9500 09-15). Arbor also supplies the RSpec-Explorer (P2-9505) for studying spectra. Check out their RSpec demo video on their internet site ArborSci.com. For low-cost hand-held classroom spectrum viewers check out *Elements, Mixtures and Molecules Spectrum Viewer* at www.hermograph.com/spectrumviewers.

Students are quite familiar with glow-in-the-dark strips used as head gear or necklaces, popular in dance spots. Or glow-in-the-dark key rings, activated by light. For the record, these phosphorescent materials contain calcium sulfide, activated by bismuth, with additional traces of copper, silver, or lead. These materials are harmless, and very different from the old zinc sulfide materials impregnated with trace amounts of radium to supply alpha particles for stimulation.

The treatment of lasers in this book is very elementary. Lasers today, though operating on the principles treated in the text, do much more than the applications cited in the book. Amplification techniques now find

lasers cutting through materials better than was done by torches and saws in the past. The applications of lasers, from dental and medical tools to military weapons, seems endless.

This chapter is a necessary background for the following two chapters. If you are not going to lecture on the quantum physics of Chapters 31 and 32, then this chapter fits very well when sandwiched between Chapters 26 and 27. Then the nature of light (Chapter 26) is followed by how light is emitted. Color (Chapter 27) picks up the sequence. Another advantage is an earlier treatment of the laser, which is likely part of your demo equipment for Chapter 28.

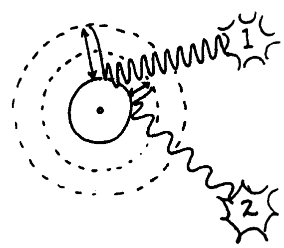
If you don't provide small diffraction gratings to your class, consider using a large demonstration grating for showing spectral lines of gas discharge tubes. Holographic diffraction grating film sheets 6" by 12" are available from Edmund Scientific Company. Sandwich a sheet between a couple of pieces of glass and you've got a first-rate demonstration grating. Arbor Scientific has bright holographic inexpensive gratings P33-0980.

Next-Time Questions:
• Absorption Spectra

Hewitt-Drew-It! Screencasts: •*Atomic Excitation* •*Atomic Spectra* •*Emission of Light* •*Lamps* •*Laser Light*

SUGGESTED LECTURE PRESENTATION

Excitation
Begin by holding a book above the lecture table and dropping it. Then hold it higher and drop it again. State that the potential energy you supplied to the book was converted to kinetic energy and then to sound energy. State that the higher you boost the book before dropping it, the louder the sound. State that a similar thing happens in the case of atoms. Parallel your book example and consider the case of an electron being boosted to a higher orbit in an atom. Just as a screen door that is pushed open against a spring snaps back and produces sound, the displaced electron snaps back to its ground state and produces light. It emits a throbbing spark of light we call a *photon*. Show that when it is boosted to higher levels, it emits a higher frequency photon upon de-excitation. Introduce the relationship $E \sim f$ for the resulting photons. Then to $E = hf$. Discuss the variety of energy-level jumps for a simple atom.



> CHECK QUESTION: Two photons are emitted as a result of the transitions shown on the board. If one photon is red and the other blue, which is which? [Be sure to draw the shorter wavelength for the greater transition, from the second level to ground state, and the longer wavelength for the smaller transition from level one to ground.]

Emission Spectra

> DEMONSTRATION: Show the spectra of gas discharge tubes. Either use a large diffraction grating that you hold in front of the tube, or pass small gratings among the class, so the spectral lines can be observed.

Cite examples of the uses of spectrometers—how very minute quantities of materials are needed for chemical analysis—how tiny samples of ores are sparked in carbon arcs and the light directed through prisms or diffraction gratings to yield precise chemical composition—note their use in fields as diverse as chemistry and criminology.

Absorption Spectra
Distinguish between emission and absorption spectra. Cite that a century ago, the chemical composition of the stars were thought to be forever beyond the knowledge of humankind—and now today we know as

much about their composition as we do the Earth's. (Figure 30.9, by the way, is exaggerated in that it shows an absorption line matching every emission line rather than the actual principle emission lines.)

Incandescence

Emphasize the discreteness of the lines from atoms in the gaseous state. Then lead into the idea of excitation in an incandescent lamp, where the atoms are in the solid state. State how in the crowded condition the energy levels interact with one another and produce a distribution of frequencies rather than discrete frequencies that characterize the gaseous state. Sketch a bell-shaped curve and label the peak of the curve as the frequency proportional to the absolute temperature of the source. Be sure to clear up any misconceptions that $f \sim T$ means that the frequency of light is proportional to the temperature of light (light can impart temperature, but doesn't have a temperature of its own. T is the temperature of the source).

Lamps

Compare the prospects of lighting via CFLs and LEDs, both in the near future and further down the road. CFLs have cause a lot of "green" excitement and the public has taken to them. The mercury in them, however, is of some concern. The development of LED bulbs has quickly progressed to bulbs that can be screwed into sockets as incandescent bulbs have always been.

Incandescence

> CHECK QUESTION: Hold up an obviously broken light bulb and ask if it is presently emitting electromagnetic energy. [Sure is, as is everything—its temperature is simply too low for the corresponding frequency to trigger the light receptors of our retinas.]

Get into the idea of the infrared part of the spectrum. Show in a sequence of radiation curves on the board how an increase in temperature brings the curve "sloshing over" into the lower frequency portion of the visible spectrum—hence the red hotness of a hot poker. Show how an increase in temperature brings the curve into the visible spectrum producing white light. Show why a hot poker does not become green hot, and how sharp the curve would have to be to produce green without sloshing into the other frequencies which result in white light. If you have discussed the treatment of overlapping distribution curves (back in Chapter 17 page 176 in this manual), you might make reference to this and quip that only narrow-minded people would expect that a hot poker could glow green-hot.

Fluorescence

Show some fluorescent materials in the room light. Explain the role of photons in the room lighting that excite the molecules in the material that produces not only reflection, but emission—hence the term *day-glow* that sometimes describes fluorescent paints.

> CHECK QUESTION: Would higher-frequency light produce more glowing, and why? [Yep, more energy per photon!]

> DEMONSTRATION: Show fluorescent materials illuminated with a black light. Discuss the observations with the black light still on, and then extinguish the light so the room is totally dark. Ask what is happening (have some phosphorescent materials in your display).

Phosphorescence

> DEMONSTRATION: Call attention to the glowing of your phosphorescent materials while the lights are off. Compare this to swinging a screen door open when you walk out of the house and hearing it slam about a minute or so later. The screen door and the excited electrons become "stuck" for a while.

Cite common examples—watch and clock faces, light switches, even party jewelry. Acknowledge watch faces activated by radioactive minerals. Discuss also the phenomena of bioluminescence. It turns out that even the deepest depths of the ocean there is a background of bioluminescence that is the subject of much study. Photo detectors at great depths sense light when objects suddenly move in water.

Lasers

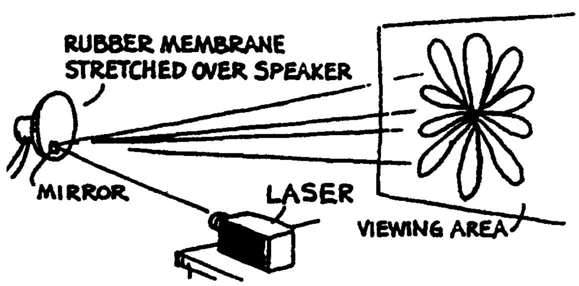
William J. Beaty reminds us that laser light travels in straight lines like any other light, and to clear up the possible misconception that laser light travels in wiggly paths as suggested by Figures 30.19 through 30.21. The common sine configuration represents the changing intensity of the electric field of light—a graph of intensity versus time or distance.

Another misconception is that laser light is always parallel light. While it's true that many lasers are designed to emit thin nonspreading beams, it is wrong to suppose this is a characteristic of laser light. Those in your supermarket check-out stand, for example, fan out. A common HeNe classroom laser contains a converging lens, a "parallelizing lens," to correct for the spreading that exists within the beam. Without it, the beam would spread. So although laser light can be *made* extremely parallel, it is not a characteristic of laser light in general.

Laser light is not necessarily brighter than other types of light. Your classroom laser puts out much less light than a flashlight bulb. A primary difference is that a laser provides a point source while an ordinary bulb is an extended source. Even weak light from a laser is concentrated by the lens of your eye to a blazing pinpoint on your retina. This is why even a weak laser is dangerous. Concentration is the factor, like the difference between looking at a frosted bulb and an unfrosted bulb of the same wattage. If a laser beam were of the same wattage of an ordinary house lamp, the beam would burn whatever it touched. A laser can concentrate light.

High-energy lasers are something else. The details of the simple helium-neon laser shown in Figure 30.22 in the text, nicely serves as a foundation for higher-energy lasers that followed. Medical applications are commonly known. Lasers are also used in cutting steel and other metals, in welding, brazing, bending materials, engraving or marking, cleaning, and as weapons, where they successfully destroy missiles. Whereas Figure 30.22 illustrates the rudiments of a laser, acknowledge the advancement of laser technology.

DEMONSTRATION: Give a laser show. Sprinkle chalk dust or smoke in the beam, show diffraction through a thin slit and so forth. An unforgettable presentation is that of Think and Do 38 on page 388 in Chapter 20 wherein a laser beam is projected on a mirror fastened to a rubber membrane that is stretched over a radio loudspeaker. Do this to music and fill the darkened room with a display of dancing lissajous patterns on the walls.



Lasers

When Conceptual Physics made its advent back in 1971, lasers were the new physics application looking for problems. A first application was visible "chalk lines" for surveying; medical applications were still on the drawing boards. The current question is what devices have no lasers!

Answers and Solutions for Chapter 30

Reading Check Questions

1. At these high frequencies, ultraviolet light is emitted.
2. Discrete means unique, that other states don't overlap it.
3. Electrons in the outer electron shells have greater potential energy.
4. The atom de-excites and emits light.
5. They are equal.
6. The relationship is $E = hf$.
7. Blue light has both a greater frequency and energy per photon.
8. Atoms can be excited without limit.
9. The colors indicate the various atoms undergoing excitation.
10. A mercury-vapor lamp puts a greater part of its energy into light than an incandescent bulb lamp does.
11. A spectroscope is a device that measures frequencies of light in a beam of light.
12. In a gaseous phase, emitted light is from well-defined energy levels of outer electron shells in atoms. In the solid phase, smearing of light occurs due to mutual interactions among neighboring atoms in close contact.
13. The relationship is $f \sim T$ (covered also in Chapter 16.)
14. Where many lines appear in an emission spectrum, empty spaces appear in an absorption spectrum.
15. Fraunhofer lines are spectral absorption lines in the solar spectrum.
16. The Doppler effect causes a stretching of waves for receding stars and compressed waves for approaching stars.
17. There is more energy per photon in UV.
18. Phosphorescence is fluorescence with a time delay between excitation and de-excitation.
19. A metastable state is a prolonged state of excitation.
20. Air contains oxygen, which oxidizes the filament. Argon does not.
21. Primary excitation is by electron impact; secondary is by photon impact.
22. A CFL is longer lasting than an incandescent bulb.
23. A LED is even longer lasting than an incandescent bulb.
24. Monochromatic light is of photons having a single frequency;
25. Coherent light is of photons having a single frequency that are in phase with one another.
26. The photons from a laser are coherent.

Think and Do

27. Grandma has seen this progression of lamps!
28. Line and band spectra are nicely shown.

Think and Solve

29. (a) The B-to-A transition has twice the energy and twice the frequency of the C-to-B transition. Therefore it will have half the wavelength, or 300 nm. Reasoning: From $c = \lambda f$,
$\lambda = c/f$. Wavelength is inversely proportional to frequency. Twice the frequency means half the wavelength.
(b) The C-to-A transition has three times the energy and three times the frequency of the C-to-B transition. Therefore it will have one-third the wavelength, or 200 nm.

Think and Explain

30. In accord with $E = hf$, a gamma ray photon greater energy because it has a higher frequency.

31. The energy levels are different for the atoms and molecules of different materials, hence the different frequencies of radiation emitted when excitation occurs. Different colors correspond to different energy changes and frequencies.
32. Higher-frequency higher-energy blue light corresponds to a greater change of energy in the atom.

33. More energy is associated with each photon of ultraviolet light than with a photon of visible light. The higher-energy ultraviolet photon can cause sunburn-producing chemical changes in the skin that a visible photon cannot do.

34. Doubling the wavelength of light halves its frequency. Light of half frequency has half the energy per photon. Think in terms of the equation $c = f\lambda$. Since the speed of light c is constant, λ is inversely proportional to f.

35. A neon tube doesn't "run out" of atoms to be excited because its atoms are re-excited over and over, without the need for "new" atoms.

36. Spectral lines are images of the slit in a spectroscope. If the slit were crescent shaped, the "lines" would also be crescent shaped.

37. Spectral "lines" would be round dots. Very nearby lines would be easier to discern than dots that might overlap. Also, if the diameter of the hole were made as small as the width of the slit, insufficient light would get through. Thus the slit images are superior.

38. Neon light is not monochromatic, so diffracted light from a neon tube produces a band of colors, most of which are various shades of red. Light from a helium-neon laser is of one color—monochromatic—showing only one of the spectral lines of neon.

39. When a spectrum of the Sun is compared with the spectrum of the element iron, the iron lines overlap and perfectly match certain Fraunhofer lines. This is evidence for the presence of iron in the Sun.

40. By comparing the absorption spectra of various nonsolar sources through Earth's atmosphere, the lines due to Earth's atmosphere can be established. Then when viewing solar spectra, extra lines and extra line intensities can be attributed to the atmosphere of the Sun.

41. Spectral-line patterns that appear in starlight also appear in the spectra of elements on Earth. Since the spectra of light from distant stars matches the spectra of elements on Earth, we conclude that we and the observable universe have the same "fingerprints" and are made of the same stuff.

42. The moving star will show a Doppler shift. Since the star is receding, it will be a red shift (to lower frequency and longer wavelength).

43. The stars are incandescent sources, where peak radiation frequency is proportional to stellar temperature. But light from gas discharge tubes is not a function of gas temperatures; it depends on the states of excitation in the gas. These states are not dependent on the temperature of the gas, and can occur whether the gas is hot or cool.

44. In accord with $E \sim f$, the higher frequency ultraviolet photon has more energy than a photon in the visible part of the spectrum, which in turn has more energy than a photon in the infrared part of the spectrum.

45. Atomic excitation occurs in solids, liquids, and gases. Because atoms in a solid are close packed, radiation from them (and liquids) is smeared into a broad distribution to produce a continuous spectrum, whereas radiation from widely-spaced atoms in a gas is in separate bunches that produce discrete "lines" when diffracted by a grating.

46. Atoms excited in high-pressure gas interfere with one another in a way similar to the way closely-packed atoms in a solid do, resulting in overlapping waves and smearing of light.

47. When tungsten atoms are close-packed in a solid, the otherwise well-defined energy levels of outer electron shells are smeared by mutual interactions among neighboring atoms. The result is an energy band composed of myriad separate levels very close together. Because there are about as many of these separate levels as there are atoms in the crystalline structure, the band cannot be distinguished from a continuous spread of energies.

48. The many spectral lines from the element hydrogen are the result of the many energy states the single electron can occupy when excited.

49. The light that is absorbed is part of a beam. The light that is indeed re-emitted goes in all directions, with very little along the direction of the illuminating beam. Hence those regions of the spectrum are dark.

50. The "missing" energy may appear as light of other colors or as invisible infrared light. If the atoms are closely packed, as in a solid, some of the "missing" energy may appear as heat. In that case, the illuminated substance warms.

51. (a) An “absorption spectrum” is observed, with certain dark lines in a background of continuous light. (b) The “emission spectrum” will contain a few bright lines, most of which will match the lines in the absorption spectrum.

52. Fluorescence is the process in which high-frequency (high energy) ultraviolet radiation converts to low-frequency (lower energy) visible radiation with some energy left over, perhaps appearing as heat. If your friend is suggesting that low-energy infrared radiation can be converted to higher-energy visible light, that is clearly a violation of the conservation of energy—a no-no! Now if your friend is suggesting that infrared radiation can cause the fluorescence of still lower-frequency infrared radiation, which is not seen as light, then your friend’s reasoning is well founded.

53. As in the previous exercise, fluorescence requires that the photons of light initiating the process have more energy than the photons of light emitted. If visible light is to be emitted, then lower-energy infrared photons cannot initiate the process.

54. Fabrics and other fluorescent materials produce bright colors in sunlight because they both reflect visible light and transform some of the Sun’s ultraviolet light into visible light. They literally glow when exposed to the combined visible and ultraviolet light of the Sun.

55. The different colors emitted by fluorescent minerals correspond to different molecules with different sets of energy states. Such minerals can therefore be visually distinguished.

56. Just as a time delay occurs with the opening and closing of a spring door, a similar time delay occurs between excitation and de-excitation in a phosphorescent material.

57. Illumination by the lower-frequency light doesn’t have sufficiently energetic photons to ionize the atoms in the material, but has photons of enough energy to excite the atoms. In contrast, illumination by ultraviolet light does have sufficient energy for ejecting the electrons, leaving atoms in the material ionized. Imparting different energies produces different results.

58. A CFL puts out less heat and more light. For the same wattage, the CFL would put out far less heat than an incandescent bulb. The chickens would be well lit, but cold.

59. LEDs have a longer life than CFLs and incandescent lamps, which lowers maintenance costs.

60. Red + green = yellow.

61. LEDs will likely predominate because they have longer lives and are mercury free.

62. The acronym says it: *m*icrowave *a*mplification by *s*timulated *e*mission of *r*adiation.

63. The photons from the photoflash tube must have at least as much energy as the photons they are intended to produce in the laser. Red photons have less energy than green photons, so wouldn’t be energetic enough to stimulate the emission of green photons. Energetic green photons can produce less-energetic red photons, but not the other way around.

64. Photons in the laser beam are coherent and move in the same direction; photons in light emitted by an incandescent lamp are incoherent and move in all directions.

65. If it weren’t relatively long-lived, there wouldn’t be enough accumulation of atoms in this excited state to produce the “population inversion” that is necessary for laser action.

66. When an excited helium atom collides with a neon atom in its ground state, energy given by the helium to the neon must match that of the metastable state of neon. If the match in energies isn’t close, boosting neon to a metastable state wouldn’t occur.

67. Your friend’s assertion violates the law of energy conservation. A laser or any device cannot put out more energy than is put into it. Power, on the other hand, is another story, as is treated in the following exercise.

68. No device can put out more energy than is put in. But if a device takes in energy at a certain rate and emits it in a shorter time interval, then it is capable of putting out higher bursts of power than it takes in.

69. *f* bar is the peak frequency of incandescent radiation—that is, the frequency at which the radiation is most intense. *T* is the Kelvin temperature of the emitter.

70. A lamp filament or any object emits radiation at all temperatures greater than absolute zero. The peak frequency of this radiation is proportional to the absolute temperature of the object. At room temperature this frequency is in the far infrared part of the spectrum and therefore can't normally be seen. When the temperature of the filament is increased, more of the radiation moves into the visible part of the spectrum and we have light.

71. Both radiate energy, but since temperatures are different, the hotter Sun emits higher frequencies of light than does Earth, and of much greater intensity.

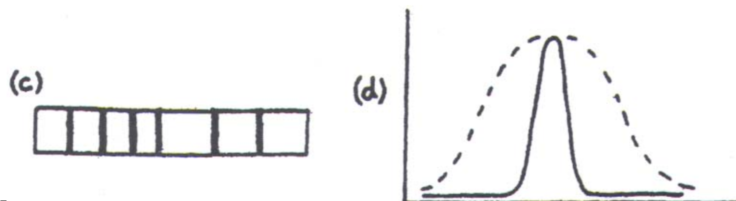
72. We can't see objects at room temperature in the dark simply because our eyes are not sensitive to the radiation the objects emit. If the temperature of the objects is increased sufficiently, then the radiation they emit is visible to us.

73. All bodies not only radiate energy, they absorb it. If radiation and absorption are at equal rates, no change in temperature occurs.

74. The metal is glowing at all temperatures, whether we can see the glow or not. As its temperature is increased, the glow reaches the visible part of the spectrum and is visible to human eyes—red. So the heated metal passes from infra-red (which we can't see) to visible red. It is red hot.

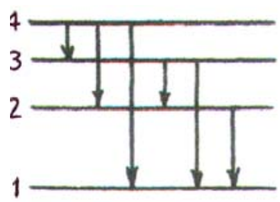
75. Star's relative temperatures—lowest for reddish; medium for whitish; and hottest for bluish.

76.



77. The solar spectrum is an absorption spectrum, with dark lines called Fraunhofer lines in honor of Joseph von Fraunhofer who d

78. Six transitions are possible, as shown. The highest-frequency transition is from quantum level 4 to level 1. The lowest-frequency transition is from quantum level 4 to level 3.



79. Energy is conserved, and frequency is proportional to a photon's energy. So the sum of the two frequencies is equal to the frequency of light emitted in the transition from quantum level 4 to the ground state, quantum level 1.

80. Yes, there is a relationship among the wavelengths, but it is not as simple as the relationship among frequencies. Because energies are additive, so are the frequencies. But since wavelength is inversely proportional to frequency, it is the inverses of the wavelengths that are additive. Thus,

$$\frac{1}{\lambda(4 \to 3)} + \frac{1}{\lambda(3 \to 1)} = \frac{1}{\lambda(4 \to 1)}$$

81. Only three, one from 4
to ground, one from 3 to ground, and one from 2 to ground. The transition from 4 to 3 would involve the same difference in energy and be indistinguishable from the transition from 3 to 2, or from 2 to ground.

Likewise, the transition from 4 to 2 would have the same change in energy as a transition from 3 to ground.

Think and Discuss

82. Its energy is very concentrated in comparison with that of a lamp.

83. Continued heating of a red-hot piece of metal will increase the peak frequency into the middle of the visible spectrum, and it will glow white hot (because all the visible frequencies are present). See the radiation curve in Figure 30.7. Continued heating will increase the peak frequency into the ultraviolet part of the spectrum, with part of it remaining in the blue and violet. So yes, we can heat a metal until it becomes blue-hot. (The reason you haven't seen blue-hot metal is because metal will vaporize before it can glow blue hot. Many stars, however, are blue-hot.)

84. The radiation curve of an incandescent source (Figure 30.7) is wide, spanning a broad band of frequencies. A star that is red hot has its peak frequency in the infrared, with only some emitted light with frequencies in the lower part of the visible spectrum. If the star is hotter, emitted light may have frequencies spanning the visible spectrum, in which case the star appears white.

85. A star with peak frequency in the ultraviolet emits enough light in the higher-frequency part of the visible spectrum to appear "violet-hot." As in the previous exercise, if it were cooler, all frequencies would be more balanced in intensity that would make it look whiter.

86. An incandescent source that peaks in the green part of the visible spectrum will also emit reds and blues, which would overlap to appear white. Our Sun is a good example. For green light and only green light to be emitted, we would have some other kind of a source, such as a laser, not an incandescent source. So "green-hot" stars are white.

31 Light Quanta

Photo openers are of Phil Wolf, CERN physicists, Anne Cox, and Gary Williams. Both Phil and Anne are physics department chairpersons at their respective colleges.

Max Planck is featured in the opening profile. In his honor is the Planck spacecraft that scans the sky for the infinitesimal but informative clues to the earliest moments of the universe.

Louis de Broglie's doctoral thesis about the wave nature of matter was so radical that his professors were uncertain about accepting it. After asking Einstein about it and gaining his approval, the thesis was accepted. Five years later de Broglie's thesis won the Nobel Prize in physics.

This chapter is part of a three-chapter sequence—Chapters 30 - 32, which serves as a transition to the quantum nature of the atom in Part 7.

Unless you wish to lecture about the physicists who led us to our present understanding of light, and how the processes and developments leading to these findings were discovered and fashioned into the building blocks of quantum mechanics, the chapter can be assigned as reading and not treated during lecture time. If lecture time is used to support the chapter, demonstrate the photoelectric effect as described below. Perhaps the concept most interesting in the chapter to expand upon in lecture is the uncertainty principle.

Practicing Physics Book:
• Light Quanta

Next-Time Questions:
• Lamp Glow

Hewitt-Drew-It! Screencasts: •*The Quantum World* •*Planck's Constant and Photons* •*Photoelectric Effect* •*Particle Diffraction* •*Quantum Uncertainty* •*The Uncertainty Principle*

SUGGESTED LECTURE PRESENTATION

Birth of the Quantum Theory
Begin by citing the flavor of physics at the turn of the century, that many in the physics community felt that the bulk of physics was in the can and only applications and engineering were left. And then along came Einstein and Max Planck, who fell through cracks that turned out to be Grand Canyons! Continue with a historical perspective.

Quantization and Planck's Constant
You may or may not wish to discuss Planck's work with blackbody radiation and how it led to the notion that energy occurs in discrete amounts called quanta (only slightly mentioned in the text).

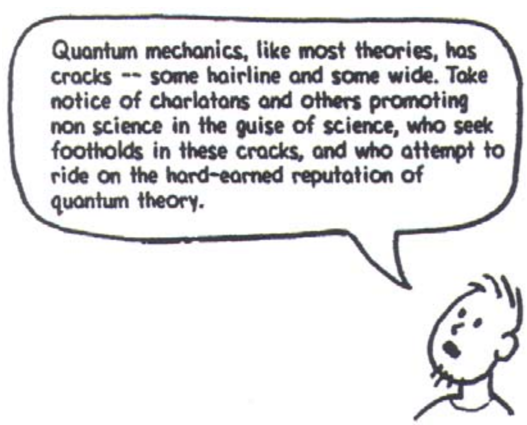
Photoelectric Effect

DEMONSTRATION: Demonstrate the photoelectric effect by placing a freshly polished piece of zinc on an electroscope and illuminate it with an open carbon arc lamp (no glass lens). To focus the beam, use a quartz lens (to pass the UV). Show that a positively charged electroscope will not discharge when the light shines on the zinc plate. But that a negatively charged electroscope will quickly lose its charge, showing that the negative charges (electrons!) are ejected form the zinc surface by the light. Show the blockage of UV light by placing a piece of glass in the path of the light beam. This is evidenced by the stopping of the discharge process. If you have a quartz prism, pass the light through a slit, then through the prism, and onto the zinc. Show that the negatively charged electroscope discharges only when the portion of the spectrum beyond the violet end strikes the zinc plate.

Go a step further as Mikhael Grote and William Heinmiller do. Have students test the effectiveness of various sunscreens and lotions. Simply spread different creams or lotions on the zinc plate before charging the electroscope. (*The Physics Teacher*, Vol. 34, Number 9, Dec. 1996.)

Asking and Answering Questions: The answers one gets often depends on the way the question is asked. This is illustrated by the two monks who wished to smoke in the prayer room of a monastery. The first monk wrote a letter to his superior asking if it was permissible to smoke while praying. The answer was a resounding no. The second monk wrote a letter to his superior asking if it was permissible to pray while smoking. The answer was a resounding yes. In a sort of similar way, many of the perplexities of quantum physics have to do with the way questions are asked, and more particularly with what kind of questions are asked. For example, asking for the energy of a hydrogen atom in its first excited state has a definite answer, accurate to one part in 10^{12}. The answer to asking exactly when the electron makes its transition to the ground state, on the other hand, is probabilistic. The probabilistic answers to such questions fosters the false notion that there are no exact answers at the quantum realm. Questions appropriate to the quantum realm, however, are crisply and precisely answered by quantum mechanics.

Quantum Physics
Cite the behavior of light as being wavelike in traveling from place to place, but being particlelike when incident upon matter, as evident in various **double slit experiments**. It travels like waves and lands like particles. Discuss the **wave-particle duality**, and the photon-by-photon buildup of the photograph of Figure 31.5. Like others, de Broglie was in the right place at the right time, for the notion of particles having wave properties was at hand. De Broglie showed Planck's constant again with his formula that relates the wavelength of a "matter wave" with its momentum. So matter, like light, has wave properties. When incident upon a target its matter nature is evident. We don't ordinarily notice the wave nature of matter only because the wavelength is so extremely small. The footnote on page 608 in the chapter illustrates this. (Interestingly enough, de Broglie did little physics after his one large contribution. He died in 1987.) Discuss the **uncertainty principle** and what it means and what it does not mean. End with Bohr's principle of **complementarity**.



Answers and Solutions for Chapter 31

Reading Check Questions

1. All three supported the wave theory.
2. The photoelectric effect supports the particle theory.
3. Planck considered the electron vibrations, not light, as quantized.
4. A quantum of light is the photon.
5. Yes, *f* stands for frequency in general.
6. Lower energy is red light; radio waves.
7. Photons of violet have more energy and are therefore more successful at dislodging electrons.
8. Ejection depends on individual encounter, not average encounter, therefore a lot of red light does no ejection, whereas a single photon of violet will.
9. They are composed of tiny units.
10. Light acts as a particle when interacting with film.
11. Light travels in a wavelike way from one location to another.
12. Light acts as a particle when encountering a detector.
13. Light behaves as a wave in transit, as a particle when absorbed.
14. The photoelectric effect is evidence of the particle nature of light.
15. Traveling through slits, light acts in a wavelike way. Hitting the screen as particle-like. The pattern of hits is wavelike.
16. Of the three, only the electron has significant quantum uncertainties.
17. The product $\Delta p \Delta x$ is equal to or more than *h* bar.
18. The measurements show one or the other, not both.
19. As with momentum, only one of the other can be precise.
20. Passive observation does not affect what is looked at; active observation, where probing occurs, does affect what is looked at.
21. Wave and particle aspects of both matter and radiation are necessary, complementary parts of the whole.
22. The ancient yin-yang symbol showed opposites as components of a wholeness.

Think and Solve

23. Frequency is speed/wavelength: $f = (3 \times 10^8 \text{ m/s})/(2.5 \times 10^{-2} \text{ m}) = 1.2 \times 10^{10}$ Hz. Photon energy is Planck's constant × frequency: $E = hf = (6.63 \times 10^{-34} \text{ J s})(1.2 \times 10^{10} \text{ Hz}) = 8.0 \times 10^{-24}$ J.

24. De Broglie wavelength = Planck's constant/momentum, so we need the electron's momentum. It is $p = mv = (9.1 \times 10^{-31} \text{ kg})(3.0 \times 10^7 \text{ m/s}) = 2.7 \times 10^{-23}$ kg m/s. The de Broglie wavelength is then $\lambda = h/p = (6.6 \times 10^{-34})/(2.7 \times 10^{-23}) = 2.4 \times 10^{-11}$ m, less than the diameter of a single atom.

25. The ball's momentum is $mv = (0.1 \text{ kg})(0.001 \text{ m/s}) = 1.0 \times 10^{-4}$ kg m/s, so its de Broglie wavelength is $h/p = (6.6 \times 10^{-34} \text{ J s})/(1.0 \times 10^{-4} \text{ kg m/s}) = 6.6 \times 10^{-30}$ m, incredibly small relative even to the tiny wavelength of the electron. There is no hope of rolling a ball slowly enough to make its wavelength appreciable.

Think and Explain

26. Saying that something is quantized is saying it is composed of elementary units. Electric charge, for example, is composed of multiples of the charge of the electron, so we say charge is quantized. A gram of pure gold is quantized in that it is made of a whole number of gold atoms. In this chapter we learn that light—radiant energy—is also quantized.

27. Classical physics is primarily the physics known before 1900 that includes the study of motion in accord with Newton's laws and the study of electromagnetism in accord with the laws of Maxwell. Classical mechanics, often called Newtonian mechanics, is characterized by absolute predictability. After 1900 scientists discovered that Newtonian rules simply don't apply in the domain of the very small—the submicroscopic. This is the domain of quantum physics, where things are "grainy" and where values of energy and momentum (as well as mass and charge) occur in lumps, or quanta. In this domain, particles and waves merge and the basic rules are rules of probability, not certainty. Quantum physics is different and not easy to visualize like classical physics. We nevertheless tend to impress our classical wave and particle models on our findings in an effort to visualize this subatomic world.

28. $E \sim f$ is a proportion. When E is divided by f we have the constant h. With h the proportion becomes the exact equation $E = hf$. So we see h is the proportionality constant for the energy and frequency of a photon of light.

29. In accord with $E = hf$, the energy of a photon with twice the frequency has twice the energy. Violet photons are about twice as energetic as red photons.

30. Higher-frequency ultraviolet light has more energy per photon.

31. It makes no sense to talk of photons of white light, for white light is a mixture of various frequencies and therefore a mixture of many photons. One photon of white light has no physical meaning.

32. Higher-frequency green beam has more energy per photon.

33. Since red light carries less energy per photon, and both beams have the same total energy, there must be more photons in the beam of red light.

34. The kinetic energy of ejected electrons depends on the frequency of the illuminating light. With sufficiently high frequency, the number of electrons ejected in the photoelectric effect is determined by the number of photons incident upon the metal. So whether or not ejection occurs depends on frequency, and how many electrons are ejected depends on the brightness of the sufficiently high-frequency light.

35. It is not the total energy in the light beam that causes electrons to be ejected, but the energy per photon. Hence a few blue photons can dislodge a few electrons, where hordes of low-energy red photons cannot dislodge any. The photons act singly, not in concert.

36. Ultraviolet photons are more energetic.

37. Protons are held within nuclei deep within atoms. To eject a proton from an atom takes about a million times more energy than to eject an electron. So one would need a high-energy gamma-ray photon rather than a photon of visible light to produce a “photoprotonic” effect.

38. The photoelectric effect mainly depends on the particle nature of light. Whether or not an electron is knocked free depends on the photon’s frequency. So the wave model is part of the picture.

39. Some automatic doors utilize a beam of light that continuously shines on a photodetector. When you block the beam by walking through it, the generation of current in the photodetector ceases. This change of current then activates the opening of the door.

40. *Electric eye*: A beam of light is directed to a photosensitive surface that completes the path of an electric circuit. When the beam is interrupted, the circuit is broken. The entire photoelectric circuit may be used as a switch for another circuit. *Light meter*: The variation of photoelectric current with variations in light intensity activates a galvanometer, or its equivalent, that is calibrated to show light intensity. *Sound track*: An optical sound track on motion picture film is a strip of emulsion of variable density that transmits light of variable intensity onto a photosensitive surface, which in turn produces an electric current of the desired variations. This current is amplified and then activates the loudspeaker.

41. The photoelectric effect is discharging the ball. Some of the excess electrons are being “knocked off” the ball by the ultraviolet light. This discharges the ball. If the ball is positively charged, however, it already has a deficiency of electrons, and knocking off more tends to increase the charge rather than decrease it. (Fewer electrons are dislodged by ultraviolet light from the positive ball than from the negative ball. Can you see why?)

42. Young’s explanation of the double-slit experiment is based on the wave model of light; Einstein’s explanation of the photoelectric effect uses a model in which light is composed of particles. The effectiveness of one model or another doesn’t invalidate the other model, particularly in this instance where the models are used to describe completely different phenomena. Models are not to be judged as being “true” or “false” but as being useful or not useful. The particle model of light is useful in making sense of the details of the photoelectric effect, whereas the wave model of light is not useful in understanding these details. On the other hand, the wave model of light is useful for understanding the details of interference, whereas the particle model is not. The effectiveness of one model over another means simply that: One model is more effective than another. As we gather more data and gain new insights, we refine our models. The fact that two quite different models are needed to describe light lead to what is called the “wave-particle duality,” a central part of quantum physics.

43. An explanation is the following: Light refracting through the lens system is understandable via the wave model of light, and its arrival spot by spot to form the image is understandable via the particle model of light. How can this be? We have had to conclude that even single photons have wave properties. These are waves of probability that determine where a photon is likely or not likely to go. These waves interfere constructively and destructively at different locations on the film, so the points of photon impact are in accord with probability determined by the waves.

44. Diffraction, polarization, and interference are evidence of the wave nature of light; the photoelectric effect is evidence of the particle nature of light.

45. A photon behaves like a wave when in transit, and like a particle when it is emitted or absorbed.

46. No. Complementarity isn't a compromise, but suggests that what you see depends on your point of view. What you see when you look at a box, for example, depends on whether you see it from one side, the top, and so on. All measurements of energy and matter show quanta in some experiments and waves in others. For light, we see particle behavior in emission and absorption, and wave behavior in propagation between emission and absorption.

47. The electron microscope.

48. By absorbing energy from the impact of a particle or photon.

49. The photon loses energy, so its frequency decreases. (Actually we say one photon is absorbed and another, lower-energy, photon is emitted.)

50. Uranium possesses more momentum. Hydrogen has the longer wavelength, which is inversely-proportional to momentum.

51. The cannonball obviously has more momentum than the BB traveling at the same speed, so in accord with de Broglie's formula the BB has the longer wavelength. (Both wavelengths are too small to measure.)

52. The principal advantage of an electron microscope over an optical microscope is its ability to see things that are too small for viewing with an optical microscope. This is because an object cannot be discerned if it is smaller than the wavelength of the illuminating beam. An electron beam has a wavelength that is typically a thousand times shorter than the wavelength of visible light, which means it can discern particles a thousand times smaller than those barely seen with an optical microscope.

53. Protons of the same speed as electrons would have more momentum, and therefore smaller wavelengths, and therefore less diffraction. Diffraction is an asset for long-wavelength radio waves, helping them to get around obstructions, but it is a drawback in microscopes, where it makes images fuzzy. Why are there not proton microscopes? There are. We call them atomic accelerators. The high momenta of high-velocity protons make it possible to extract detailed information on nuclear structure, illuminating a domain vastly smaller than the size of a single atom.

54. Planck's constant would be zero.

55. If somebody looks at an electron on the tip of your nose with an electron beam or a light beam, then its motion as well as that of surrounding electrons will be altered. We take the view here that passively looking at light after it has reflected from an object does not alter the electrons in the object. We distinguish between passive observation and probing. The uncertainty principle applies to probing, not to passive observation. (This view, however, is not held by some physicists who assert any measure, passive or probing, alters that being measured at the quantum level. These physicists argue that passive observation provides knowledge, and that without this knowledge, the electron might be doing something else or might be doing a mixture, a superposition, of other things.)

56. The uncertainty principle refers only to the quantum realm, and not the macroworld.

57. Heisenberg's uncertainty principle applies *only* to quantum phenomena. However, it serves as a popular metaphor for the macro domain. Just as the way we measure affects what's being measured, the way we phrase a question often influences the answer we get. So to various extents we alter that which we wish to measure in a public opinion survey. Although there are countless examples of altering circumstances by measuring them, the uncertainty principle has meaning only in the sub-microscopic world.

58. No, for there is an important distinction between properties that are measurable and properties that are predictable, whether classical or quantum mechanical. As an example of a classical system for which exact prediction is not possible, consider a pinball machine. You could take a slow-motion movie of a ball that makes its way down through the forest of metal pins to finally reach a position at the bottom. You could analyze this movie to understand everything that happened. By hindsight (20/20 vision!) you could see how the ball responded to interaction with each pin. But this hindsight does not mean you can predict the final position of the next ball you drop through the maze of pins because the ball is sensitive to the tiniest differences in its initial speed and each interaction with a pin. This is classical uncertainty. In the quantum world, uncertainty is of a more fundamental kind, but the idea is the same. Knowing by measurement exactly how an electron moved does not enable you to predict just how it will move in the future.

59. The uncertainty principle refers only to the quantum realm, and not the macroworld. Air escaping from a tire is a macro-world event.

60. The question is absurd, with the implication that eradicating butterflies will prevent tornadoes. If a butterfly can, in principle, cause a tornado, so can a billion other things. Eradicating butterflies will leave the other 999,999,999 causes untouched. Besides, a butterfly is as likely to *prevent* a tornado as to cause one.

61. Unless the term is meant to leap into a completely different realm, no, for a quantum leap is the *smallest* transition something can undergo.

62. This is perhaps the extreme in altering that which is being measured by the process of measuring itself, as well as an extreme case of academic misbehavior. The bristlecone pine, Old Methuselah, was the oldest known living thing in the world.

Think and Discuss

63. Finding materials that would respond photoelectrically to red light was difficult because photons of red light have less energy for image production than photons of green or blue light.

64. Conversion is from high-frequency high-energy stages to lower ones. If the reverse occurred, energy conservation would be violated.

65. The energy of red light is too low per photon to trigger the chemical reaction in the photographic crystals. Very bright light simply means more photons that are unable to trigger a reaction. Blue light, on the other hand, has sufficient energy per photon to trigger a reaction. Very dim blue light triggers fewer reactions only because there are fewer photons involved. It is safer to have bright red light than dim blue light.

66. When a photon of ultraviolet light encounters a living cell, it transfers to the cell an amount of energy that can be damaging to the cell. When a photon of visible light encounters a living cell, the amount of energy it transfers to the cell is less, and less likely to be damaging. Hence skin exposure to ultraviolet radiation can be damaging to the skin while exposure to visible light generally is not.

67. There will be colors toward the red end of the spectrum where the meter will show no reading, since no electrons are ejected. As the color is changed toward the blue and violet, a point will be reached where the meter starts to give a reading. If a color for which the meter reads zero is made more intense, the meter will continue to read zero. If a color for which the meter shows a reading is made more intense, the current recorded by the meter will increase as more electrons are ejected.

68. We can never definitely say what something *is*, only how it behaves. Then we construct models to account for the behavior. The photoelectric effect doesn't prove that light is corpuscular, but supports the corpuscular model of light. Particles best account for photoelectric behavior. Similarly, interference experiments support the wave model of light. Waves best account for interference behavior. We have models to help us conceptualize what something *is*; knowledge of the details of how something behaves helps us to refine the model. It is important that we keep in mind that our models for understanding nature are just that: models. If they work well enough, we tend to think that the model represents what *is*.

69. The more massive proton has more momentum, while the electron with its smaller momentum has the longer wavelength.

70. The twice-as-fast electron has twice the momentum. By de Broglie's formula, wavelength = *h*/momentum, twice the momentum means half the wavelength. The slower electron has the longer wavelength.

71. As velocity increases, momentum increases, so by de Broglie's formula, wavelength decreases.

72. The momenta of moving things in our everyday environment are huge relative to the momenta of submicroscopic particles even when the everyday things are very slow and the particles are very fast. This is because the masses of the everyday objects are so huge compared with the particle masses. The large momenta, in accord with de Broglie's formula, correspond to incredibly short wavelengths. See the footnote about this in the chapter.

73. Planck's constant would be much much larger than its present value.

74. In the best spirit of science, from our observations we develop a theory that gives meaning to those observations. However, it is often the case that belief in a theory precedes observations and influences our perception of those observations and the meaning we give them. We should be aware of this "human factor." Sometimes it is very beneficial and sometimes it is not.

75. We don't know if an electron *is* a particle or a wave; we know it *behaves* as a wave when it moves from one place to another and behaves as a particle when it is incident upon a detector. The unwarranted assumption is that an electron must *be* either a particle *or* a wave. It is common to hear some people say that something can only be either this or that, as if both were not possible (like those who say we must choose between biological evolution *or* the existence of a supreme being).

32 The Atom and the Quantum

The Part Seven opening photo is of William Davis, son of close friends marine-biologist Alan and Fe Davis.

Chapter opener photos are of four quantum physicists, all high achievers and a credit to their teaching institutions, David Kagan at California State University at Chico, Roger King at City College of San Francisco, Dean Zollman at Kansas State University, and Art Hobson at the University of Arkansas.

The profile for this chapter is Niels Bohr.

This is a history-oriented chapter, a continuation of Chapters 30 and 31. It is background for Chapters 33 and 34, but is not prerequisite to them. This chapter can, with some discussion of atomic spectra, stand on its own as a continuation of Chapter 11, *The Atomic Nature of Matter*. For a short course, Chapter 11 followed by most of this chapter should work quite well. You may wish to lecture about the physicists who took part in the development of quantum mechanics. Ken Ford's new book, *The Quantum World—Quantum Physics for Everyone*, is a flavorful resource. You can build from the Thompson plum-pudding model of the atom, to Rutherford's gold foil experiments, and to the Bohr model. Apply de Broglie waves to the electrons that surround the atomic nucleus, and tie this to the relative sizes of the atoms.

Quantum mechanics has more cracks than most theories of physics—some hairline and some wide. Take notice of charlatans and others who promote junk science in the guise of science, who seek footholds in these cracks, and who attempt to ride on the hard-earned reputation of quantum theory.

Suggested complementary reading:

Ford, K. W. *The Quantum World: Quantum Physics for Everyone*. Cambridge, MA: Harvard University Press, 2004. A fascinating account of the development of quantum physics with emphasis on the participating physicists.

Ford, K. W. *101 Quantum Questions: What You Need to Know About the World You Can't See*. MA: Harvard University Press, 2011.

I was lucky to illustrate these two books by Ken Ford, both down-to-earth reading. And to enjoy his passion of soaring (in addition to his love of quantum physics) consider Ken's:
In Love With Flying, Philadelphia: H Bar Press, 2007.

Gamow, George. *Thirty Years That Shook Physics*. New York: Dover, 1985. A historical tracing of quantum theory by someone who was part of it.

Hey, A. J., and P. Walters. *The Quantum Universe.* New York: Cambridge University Press, 1987. A broad view of modern physics with many illustrations.

Pagels, H. R. *The Cosmic Code: Quantum Physics as the Language of Nature*. New York: Simon & Schuster, 1982. An oldie but goody book for the general reader.

Gleick, James. *Genius: The Life and Science of Richard Feynman*. New York: Vintage, 1993. An inspiring book about an intriguing person.

I include this chapter as supplementary reading for students who are interested in this major area of physics that is more removed from their everyday environment. I do not lecture on this material and have no suggested lecture for this chapter.

Discussion of the figures in the chapter is instructive. Do any of your students even know about the CRT TV tube shown in Figure 32.4? Millikan's oil drop experiment, Figure 32.5, is fascinating. And the Ritz combination principle of Figure 32.9 is a topic I found intriguing back when I was first introduced to it. That the numbers tell the story is quite interesting! Also interesting is how the orbiting wave forms of Figure 32.10 nicely lead to the graphics of Figure 32.11. And how the models of the atom progressed, as simplified in Figure 32.13.

Quantum physics is concerned with the extremely small. Today's physicists, after all, are involved in exploring extremes: the outer limits of the fast and the slow, hot and cold, few and many, and big and small. In a light sense it can be said that everything in the middle is engineering.

The chapter discusses the character of quantum mechanics. There is some confusion in the minds of many people about the wave-particle duality. Much of this confusion is failing to see that light behaves as a wave when it travels in empty space, and lands like a particle when it hits something. It is mistaken to insist it must be both a particle and a wave at the same time. This is not the case, despite some writers who try to make this mysteriously profound. What something *is* and *what it does* are not the same. Another misconception fostered in popular and not-so-popular literature is that quantum theory is nondeterministic and that it is acausal. Solutions to the fundamental quantum equation are unique, continuous, and incorporate the principle of causality. Another misconception is that quantum theory reveals nature as a game of probability. Although some predictions about certain quantities are sometimes probabilistic, it doesn't follow that the predictions of quantum mechanics are necessarily uncertain. Quantum mechanics, in fact, leads to extremely accurate results (it predicts for example, the energy of the hydrogen atom in its ground state to one part in 10^{12}). Whether quantum mechanics gives definite or probabilistic answers to questions depends on the nature of the questions. For questions inappropriate to the quantum level, quantum mechanics gives probabilistic answers. For appropriate questions, its answers are definite. See more on this in the Reference Frame essay, *Ask a Foolish Question...by* Herman Feshback and Victor Weisskopf in the October 1988 issue of *Physics Today*.

In graduate school I was disappointed in myself for not being able to visualize quantum mechanics. I felt personally deficient. At the time, I would have benefited from this Feynman quote: "I think it is safe to say that no one understands quantum mechanics. Do not keep saying to yourself, if you can possibly avoid it, 'but how can it get like that?' because you will go 'down the drain' into a blind alley from which nobody has yet escaped. Nobody knows how it can be like that."

Something that I would also have benefited from back then was the visual materials available today. A great example is the Physlets® that are featured in *Physlet Quantum Physics*, by Anne J. Cox, Mario Belloni, and Wolfgang Christian, published by Prentice Hall but now freely available at www.compadre.org/physlets.

Another source that provides visualization of quantum physics is the work of Dean Zollman and his creative friends at Kansas State University. See http://web.phys.ksu.edu/vqm/. Dean has enhanced visualizing quantum mechanics.

The chapter treats the matter-wave concept that gives a clearer picture of the electrons that "circle" the atomic nucleus. Instead of picturing them as tiny BBs whirling like planets, the matter-wave concept suggests we see them as smeared standing waves of energy—existing where the waves reinforce, and nonexisting where the waves cancel (Figures 32.11 and 32.12). This is also highlighted in my screencast *Matter Waves*.

The philosophical implications of quantum mechanics is left to your lecture. At minimum you might warn your class that there are many people who have much to say about quantum physics who don't understand it. Quantum physics does not come in the neat package that Newtonian physics comes in, and is not all sewed up like other less complex bodies of knowledge. It is an ill-understood theory. Because it works so well it is a widely respected theory. We must watch for anything weird being attributed to quantum mechanics, and be wary of pseudoscientists who attempt to fit their own theories into the cracks of quantum mechanics, and ride on the back of its hard-earned reputation.

A few words about Planck's constant. If its numerical value were just a bit higher or lower, stars wouldn't shine. Likewise for the gravitational constant *G*, where a slight change would mean stars wouldn't exist—nor would we. Aha, does this mean that the precise value of these and other fundamental physical constants are coincidentally "just right" for a universe, for life … and, especially, us? A lot of people wonder about this "fine-tuning" of the constants. Some hypothesize that the constants preceded the advent of the universe, and some offer supernatural explanations.

But I don't see that fine-tuning needs an explanation. After all, do we need an explanation as to why π = 3.14159? The way I see it, constants are measurements of a nature that exists, not the reason for that existence. Given what we know now, we can only say that nature determines the constants, the constants don't determine nature.

Now as to why the universe exists at all, no scientific explanation is convincing. Nobody knows. But that's a much bigger story.

New to this edition is a box on the Higgs Boson, page 612.

Practicing Physics Book:
• Light Quanta

Next-Time Questions:
• Zinc Ball on Electroscope

Hewitt-Drew-It! Screencast: •*Matter Waves*

Answers and Solutions for Chapter 32

Reading Check Questions

1. Most particles remain undeflected because of the empty space within atoms.
2. Rutherford discovered the atomic nucleus, that it was tiny, positive, and massive.
3. Franklin postulated that electricity is an electric fluid that flows from place to place.
4. A cathode ray is a beam of electrons.
5. Deflection of the ray indicated the presence of electric charge.
6. J.J. Thomson discovered the existence of electrons.
7. Robert Millikan found the mass and charge of the electron.
8. Balmer discovered regularity in atomic spectra.
9. Rydberg and Ritz discovered that the frequency of a spectral line in the spectrum of an element equals the sum or difference of two other spectral lines.
10. Bohr postulated light emission was the result of an electron transition between electron orbits in an atom.
11. Yes, if there is at least one intermediate energy state that the electron can transition to along the way.
12. The relationship is given by $\Delta E \sim f$.
13. The circumferences of orbits are discrete because they are made up of particular whole-number wavelengths of the electron.
14. In the first orbit, one wavelength makes up the circumference. In the second, two wavelengths. In the n^{th} orbit, n wavelengths.
15. Electrons don't spiral because they are composed of waves that reinforce themselves.
16. The wave function represents the possibilities that can occur for a quantum system.
17. The probability density function is the square of the wave function.
18. An electron's distance from the nucleus, most of the time, exists at a location described by Bohr's first orbit.
19. What corresponds is the overlap between new and old theories, if new theory is valid.
20. Schrodinger's equation would apply to the solar system, but not be useful.

Think and Explain

21. Photons from the ultraviolet lamp have greater frequency, energy, and momentum. Only wavelength is greater for photons emitted by the TV transmitter.

22. Blue, which has a higher frequency, and therefore greater photon energy.

23. A small fraction of the alpha particles were deflected (scattered) through a large angle, indicating such a strong electric field within the atom that the positive charge must be concentrated in a small central core—a core that is massive as well as small because the rebounding alpha particles showed no appreciable loss of KE.

24. The dense concentration of positive charge and mass in the atomic nucleus accounts for the backscattering of alpha particles as they ricochet off the gold atoms of the thin foil. This backscattering would not occur if the positive charge and mass of the atom were spread throughout the volume of the atom, just as a golf ball would not bounce backward when striking a piece of cake, or even when colliding with a tennis ball or another golf ball. A golf ball will bounce backward if it strikes a massive object such as a bowling ball, and in a similar way, some of the alpha particles bounce backward when encountering the massive atomic nucleus, and also the enormously strong electric field in its vicinity.

25. Rutherford's experiments showed that the positive charge must be concentrated in a small core, the atomic nucleus.

26. Spectral lines are as characteristic of the elements as fingerprints are of people. Both aid identification.

27. The same amount of energy is needed to return the electron, as it gave to the photon when dropping to the ground state.

28. If the energy spacings of the levels were equal, there would be only two spectral lines. Note that a transition between the 3^{rd} and 2^{nd} level would have the same difference in energy as a transition

between the 2nd and first level. So both transitions would produce the same frequency of light and produce one line. The other line would be due to the transition from the 3rd to the first level.

29. The smallest orbit would be one with a circumference equal to one wavelength, according to the de Broglie model.

30. The particle nature of the electron best explains the photoelectric effect, while the wave nature best explains the discreteness of energy levels.

31. If we think of electrons as orbiting the nucleus in standing waves, then the circumference of these wave patterns must be a whole number of wavelengths. In this way the circumferences, and also the radii of orbits are discrete. Since energy depends upon this radial distance, the energy values are also discrete. (In a more refined wave model, there are standing waves in the radial as well as the orbital direction.)

32. Helium's electrons are in one filled shell. The filled shell means that bonding with other elements is rare. Lithium has two shells, the first filled and the second with only one of eight electrons in it, making it very reactive with other elements. The shell concept was too brief in Chapter 11 for this question to be asked then.

33. The frequency of every photon is related to its energy by $E = hf$, so if two frequencies add up to equal a third frequency, two energies add up to equal a third energy. In a leapfrog transition such as from the third to the first energy level in Figure 32.10, energy conservation requires that the emitted energy be the same as the sum of the emitted energies for the cascade of two transitions. Therefore the frequency for the leapfrog transition will be the sum of the frequencies for the two transitions in the cascade.

34. Yes. In atoms, electrons move in waves with speeds on the order of 2 million m/s.

35. Constructive interference to form a standing wave requires an integral number of wavelengths around one circumference. Any number of de Broglie wavelengths not equal to a whole number would lead to destructive interference, preventing the formation of a standing wave.

36. Both use Bohr's concept of energy levels in an atom. An orbital is represented by the easier-to-visualize orbit.

37. The answer to both questions is yes. Since a particle has wave properties and a wavelength related to its momentum, it can exhibit the same properties as other waves, including diffraction and interference.

38. The amplitude of a matter wave is called its wave function, represented by the symbol ψ. Where ψ is large, the particle (or other material) is more likely to be found. Where ψ is small, the particle is less likely to be found. (The actual probability is proportional to ψ^2.)

39. Atoms would be larger if Planck's constant were larger. We can see this from de Broglie's equation (wavelength = h/momentum), where if h were larger for a given momentum, the wavelengths of the standing waves that comprise electron shells would be larger, and hence atoms would be larger.

40. What waves is the probability amplitude.

41. Both are consistent. The correspondence principle requires agreement of quantum and classical results when the "graininess" of the quantum world is not important, but permits disagreement when the graininess is dominant.

42. They overlap for a collection of atoms large enough for classical physics to have some validity but small enough for quantum effects still to be present. For smaller atomic groupings, quantum mechanic dominates. For larger groupings, Newton's laws dominate.

43. Bohr's correspondence principle says that quantum mechanics must overlap and agree with classical mechanics in the domain where classical mechanics has been shown to be valid.

44. Narrowly defined, the correspondence principle applies only to the transition from quantum to classical behavior, which takes place in the atomic and molecular domain. But we can define the principle more broadly, stating that a theory for one domain or set of circumstances, and another theory for another domain and another set of circumstances (like a theory for small things and a theory for big things, or a theory for slow things and a theory for fast things, or one for cold things and another for hot things) should correspond to each other in the region where the domains overlap. This broadened definition of the correspondence principle is relevant for all good theory in all fields of knowledge.

45. It is the wave nature of matter that keeps atoms apart and gives bulk to matter in the world around us. Otherwise everything would collapse and there would be no matter as we know it.

46. The speed of light is large compared with the ordinary speeds with which we deal in everyday life. Planck's constant is small in that it gives wavelengths of ordinary matter far too small to detect and energies of individual photons too small to detect singly with our eyes.

47. Open-ended.

Think and Discuss

48. It would emit a continuous spectrum. Its energy would change gradually and continuously as it spiraled inward and it would radiate at its rotational frequency, which would be continuously increasing.

49. Electrons can be boosted to many energy levels, and therefore make many combinations of transitions to ground level and levels in between. The vast variety of transitions produce the vast numbers of spectral lines in a spectroscope. Even hydrogen, with a single electron, has many lines, most of which are in the ultraviolet and infrared.

50. The laws of probability applied to one or a few atoms give poor predictability, but for hordes of atoms, the situation is entirely different. Although it is impossible to predict which electron will absorb a photon in the photoelectric effect, it is possible to predict accurately the current produced by a beam of light on photosensitive material. We can't say where a given photon will hit a screen in double-slit diffraction, but we can predict with great accuracy the relative intensities of a wave-interference pattern for a bright beam of light. Predicting the kinetic energy of a particular atom as it bumbles about in an atomic lattice is highly inaccurate, but predicting the average kinetic energy of hordes of atoms in the same atomic lattice, which measures the temperature of the substance, is possible with high precision. The indeterminacy at the quantum level can be discounted when large aggregates of atoms so well lend themselves to extremely accurate macroscopic prediction.

51. Electrons have a definite mass and a definite charge, and can sometimes be detected at specific points—so we say they have particle properties; electrons also produce diffraction and interference effects, so we say they have wave properties. There is a contradiction only if we insist the electron may have only particle OR only wave properties. Investigators find that electrons display both particle and wave properties.

52. Classical physics predicts that accelerating charged particles should emit radiation. If this happened, the loss of energy should be accompanied by a spiraling of the electron into the atomic nucleus (akin to the fate of satellites that encounter the atmosphere in low Earth orbit.

53. Einstein thought quantum mechanics is not fundamental, but has underpinnings yet to be discovered.

54. The philosopher was speaking of classical physics, the physics of the macroscopic world, where to a high degree of accuracy the same physical conditions do produce the same results. Feynman was speaking of the quantum domain where for small numbers of particles and events, the same conditions are not expected to produce the same results.

33 Atomic Nucleus and Radioactivity

Photo openers show two instructors with different radiation counters: Stan Micklavzina with a Geiger counter, and Roger Rassool with a scintillation counter. The impressive photo in the center is the world famous hot springs in Pamukkale, Turkey. I took a dip in these springs in 1995 and found them most intriguing. Like hot springs all around the world, their source of energy is primarily radioactive decay in Earth's interior. The 4th photo is of Leilah McCarthy of CCSF lecturing on radioactive half-life.

The personality profile for this chapter is Marie Curie. Most appropriate!

The chapter begins with X-rays and presents a relatively extensive treatment of radioactivity and its applications. Formulas for decay reactions are illustrated with supporting sketches that enable better comprehension. The background for this material goes back to Chapter 11. This chapter is a prerequisite to Chapter 34.

Ask your students if they want to produce X-rays. To do so, simply unroll a roll of Scotch tape! This creates electrostatic charges that jump across the gap between the tape and the roll, which can produce X-rays. That's if the process is done in a vacuum. In air, the electrons are too slow to produce them. But try unrolling tape in a completely dark room and you'll notice a faint glow.

The energy of gamma-ray photons is more than 100 kilo-electron-volts (keV), which is some 100,000 times more than a photon of visible light. All photons emitted by atomic nuclei are classified as gamma rays, even the rare ones of less than 100 keV. The sunlight we enjoy began as energetic gamma rays in the Sun's core and degraded into visible light during its passage through overlaying layers of gas. If watching stars on a calm night seems a tranquil experience, gamma rays betray the true violence of the universe!

In the text it is stated that a couple of round-trip flights across country exposes one to as much radiation one receives in a normal chest X-ray. More specifically, a dose of 2 millirems is typically received in flying across the United States in a jet. This is the same dose received annually from those old luminous dial wristwatches. Cosmic radiation at sea level imparts 45 millirems annually, and radiation from the Earth's crust imparts about 80 millirems. Living in a concrete or brick house makes this figure slightly higher, for these materials contain more radioactive material than wood. The human body contains small amounts of carbon-14, potassium-40, and traces of uranium and thorium daughter products, which give an annual dose of 25 millirems. So the total natural background radiation annually is about 150 millirems. This makes up about 56% of the radiation the average person encounters, the rest being mainly medical and dental X-rays.

Before being retired, the former high-flying British-French SST, the Concorde, was equipped with radiation detectors that signaled the pilots when a level of 10 millirems per hour was reached (during a

solar flare, for example). The pilots were required to descend to lower altitudes at 50 millirems per hour. According to a report by the British government after a year of Concorde operation, none of the alarms had ever gone off. Concorde pilots were limited to 500 hours flying time per year, compared to 1000 hours for crews on conventional aircraft.

Dentists routinely cover a patient with a leaded apron when making dental X-rays. Which airline will be first to provide similar protection to its airline personnel? I'm told by a seasoned pilot that life span for pilots is considerably below average. I find it incredible that being in the presence of cosmic days, day after day, doesn't cause a stir today. In my view, it's only a matter of time when leaded fabrics will be above the pilots in their cabin and the location where flight attendants spend much time. Perhaps the weight of such protection for passengers is considered prohibitive. In any event, most flying by the public is occasional and the danger is as tolerated as the dangers of being in automobiles, the number-one killer.

Common smoke detectors in the home make use of the very low dose of about 2 microcuries of americium-241, used to make the air in the detector's ionization chamber electrically conductive. When smoke enters the chamber it inhibits the flow of electricity, which activates the alarm. The lives saved each year by these devices number in the thousands (which dwarfs the numbers seriously harmed by radiation).

Computed tomography (CT) scans are created with the use of a 360-degree X-ray scan and computer assembly of the resulting images. These scans allow for cross-sectional views of body organs and tissues. Images are sharp, focused, and three-dimensional. X-ray exposure, however is many times that of standard X-rays. A single abdominal scan can expose a patient to 500 times more radiation than does a conventional chest X-ray. A similar looking machine is the MRI, which like the sonogram, provide images of the body with no radiation whatever. MRIs and sonograms involve no radiation.

The fact that the source of the Earth's heat is radioactive decay is not generally well known. More generally, people fear anything suggestive of radioactivity. When I was discussing this while driving through the volcano park in Hawaii with my guests, the Hopkinson family from Vancouver, physics teacher Peter Hopkinson replied that we have to be careful about using the *R* word. His daughter Jean humorously replied, "you mean r*adioactivity*?" The word *nuclear* also, is frightening to many people, which is the main reason why the name NMR (nuclear magnetic resonance) has been changed to MRI (magnetic resonance imaging)! The box on food irradiation in this chapter highlights another example of public distrust of anything "nuclear."

Being ignorant of radioactive decay, Lord Kelvin (1824 - 1907) made the extravagant claim that the age of Earth was between 20 to 400 million years. Penetration of Earth's crust by bore-holes and mines showed that temperature increases with depth. This means there is a flow of heat from the interior to the surface. Kelvin argued that this loss of heat meant Earth had been progressively hotter in the past. His premise was that the molten interior of Earth was the remnant of its hot birth. With this assumption and the rate at which Earth loses heat, Kelvin calculated the age of Earth. He allowed wide limits, due to uncertainties, and pronounced Earth's age as between 20 and 400 million years. This initiated a great controversy with geologists of Victorian times. Despite their protests, Kelvin felt justified by 1897 in narrowing his limits to 20 and 40 million years. It is interesting to note that with the superior data of the present day, the solution to Kelvin's problem, as he posed it, is between 25 and 30 million years. Although radioactivity had just been discovered (1896), Kelvin didn't acknowledge its role in heating Earth's interior. Sadly, when this was pointed out to him, he held to his previous hard earned but incorrect views. (How many people do you know who are comfortable in admitting when they're wrong?) Was it Bernard Shaw who said that human progress depends on finite lifetimes of people?

We don't say an electric heater is cooling because it is losing heat. From the moment when it is first switched on it is losing energy, as evidenced by the heated surroundings. The heater gets hotter until a balance is achieved between the heat electrically generated and the heat lost by radiation, conduction, and convection. Only when the current is reduced or switched off does cooling begin. Kelvin's treatment of his problem was concerned with the case of the current being turned off; when there was no internal source of heat at all. With the discovery of radioactivity and knowledge that Earth's interior has a source of energy,

estimates of Earth's age based on the outward heat flow become valueless. Volcanic activity shows Earth has ample heat-generating resources.

The Practice Page for Chapter 17, *Our Earth's Hot Interior*, highlights this. If you didn't assign it earlier, do so now. A note of interest: The reason the Practice Page on the radioactivity in Earth's interior is in "an early" Chapter 17 in the Practicing Physics Book is because I feel the topic too important to place in this late chapter. Why? Because it is common to race through the end material of a physics book and to never get to radioactivity. As mentioned earlier, educated people can cite the acceleration due to Earth gravity, but very few can correctly answer the question, "What is the principle source of the Earth's internal heat?" I strongly feel radioactivity should be a part of a physics course.

Note the box on Food Irradiation in this chapter. Many people vigorously and actively oppose it, based on their perception of its dangers. Ironically, hundreds die of food poisoning in the U.S. each week—deaths that would have been averted if the food eaten had been irradiated. How many published photographs of the people who die daily would it take to re-channel the misplaced zeal of those who actively oppose food irradiation?

Practicing Physics Book:
- Radioactivity
- Natural Transmutation
- Nuclear Reactions

Problem Solving Book:
There are ample problems on radioactive processes

Laboratory Manual:
- Get a Half-Life *Radioactivity* (Activity)
- Radioactive Speed Dating *Radiometric Dating Simulation* (Tech Lab)

Next-Time Questions:
- Age of the Earth
- Radioactive Cookies
- Child's Balloon
- Radioactive Chromium
- Hot Spring
- Radioactive Gasoline
- Ancient Axe
- Geiger Counter

Hewitt-Drew-It! Screencasts: •*Radioactivity* •*The Strong Force* •*Radioactive Half-Life* •*Transmutation* •*Carbon Dating*

SUGGESTED LECTURE PRESENTATION

Begin by commenting on young William's statement about the warmth of the hot spring in the Part 7 opener—that radioactivity is nothing new and is as natural as hot springs and geysers. It in fact powers them. When electricity was first harnessed, people were fearful of it and its effects on life forms. Now it is commonplace, because its dangers are well understood. We are at a similar stage with regard to anything called nuclear. Even the very beneficial medical science *nuclear magnetic resonance* (*NMR*) has undergone a name change to *magnetic resonant imaging* (*MRI*). Why? "I don't want *my* Aunt Minnie near any *nuclear* machine!" The events of Fukushima add to the negativity concerning anything nuclear.

Hundreds of thousands of Americans live in houses that have a yearly radiation dose from radon in the ground equal to the dose residents living in the vicinity of Chernobyl received in 1986 when one of its reactors exploded and released radioactive materials into the environment (Go back to *Scientific American*, May, 1988). This is not to say it is unharmful to live in the vicinity of radon emission, but to say that radioactivity is not a modern problem and not a byproduct of science per se. It's been with us since day 1.

X-Rays and Radioactivity

Begin by comparing the emission of x-rays with the emission of light, showing that x-rays are emitted when the innermost electrons of heavy elements are excited. Then discuss medical and dental applications of X-rays, citing the newer photographic films now available that permit very short exposures of low intensity, and therefore safer dosages. Cite also the fact that the eye is the part of the body most prone to radiation damage—something that seems to be ignored by many dentists when making exposures of the teeth (and inadvertently, the eyes). (Why not eye masks as well as chest masks?)

Alpha, Beta, and Gamma Rays
Distinguish between alpha, beta, and gamma rays. If you've covered electricity and magnetism, ask if the rays could be separated by an electric field, rather than the magnetic field depicted in Figure 33.3.

Environmental Radiation
Radiation is not good for anybody, but we can't escape it. It is everywhere. However, we can take steps to avoid unnecessary radiation. Radiation, like everything else that is both damaging and little understood, is usually seen to be worse than it is. You can alleviate a sense of hopelessness about the dangers of radiation by pointing out that radiation is nothing new. It not only goes back before science and technology but before Earth came to be. It goes back to day 1. It is a part of nature that must be lived with. Good sense simply dictates that we avoid unnecessary concentrations of radiation.

Units and Doses of Radiation
There is much data here that may take more effort to learn than is worthwhile. Go easy on this. The general idea and comparisons are sufficient.

The Atomic Nucleus and the Strong Force
With no strong force in the atomic nucleus there would be no elements other than hydrogen. Everybody is interested in quarks. Discuss quarks—briefly.

Make the point that although neutrons provide a sort of nuclear cement, too many of them separate the protons and lead to instability. The nuclear fragments of fission (Chapter 34) are radioactive because of their preponderance of neutrons.

Radioactive Half-Life
Talk of jumping halfway to the wall, then halfway again, then halfway again and so on, and ask how many jumps will get you to the wall. Similarly with radioactivity. Of course, with a sample of radioactivity, there is a time when all the atoms undergo decay. But measuring decay rate in terms of this occurrence is a poor idea if only because of the small sample of atoms one deals with as the process nears the end of its course. Insurance companies can make accurate predictions of car accidents and the like with large numbers, but not so for small numbers. Dealing with radioactive half-life at least insures half the large number of atoms you start with.

> CHECK QUESTIONS: If the half-life of a certain isotope is one day, how much of the original isotope in a sample will still exist at the end of two days? Three days? Four days?

Pose the Check Yourself question on page 632 about the archaeologist finding an ancient axe handle in a cave. It makes a good lecture skit, after explaining the nitrogen-carbon-nitrogen cycle. Note that the screencast *Carbon Dating* treats this topic.

In discussing the exponential nature of radioactive half-life you may wish to cite the exponential nature of growth and doubling time. This is treated in Appendix E, a very timely topic. If the only ultimate check on growth of human populations is misery, the population will likely grow until it is miserable enough to stop its growth.

Radiation Detectors
Discuss and compare the various radiation detectors, beginning with the Geiger and scintillation counters shown in Figure 33.17. Figure 33.20 shows tracks left by streams of charged particles traveling through liquid hydrogen. Ask your class to hypothesize why the spiral shapes instead of the circular or helical

shapes that a magnetic field would produce. (The track is there only because of an interaction with the liquid hydrogen, slowing by friction of sorts.) The conceptually nice bubble chamber is fading fast and arrays of fine wires in concert with fast computers have replaced them.

> DEMONSTRATION: Show a cloud chamber in action (such as a simple one shown by my dear late friend Walt Steiger in Figure 33.19).

Natural and Artificial Transmutation of Elements
Introduce the symbolic way of writing atomic equations. Write some transmutation formulas on the board while your students follow along with their books opened to the periodic table in Chapter 11. A repetition and explanation of the reactions shown in Figure 33.22 is in order, if you follow up with one or two new ones as Check Questions. Be sure that your class can comfortably write equations for alpha decay before writing equations for beta decay, which are more complex because of the negative charge. Your treatment is the same for both natural and artificial transmutations.

Radioactive Isotopes
Acknowledge the use of these in so many common devices. One is the ionization smoke detectors where particles of smoke are ionized as they drift by a beta emitter to complete an electric circuit to sound an alarm. Ironically while many people fear anything associated with *nuclear* or *radioactivity*, these devices save thousands of lives each year.

The box on Food Irradiation can elicit class discussion.

> NEXT-TIME QUESTION: With the aid of the periodic table, consider a decay-scheme diagram similar to the one shown in Figure 33.22 but beginning with U-235 and ending with an isotope of lead. Use the following steps and identify each element in the series with its chemical symbol. What isotope does this produce? [Pb-207]

1. Alpha	5. Beta	9. Beta
2. Beta	6. Alpha	10. Alpha
3. Alpha	7. Alpha	11. Beta
4. Alpha	8. Alpha	12. Stable

Answers and Solutions for Chapter 33

Reading Check Questions

1. Roentgen discovered the emission of "new kind of rays."
2. X-rays are high-frequency electromagnetic radiation.
3. Becquerel discovered that uranium emitted a new kind of penetrating radiation.
4. The Curies discovered polonium and radium.
5. Gamma rays have no electric charge.
6. Gamma rays are higher in frequency than X-rays.
7. A rad is a unit of absorbed energy. A rem is a measure of radiation based on potential damage (roentgen equivalent man).
8. Humans receive more radiation from natural sources than artificial sources.
9. Yes, the human body *is* radioactive. Radioactive potassium is in all humans.
10. Radioactive tracers are radioactive isotopes used to trace pathways in living things.
11. Protons and neutrons are two different nucleons.
12. The presence of a strong attractive force between nucleons in the nucleus prevents protons from repelling out of the nucleus.
13. Because the strong force is short range, protons in a large nucleus are farther apart on average than in a small nucleus, and the strong force is less effective between wide-apart protons.
14. Neutrons play the role of a nuclear cement in nuclei and also act to space protons apart.
15. Larger nuclei contain a larger percentage of neutrons.
16. Rate of decay is greater for elements with short half-lives.
17. The half-life of Ra-226 is 1620 years.
18. A trail in the tube is composed of freed electrons and positive ions.
19. A Geiger counter senses radiation by ionization.
20. A scintillation counter senses radiation by flashes of light.
21. A transmutation is the changing of an element to another element.
22. The transmutation of thorium by alpha emission produces an element with 2 less protons in the nucleus, to atomic number 88.
23. When thorium emits a beta particle, it transmutes to an element with atomic number increased by 1, to atomic number 91.
24. There is a mass reduction of 4 for alpha emission, and no change in mass for beta emission.
25. When an element emits an alpha particle, atomic number decreases by 2. For emission of a beta particle, atomic number increases by 1. For gamma emission, no change in atomic number.
26. Uranium ultimately transmutes to lead.
27. Ernest Rutherford in 1919 was the first to intentionally transmute elements.
28. When nitrogen captures a neutron it transmutes to carbon-14.
29. Most of the carbon we ingest is carbon-12.
30. Uranium is continually transmuting to lead, so deposits of uranium also contain lead.

Think and Do

31. The point is that radioactivity is not something new, but is part of nature.

Think and Solve

32. At the end of the second year 1/4 of the original sample will be left; at the end of the third year, 1/8 will be left; and at the end of the fourth year, 1/16 will be left.

33. The half-life of the material is two hours. A little thought will show that 160 halved 4 times equals 10. So there have been four half-life periods in the 8 hours. And 8 hours/4 = 2 hours.

34. One-sixteenth will remain after 4 half-lives, so $4 \times 30 = 120$ years.

35. Nine hours have elapsed at 3:00 p.m. That's $9/1.8 = 5$ half-lives. So $(1/2) \times (1/2) \times (1/2) \times (1/2) \times (1/2) = 1/32$ the original amount, 0.0313 milligram. At midnight, 18 hours later, $18/1.8 = 10$ half lives have elapsed. $(1/2)^{10}$ is about 1/1000 of the original, about 0.001 milligram. If the hospital needs F-18 the next day, it should produce it the next morning.

36. The intensity is down by a factor of 16.7 (from 100% to 6%). How many factors of two is this? About 4, since $2^4 = 16$. So the age of the artifact is about 4×5730 years or about 23,000 years.

37. There are 500 gallons in the tank since, after mixing, the gallon you withdraw has 10/5000 = 1/500 of the original radioactive particles in it.

Think and Rank

38. C, B, A.

39. a. B=C, A.
b. C, A=B**.**
c. B=C, A.

40. a. B, C, A.
b. C, A, B.

Think and Explain

41. Kelvin was not aware of radioactive decay, a source of energy to keep Earth warm for billions of years.

42. X-rays are high-frequency electromagnetic waves, and are therefore most similar to even higher-frequency electromagnetic waves—gamma rays. Alpha and beta rays, in contrast, are streams of material particles.

43. Gamma radiation is in the form of electromagnetic waves, while alpha and beta radiations consist of particles having mass.

44. A radioactive sample is always a little warmer than its surroundings because the radiating alpha or beta particles impart internal energy to the sample. (Interestingly, the heat energy of the Earth originates with radioactive decay in the Earth's interior.)

45. It is impossible for a hydrogen atom to eject an alpha particle, for an alpha particle is composed of four nucleons—two protons and two neutrons. It is equally impossible for a 1-kg melon to disintegrate into four 1-kg melons.

46. Alpha and beta rays are deflected in opposite directions in a magnetic field because they are oppositely charged—alphas are positive and betas negative. Gamma rays have no electric charge and are therefore undeflected.

47. The alpha particle has twice the charge, but almost 8000 times the inertia (since each of the four nucleons has nearly 2000 times the mass of an electron). So the much-greater mass of the alphas more than compensates for their double charge and lower speed.

48. Alpha and beta particles are pushed oppositely by an electric field; gamma rays are unaffected. If the particles move across (rather than along) the field lines, the paths of alpha and beta particles are bent oppositely, similar to what happens in a magnetic field. Gamma rays, in any case, traverse the field undeflected.

49. Alpha radiation decreases the atomic number of the emitting element by 2 and the atomic mass number by 4. Beta radiation increases the atomic number of an element by 1 and does not affect the atomic mass number. Gamma radiation does not affect the atomic number or the atomic mass number. So alpha radiation results in the greatest change in both atomic number and mass number.

50. Gamma and beta radiation both produce *no* change in mass number. Only gamma radiation produces no change in atomic number. Whereas beta radiation changes only atomic number, alpha radiation changes both mass number and atomic number.

51. Gamma predominates inside the enclosed elevator because the structure of the elevator shields against alpha and beta particles better than against gamma-ray photons.

52. Because of the fact that like charges repel, and that protons have the same sign of charge (positive) as the target atomic nuclei, the protons must be driven into the target area with enormous energies if they are to bombard the nuclei. Lower-energy protons would be easily electrically repelled by any nuclei they approach.

53. An alpha particle undergoes an acceleration due to mutual electric repulsion as soon as it is out of the nucleus and away from the attracting nuclear force. This is because it has the same sign of charge as the nucleus. Like charges repel.

54. All isotopes have the same number of protons, but different number of neutrons.

55. Because it has twice as much charge as a beta particle, an alpha particle interacts more strongly with atomic electrons and loses energy more rapidly by ionizing the atoms. (The slower speed of the alpha particle also contributes to its ability to ionize atoms more effectively.)

56. They repel by the electric force, and attract each other by the strong nuclear force. With the help of neutrons, the strong force predominates. (If it didn't, there would be no atoms beyond hydrogen!) If the protons are separated to where the longer-range electric force overcomes the shorter-range strong force, they fly apart.

57. Within the atomic nucleus, it is the strong nuclear force that holds the nucleons together, and the electric force that mutually repels protons and pushes them apart.

58. The existence of atomic nuclei containing many protons is evidence that something stronger than electric repulsion is occurring in the nucleus. If there were not a stronger attractive nuclear force to keep the repelling electrical force from driving protons apart, the nucleus as we know it wouldn't exist.

59. Yes, indeed!

60. A positively charged hydrogen atom, an ion, is the nucleus of the atom, since no electron remains. It is usually a proton, but could be a deuteron or triton, one of the nuclei of heavier hydrogen isotopes.

61. Chemical properties have to do with electron structure, which is determined by the number of protons in the nucleus, not the number of neutrons.

62. In accord with the inverse-square law, at 2 m, double the distance, the count rate will be 1/4 of 360 or 90 counts/minute; at 3 m, the count rate will be 1/9 of 360, or 40 counts/minute.

63. The spiral path of charged particles in a bubble chamber is the result of a slowing of the particles due to collisions with atoms, usually hydrogen, in the chamber. The slower-moving charged particles bend more in the magnetic field of the chamber and their paths become spirals. If the charged particles moved without resistance, their paths would be circles or helixes.

64. Number of nucleons and electric charge.

65. The mass of the element is 157 + 100 = 257. Its atomic number is 100, the transuranic element named fermium, after Enrico Fermi.

66. When a nucleus of radium (atomic number 88) emits an alpha particle, its atomic number reduces by 2 and it becomes the nucleus of the element radon (atomic number 86). The resulting atomic mass number is reduced by 4. If the radium was of the most common isotope 226, then the radon isotope would have atomic mass number 222.

67. After the polonium nucleus emits a beta particle, the atomic number increases by 1 to become 85, and the atomic mass number is unchanged at 218.

68. When an alpha particle is emitted by polonium-218, the atomic number decreases by 2 to become 82, and the atomic mass number decreases by 4, becoming 214.

69. Both have 92 protons, but U-238 has more neutrons than U-235.

70. The deuterium nucleus contains 1 proton and 1 neutron; the carbon nucleus, 6 protons and 6 neutrons; the iron nucleus, 26 protons and 30 neutrons; the gold nucleus, 79 protons and 118 neutrons; the strontium nucleus, 38 protons and 52 neutrons; and the uranium nucleus, 92 protons and 146 neutrons.

71. An element can decay to an element of greater atomic number by emitting electrons (beta rays). When this happens, a neutron in the nucleus becomes a proton and the atomic number increases by one.

72. If it emits two beta particles for each alpha particle, the same element results.

73. When a phosphorus nucleus (atomic number 15) emits a positron (a positively-charged electron) the charge of the atomic nucleus decreases by 1, converting it to the nucleus of the element silicon (atomic number 14).

74. If strontium-90 (atomic number 38) emits betas, it should become the element yttrium (atomic number 39); hence the physicist can test a sample of strontium for traces of yttrium by spectrographic means or other techniques. To verify that it is a “pure” beta emitter, the physicist can check to make sure that the sample is emitting no alphas or gammas.

75. If nuclei were composed of equal numbers of protons and electrons, nuclei would have no net charge. They wouldn’t hold electrons in orbit. The fact that atoms do have a positive nucleus and orbiting electrons contradicts your friend’s assertion.

76. Radium is a “daughter” element, the result of the radioactive decay of long-live uranium. So as long as uranium exists, radium will exist.

77. Agree with your friend that sees helium gas as being alpha particles. It’s true, alpha particles emitted by radioactive isotopes in the ground slow down and stop, capture two electrons, and become helium atoms. Our supplies of helium come from underground. Any helium in the atmosphere is soon dissipated into space.

78. Your friend will encounter more radioactivity from the granite outcroppings than he or she will in the same time near a nuclear power plant. Plus, at high altitude your friend will be treated to increased cosmic radiation. But the radiations encountered in the vicinity of the plant, on the granite outcropping, or at high altitude are not appreciably different than the radiation one encounters in the “safest” of situations. Advise your friend to enjoy life anyway!

79. The Earth’s natural energy that heats the water in the hot spring is the energy of radioactive decay. Just as a piece of radioactive material is warmer than its surroundings due to thermal agitation from radioactive decay, the interior of the Earth is similarly warmed. The great radioactivity in the Earth’s interior therefore heats the water, but doesn’t make the water itself radioactive. The warmth of hot springs is one of the “nicer effects” of radioactive decay.

80. You can tell your friend who is fearful of the radiation measured by the Geiger counter that his attempt to avoid the radiation by avoiding the instrument that measures it is useless. Your friend might as well avoid thermometers on a hot day in effort to escape the heat. If it will console your fearful friend, tell him or her that ancestors from time zero have endured about the same level of radiation he or she receives whether or not standing near the Geiger counter. There have been no better options. Make the best of the years available anyway!

81. Dinosaur bones are simply much too old for carbon dating because too little carbon-14 is left in the bones after that long a time.

82. (a) No, not a few years old. Too small a fraction of the carbon-14 has decayed. You couldn’t tell the difference between an age of a few years and a few dozen or even a hundred years.
(b) Yes, in a few thousand years a significant fraction of the carbon-14 has decayed. The method gives best results for ages not so very different from the half-life of the isotope.
(c) No, not a few million years old. Essentially all of the carbon-14 will have decayed. There will be none left to detect. You wouldn’t be able to distinguish between an age of a million or ten million or a hundred million years.

83. Stone tablets cannot be dated by the carbon dating technique. Nonliving stone does not ingest carbon and transform that carbon by radioactive decay. Carbon dating works for organic materials.

84. Open-ended.

Think and Discuss

85. Starting from birth, a human population has a certain half-life, the time until half have died, but this doesn't mean that half of those still living will die in the next equal interval of time. For radioactive atoms, the chance of "dying" (undergoing decay) is always the same, regardless of the age of the atom. A young atom and an old atom of the same type have exactly the same chance to decay in the next equal interval of time. This is not so for humans, for whom the chance of dying increases with age.
86. Eight alpha particles and six beta particles are emitted in the decay chain from U-238 to Pb-206. The numbers are the same for the alternate routes.
87. The elements below uranium in atomic number with short half-lives exist as the product of the radioactive decay of uranium or another very long-lived element, thorium. For the billions of years that the uranium and thorium last, the lighter elements will be steadily replenished.
88. Although there is significantly more radioactivity in a nuclear power plant than in a coal-fired power plant, almost none of it escapes from the nuclear plant, whereas most of the radioactivity existing in a coal-fired plant escapes through the stacks. As a result, a typical coal plant injects more radioactivity into the environment than does a typical nuclear plant.
89. The irradiated food does not become radioactive as a result of being zapped with gamma rays. This is because the gamma rays lack the energy to initiate the nuclear reactions in atoms in the food that could make them radioactive.
90. The reading would be the same! With a half-life of billions of years, its decreased rate is negligible in a 60-year span.

34 Nuclear Fission and Fusion

Photo openers feature leading pioneers of nuclear fission and fusion: Lise Meitner, Otto Frisch, Otto Hahn, Enrico Fermi, and Robert J. Oppenheimer. This chapter's personality profile is Lise Meitner.

The material in this chapter is of great technological and sociological importance. Nuclear bombs are not avoided in the applications of nuclear energy, but discussion of other applications emphasize positive aspects of nuclear power and its potential for improving the world. Much of the public sentiment against nuclear power has been due to a distrust of what is generally not understood, and the nuclear disaster in Fukushima, Japan. Fear is also enhanced with the possibility of nuclear fuel falling into groups who seek a nuclear bomb not to safeguard themselves, but to deploy it on others! This IS a frightening scenario. In this climate, we have a responsibility to provide our students with an understanding of the basic physics of nuclear power. In your physics class, an appropriate slogan is "KNOW NUKES."

Note that in this text, the energy release from the opposite processes of fission and fusion is approached from the viewpoint of decreased mass rather than the customary treatment of increased binding energy. Hence the usual binding energy curve is "tipped upside-down" in Figure 34.16, and shows the relationship of the mass per nucleon versus atomic number. I consider this way conceptually more appealing, for it shows that any reaction involving a decrease in mass releases energy in accordance with mass-energy equivalence. Everyone is familiar with the equation $E = mc^2$ and this is where it is best applied.

Mass-energy can be measured in either joules or kilograms (or in ergs or grams). For example, the kinetic energy of a 2-gram beetle walking 1 cm/s = 1 erg, and the energy of the Hiroshima bomb = 1 gram. So we can express the same quantity in essentially different units.

In a uranium mine in Western Africa in the Republic of Gabon, at Oklo, a mining geologist in 1972 discovered evidence of an ancient natural nuclear fission reactor that produced sustained low-level power for several hundred thousand years. The sustained fission reactions occurred about two billion years ago, when concentrations of U-235 were higher than they are now. The byproduct isotopes of this ancient reactor have been found to be almost exactly those found in present day reactors—even with the production of plutonium. So it's interesting to note that the achievement of Fermi and his team of some of the brightest minds in modern physics and engineering duplicated what nature did some two billion year ago. (Go back to "The Workings of an Ancient Nuclear Reactor" in the November 2005 *Scientific American*.)

Nuclear waste need not plague future generations indefinitely, as is commonly thought. Teams of scientists are presently designing devices in which long-lived radioactive atoms of spent reactor fuel can be transformed to short-lived, or nonradioactive, atoms. See the still-relevant article "Will New Technology Solve the Nuclear Waste Problem?" in *The Physics Teacher*, Vol. 35, Feb. 1997, or recent information on the Internet.

One of my general lectures that makes sweeping generalizations about fusion power and an idealized description of a fusion torch is available on the DVD set, *Conceptual Physics Alive*! *The San Francisco*

Years. The 3-disc set is available from Media Solutions (mediasolutions-sf.com) or other vendors. It goes into a speculative and entertaining scenario of a follow-up device to a star-hot flame called the fusion torch—a replicator, similar to that described by Arthur C. Clark in his 1963 book, *Profiles of the Future*.

Practicing Physics Book:
• Nuclear Reactions

Problem Solving Book:
With ample problems on fission and fusion

Laboratory Manual:
• Chain Reaction Nuclear Fission (Activity)

Next-Time Questions:
• Fission and Neutron Count   • Fission Reaction   • Oxygen Decay
• Fusion Reactions   • Fission-Fusion Curve

Hewitt-Drew-It! Screencasts: •*Nuclear Fission* •*Fission Power* •*Plutonium and Breeding* •*Nuclear Fusion* •*Controlled Fusion*

SUGGESTED LECTURE PRESENTATION

Nuclear Fission

Briefly discuss the world atmosphere back in the late 1930s when fission was discovered in Germany, and how this information was communicated to American physicists who urged Einstein to write his famous letter urging President Roosevelt to consider its potential in warfare. The importance of the fission reaction was not only the release of enormous energy, but the ejected neutrons that could stimulate other fissions in a chain reaction. In the practice of writing equations from the previous chapter, write on the board (or its equivalent) the reaction shown that accompanies the art at the beginning of the chapter (page 639) and discuss its meaning. To give some idea as to the magnitude of the 200,000,000 eV of energy associated with one fission reaction, state that New York City is powered by water falling over Niagara Falls, and that the energy of one drop over the falls is 4 eV; the energy of a TNT molecule is 30 eV, the energy of a molecule of gasoline oxidizing is 30 eV. So 200,000,000 eV is impressive. (Spelling it out like this rather than saying 200 Mev underscores the comparison of fission and conventional energy sources.) Discuss the average 3 neutrons that are kicked out by the reaction and what a chain reaction is (Figure 34.2). Discuss critical mass, and a nuclear device, simplified in Figure 34.5.

Nuclear Reactors

A piece of uranium or any radioactive material is slightly warmer than ambient temperature because of the thermal activity prodded by radioactive decay. Fission reactions are major nuclear proddings, and the material becomes quite hot—hot enough to boil water and then some. Make clear that a nuclear reactor of any kind is no more than a means to heat water to steam and generate electricity as a fossil fuel plant does. The principle difference is the fuel used to heat the water. You could quip that nuclear fuel is closer to the nature of the Earth than fossil fuels, whose energies come from the Sun.

Discuss how scaling (Chapter 12) plays an important role in critical mass (Figure 34.4). There's much more surface area compared to mass or volume for small pieces of material. And neutron escape is through surface, which if is small compared with the piece, means a chain reaction soon spends itself. For larger pieces, a chain reaction can build up and initiate an explosion.

Discuss the mechanics of a reactor via Figure 34.9. Just as the early automobiles mimicked horse-drawn buggies, energy output by today's reactors is by turning water into steam.

Plutonium

Show the production of plutonium via the equation suggested by Figure 34.10. Make this two steps, from U-238 + n —> Np-239. Then by beta decay Np-239 to Pu-239. Neptunium's half-life of 2.3 days quickly produces plutonium, with a half-life of 24,000 years. Acknowledge that to some degree all reactors produce plutonium.

Breeder Reactors

Reactors designed to maximize the production of plutonium are the breeder reactors. Make clear that they don't make something from nothing, but merely convert a nonfissionable isotope of uranium (U-238) to a fissionable isotope of plutonium (Pu-239).

Mass-Energy Equivalence

A brief discussion of what $E= mc^2$ says and what it doesn't say should be understood. This is the most important part of your lecture—the *why* of nuclear power.

Begin by supposing that one could journey into fantasy and compare the masses of different atoms by grabbing their nuclei with bare hands and shaking the nuclei back-and-forth. Show with hand motion, holding an imaginary giant nucleus, how the difference might appear in shaking a hydrogen atom and a lead atom. State that if you were to plot the results of this investigation for all the elements, that the relationship between mass and atomic number would look like Figure 34.15, (which you draw on the board). Ask if this plot is a "big deal?" The answer is "no," it simply shows that mass increases with the number of nucleons in the nucleus. No surprise.

Distinguish between the mass of a nucleus and the mass of the nucleons that make up a nucleus. Ask what a curve of mass/nucleon versus atomic number would look like—that is, if you divided the mass of each nucleus by the number of nucleons composing it, and compared the value for different atoms. If all nucleons had the same mass in every atomic configuration, then of course the graph would be a horizontal line. But the masses of nucleons differ. The interrelationship between mass and energy is apparent here, for the nucleons have "mass-energy," which is manifest partly in the "congealed" part, which is the material matter of the nucleons, and the other part which we call binding energy. The most energetically bound nucleus has the least mass/nucleon (iron). Go into the nucleon shaking routine again and demonstrate how the nucleons become easier to shake as you progress from hydrogen to iron. Do this by progressing from the student's left to right the full length of your lecture table. Indicate how they become harder to shake as you progress beyond iron to uranium. Then draw the curve that represents your findings, and you have Figure 34.16 on the board. Announce that this is the most important graph in the book! Note that it is followed up by the same graph emphasizing fission, then fusion (Figures 34.17 and 34.19).

From the curve you can show that any nuclear reaction that produces products with less mass than before reaction, will release energy, and any reaction in which the mass of the products is increased will require energy. Further discussion will show how the opposite processes of fission and fusion release energy.

> CHECK QUESTIONS: Will the process of fission or fusion release energy from atoms of lead? Gold? Carbon? Neon? (Be careful in selecting atoms too near atomic number 26 in this exercise—for example, elements slightly beyond 26 when fissioned will have more massive products, that extend "up the hydrogen hill"; elements near 26 when fused will combine to elements "up the uranium hill." Acknowledging this point, however, may only serve to complicate the picture—unless, of course, a student raises the subject in class.)

State how the graph can be viewed as a pair of "energy hills" on both sides of a valley, and that to progress "down" the hill is a reaction with less mass per nucleon and therefore a gain in energy.

Nuclear Fusion

By way of the energy-hill-valley idea, there are two sides of the valley that go downward. Going from hydrogen down to iron is more steep—more mass "defect" in combining light nuclei than splitting heavy ones. This combining atomic nuclei is nuclear fusion—the energy releasing process of the Sun and the stars.

CHECK QUESTION: Will the process of fission or fusion release energy from the nucleus of iron? [Neither! Iron is the nuclear sink; either process results in "going up the hill," gaining rather than losing mass.]

In effort to keep page count down, this edition does not feature the **Fusion Torch and Recyling**, as in previous editions. Nor does it discuss the various developments in *inertial confinement fusion*, induced by lasers, electron beams, and ion beams. None of these schemes has shown the promise expected in past years.

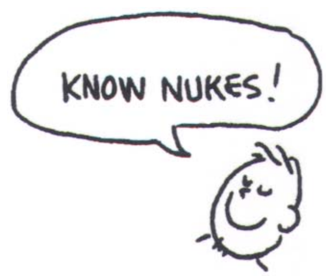
This is a period of transition—in some ways characterized by tough times, but overall, an interesting time to be alive. Particularly for those who are participating in the transition for positive change—for those who have not lost patience and retreated from knowledge into irrationality in its many generally-respected forms. Past centuries are often romanticized. Ask how many of your students would prefer living, say before the time of Galileo, during the Dark Ages. Too often the future is degraded. Back in the late 90s I saw an impressive I-Max 3-D movie, *L-5*. In this movie the future is seen in a positive light, a triumph of problem solving in a future space habitat. But, unfortunately, not the usual diet for movie goers.

Here's some recommended reading:

Bodansky, D, *Nuclear Energy: Principles, Practices, and Prospects,* 2nd ed., Springer, NY (2004).

Hannum, W. H., and G. E. Marsh, G. S. Stanford, *Physics and Society* 33(3), 8 (July 2004); see http://www.aps.org/units/fps.

Vandenbosch, R, and S. E. Vandenbosch, *Physics and Society* 35((3), 7 (July 2006); see http://www.aps.org/units/fps.



Answers and Solutions for Chapter 34

Reading Check Questions

1. Very little uranium in mines is the fissionable isotope U-235.
2. In a large piece of uranium neutrons are less able to reach beyond the surface, which increases the chances of fission.
3. Critical mass is the amount beyond which spontaneous fission occurs.
4. More leakage occurs for the two separate pieces because they have more surface area per volume than two pieces stuck together.
5. The two methods were gas diffusion and centrifuge separation.
6. (1) Cause fission, (2) escape, (3) be absorbed.
7. Nuclear fuel, control rods, a moderator, and a fluid to extract heat.
8. Control rods and the presence of U-238 are safeguards to escalation in a reactor.
9. The isotope is U-239.
10. The isotope is Np-239.
11. The isotope is Pu-239.
12. Both U-235 and Pu-239 are fissionable.
13. The effect is the production of plutonium.
14. Both U-235 and Pu-239 undergo fission.
15. U-238 breeds to become Pu-239.
16. Both a nuclear reactor and fossil-fuel plant boil water to become steam that drives a generator.
17. Advantages: (1) Plentiful electricity, (2) saving fossil fuels for materials, (3) no atmospheric pollution. Drawbacks: (1) Waste storage, (2) danger of weapons proliferation, (3) release of radioactivity, and (4) risk of accident.
18. The celebrated equation is $E = mc^2$.
19. Yes, yes, with the form of energy as increased mass.
20. Least deflected are the massive ions (inertia).
21. Figure 34.35 shows mass vs atomic number, while Figure 34.16 shows mass *per nucleon* vs atomic number.
22. Mass per nucleon is greatest for hydrogen; least for iron.
23. Mass per nucleon decreases in fission fragments.
24. Reduced mass is manifest as released energy.
25. Progressing toward iron means less mass per nucleon.
26. Helium has less mass than the sum of the hydrogen masses.
27. Helium would have to be fused to release energy.
28. Deuterium and tritium fuse best at relatively moderate temperatures.
29. Deuterium is abundant, found in ordinary water. Tritium is scarce and must be created.
30. Thermonuclear fusion is responsible for sunshine.

Think and Do

31. Open ended.

Think and Solve

32. The energy released by the explosion in kilocalories is (20 kilotons)(4.2×10^{12} J/kiloton)/(4,184 J/kilocalorie) = 2.0×10^{10} kilocalories. This is enough energy to heat 2.0×10^{10} kg of water by 1 °C. Dividing by 50, we conclude that this energy could heat 4.0×10^8 kilograms of water by 50 °C. This is nearly half a million tons.

33. When Li-6 absorbs a neutron, it becomes Li-7, made of 3 protons and 4 neutrons. If this Li-7 nucleus splits into two parts, one of which is a nucleus of tritium containing one proton and two neutrons, the other must be made of two protons and two neutrons. That is an alpha particle, the nucleus of ordinary helium. It is the tritium, not the helium, that fuels the explosive reaction.

34. The neutron and the alpha particle fly apart with equal and opposite momenta. Since the neutron has one-fourth the mass of the alpha particle, it has four times the speed. Also consider the kinetic-energy equation, KE = (1/2) mv^2. For the neutron, KE = (1/2) $m(4v)^2 = 8\,mv^2$, and for the alpha particle, KE = (1/2) $(4m)v^2 = 2\,mv^2$. The KEs are in the ratio of 8/2, or 80/20. So we see that the neutron gets 80% of the energy, and the alpha particle 20%. (Alternative method: The formulas for momentum and KE can be combined to give KE = $p^2/2m$. This equation tells us that for particles with the same momentum, KE is inversely proportional to mass.)

Think and Rank

35. A, B, C, D.
36. A, B, C, D.

Think and Explain

37. Fission.

38. Non-enriched uranium—which contains more than 99% of the non-fissionable isotope U-238—undergoes a chain reaction only if it is mixed with a moderator to slow down the neutrons. Uranium in ore is mixed with other substances that impede the reaction with no moderator to slow down the neutrons, so no chain reaction occurs. (There is evidence, however, that several billion years ago, when the percentage of U-235 in uranium ore was greater, a natural reactor existed in Gabon, West Africa.)

39. Electric repulsion between protons reaches across the whole nucleus, affecting all protons, whereas the attractive nuclear force reaches only from one nucleon to nearer neighbors. So the greater the number of protons in a nucleus, the greater the likelihood that mutual electrical repulsion will overcome the attractive nuclear forces and lead to fission.

40. A neutron makes a better "bullet" for penetrating atomic nuclei because it has no electric charge and is therefore not electrically repelled by an atomic nucleus.

41. In a large piece of fissionable material a neutron can move farther through the material before reaching a surface. Larger volumes of fissionable material have proportionally less area compared to their greater volumes, and therefore lose less neutrons.

42. No. The flattened shape has more surface area, and therefore more neutron leakage, making it subcritical.

43. Critical mass is the amount of fissionable mass that will just sustain a chain reaction without exploding. This occurs when the production of neutrons in the material is balanced by neutrons escaping through the surface. The greater the escape of neutrons, the greater the critical mass. We know that a spherical shape has the least surface area for any given volume, so for a given volume, a cube shape would have more area, and therefore more "leakage" of the neutron flux. So a critical-mass cube is more massive than a critical-mass sphere. (Look at it this way: A sphere of fissionable material that is critical will be subcritical if flattened into a pancake shape—or molded into any other shape—because of increased neutron leakage.)

44. The process of assembling small pieces of fission fuel into a single big piece increases average traveling distance, decreases surface area, reduces neutron leakage, and increases the probability of a chain reaction and an explosion.

45. Because plutonium releases more neutrons per fission event, plutonium can stand more neutron leakage and still be critical. So plutonium has a smaller critical mass than uranium in a similar shape.

46. Only trace amounts of plutonium can occur naturally in U-238 concentrations. When U-238 captures a stray neutron it becomes U-239 and after beta emission becomes Np-239, which further transforms by beta emission to Pu-239. Because of its relatively short half-life (24,360 years) it doesn't last long. Any plutonium initially in Earth's crust has long since decayed.

47. Plutonium builds up over time because it is produced by neutron absorption in the otherwise inert U-238.

48. The resulting nucleus is ${}_{92}U^{233}$. The mass number is increased by 1 and the atomic number by 2. U-233, like U-235, is fissionable with slow neutrons. (Notice the similarity to the production of ${}_{94}Pu^{239}$ from ${}_{92}U^{238}$.)

49. One purpose of a separate water cycle is to restrict radioactive contamination of the reactor water with the reactor itself and to prevent interaction of the contaminants with the outside environment. Also, the primary water cycle can operate at higher pressure and therefore at higher temperature (well above the normal boiling point of water).

50. When a neutron bounces from a carbon nucleus, the nucleus rebounds, taking some energy away from the neutron and slowing it down so it will be more effective in stimulating fission events. A lead nucleus is so massive that it scarcely rebounds at all. The neutron bounces with practically no loss of energy and practically no change of speed (like a marble from a bowling ball).

51. The mass of an atomic nucleus is less than the sum of the masses of the separate nucleons that compose it. Consider the work that must be done to separate a nucleus into its component nucleons, which according to $E = mc^2$, adds mass to the system. Hence the separated nucleons are more massive than the original nucleus. Notice the large mass per nucleon of hydrogen in the graph of Figure 34.16. The hydrogen nucleus, a single proton, is already "outside" in the sense that it is not bound to other nucleons.

52. If the difference in mass for changes in the atomic nucleus increased tenfold (from 0.1% to 1.0%), the energy release from such reactions would increase tenfold as well.

53. Fission and fusion are alike in that both are energy-releasing nuclear reactions that involve transformation of one or more elements into other elements. However, they differ in important ways: Fission doesn't require high temperatures; fusion does. Fission involves heavy nuclei; fusion involves light nuclei. As the names imply, fission is the splitting apart of a nucleus while fusion is the joining together of nuclei. The concept of critical mass applies to fission, but not to fusion.

54. Both chemical burning and nuclear fusion require a minimum ignition temperature to start and in both the reaction is spread by heat from one region to neighboring regions. There is no critical mass. Any amount of thermonuclear fuel or of combustible fuel can be stored.

55. Copper, atomic number 29, fused with zinc, atomic number 30, becomes the rare earth element praseodymium, atomic number 59.

56. The fusion of 2 hydrogen nuclei with an oxygen nucleus would produce a nucleus of neon, atomic number 10.

57. Aluminum. (Two carbons fuse to produce manganese, atomic number 12. Beta emission would change it to aluminum, atomic number 13.)

58. Although more energy is released in the fissioning of a single uranium nucleus than in the fusing of a pair of deuterium nuclei, the much greater number of lighter deuterium atoms in a gram of matter than the heavier uranium atoms in a gram of matter, results in more energy liberated per gram for the fusion of deuterium.

59. If enough fission fuel is localized, it will spontaneously undergo a chain reaction when triggered by a single neutron. Fusion fuel, on the other hand, is like combustible fuel, not a chain-reacting substance. It has no "critical mass," and can be stored in large or small amounts without undergoing spontaneous ignition.

60. A hydrogen bomb produces a lot of fission energy as well as fusion energy. Some of the fission is in the fission bomb "trigger" used to ignite the thermonuclear reaction and some is in fissionable material that surrounds the thermonuclear fuel. Neutrons produced in fusion cause more fission in this blanket. Fallout results mainly from the fission.

61. A major potential advantage of fusion power over fission power has to do with the fuel for each: Fusion fuel (heavy hydrogen) is plentiful on Earth, especially in the world's oceans, whereas fission fuel (uranium and plutonium) is a much more limited resource. (This imbalance holds in the universe as well.) A second advantage of fusion power has to do with the byproducts: Whereas fission produces appreciable radioactive wastes, the chief byproduct of fusion is nonradioactive helium (although neutrons released in fusion can cause radioactivity in surrounding material).

62. You don't get something for nothing. There is great misunderstanding about hydrogen. To release it from water or other chemicals costs more energy than you recover when you burn it. Hydrogen represents stored energy, like a battery. It's made in one place and used in another. It burns without pollution, a big advantage, but it should be regarded as a storage and transport medium for energy, not as a fuel.

63. Ruthenium. (U with atomic number 92 splits into palladium, atomic number 46, which emits an alpha particle with atomic number 2. This results in an element having atomic number 44, ruthenium.)

64. The KE of the fission products is converted into heat energy for boiling water to turn a turbine.

65. No. U-235 (with its shorter half-life) undergoes radioactive decay six times faster than U-238 (half-life 4.5 billion years), so natural uranium in an older Earth would contain a much smaller percentage of U-235, not enough for a critical reaction without enrichment. (Conversely, in a younger Earth, natural uranium would contain a greater percentage of U-235 and would more easily sustain a chain reaction.)

Think and Discuss

66. A fission reactor has a critical mass. Its minimum size (including moderator, coolant, etc.) is too large to power a small vehicle (although it is practical as a power source for submarines and ships). Indirectly, fission can be used to power automobiles by making electricity that is used to charge electric car batteries.

67. To predict the energy release of a nuclear reaction, simply find the difference in the mass of the beginning nucleus and the mass of its configuration after the reaction (either fission or fusion). This mass difference (called the "mass defect") can be found from the curve of Figure 34.16 or from a table of nuclear masses. Multiply this mass difference by the speed of light squared: $E = mc^2$. That's the energy release!

68. Each fragment would contain 46 protons (half of 92) and 72 neutrons (half of 144), making it the nucleus of Pd-118, an isotope of palladium, element number 46.

69. Fusing heavy nuclei (which is how the heavy transuranic elements are made) costs energy. The total mass of the products is greater than the total mass of the fusing nuclei.

70. Splitting light nuclei (which happens in particle accelerators) costs energy. As the curve in Figure 34.16 shows, the total mass of the products is greater than the total mass of the initial nucleus.

71. Energy would be released by the fissioning of gold and from the fusion of carbon, but by neither fission nor fusion for iron. Neither fission nor fusion results in a decrease of mass for iron.

72. If uranium were split into three parts, the segments would be nuclei of smaller atomic numbers, more toward iron on the graph of Figure 34.16. The resulting mass per nucleon would be less, and there would be more mass converted to energy in such a fissioning.

73. If the mass per nucleon varied in accord with the shape of the curve of Figure 34.15 instead of the curve of Figure 34.16, then the fissioning of all elements would liberate energy and all fusion processes would absorb rather than liberate energy. This is because all fission reactions (decreasing atomic number) would result in nuclei with less mass per nucleon, and all fusion reactions (increasing atomic number) would result in the opposite; nuclei of more mass per nucleon.

74. Whereas a pair of hydrogen nuclei collectively weigh more when apart than when locked together, a pair of nuclei half as heavy as uranium nuclei would weigh more when fused together than when apart.

75. The initial uranium has more mass than the fission products.

76. The initial hydrogen nuclei have more mass than the fusion products.

77. Energy from the Sun is our chief source of energy, which itself is the energy of fusion. Harnessing that energy on Earth has proven to be a formidable challenge.

78. Radioactivity in the Earth's core provides the heat that keeps the inside molten, and warms hot springs and geysers. Nuclear fusion releases energy in the Sun that bathes Earth in sunshine.

79. Such speculation could fill volumes. The energy and material abundance that is the possible outcome of a fusion age will likely prompt several fundamental changes. Obvious changes would occur in the fields of commerce. Also, global warming by humans would be greatly reduced. Regional wars based on oil scarcity would be reduced. More development would likely reach undeveloped parts of the world. A fusion age would likely see changes that would touch every facet of human life.

80. The comparisons are many. Foremost are these: Conventional fossil-fuel power plants consume our natural resources and convert them into greenhouse gases and poisonous contaminants that are discharged into the atmosphere, producing among other things, global climate change and acid rain. A lesser environmental problem exists with nuclear power plants, which do not pollute the atmosphere. Pollution from nukes is concentrated in the radioactive waste products from the reactor core. Any rational discussion about the drawbacks of either of these power sources must acknowledge that *both* are polluters—so the argument is about which form of pollution are we more willing to accept in return for electrical power. (Before you say "No Nukes!," rational thinking suggests that you first be able to say that you "Know Nukes!.")

81. In 1 billion years U-235 on Earth would be in short supply and fission power would likely be a thing of the past.

35 Special Theory of Relativity

The Part Eight photo opener is my granddaughter, Grace Hewitt.

The photo openers feature Ken Ford, Albert Einstein, and Edwin F. Taylor, three relativity experts—the one in the center being the most famous.

The personality profile for this chapter is Albert Einstein! (Regrettably, his picture on a bicycle in previous editions wasn't "approved" for this edition ☹. The profile continues in the next chapter.

The ideas discussed in this chapter are perhaps the most exciting in the book. But for most students they are difficult to comprehend. Regardless of how clearly and logically this material is presented, students will find that they do not sufficiently "understand" it. This is understandable for so brief an exposure to a part of reality untouched by conscious experience. The purpose of this chapter is to develop enough insight into relativity to stimulate further student interest and inquiry.

Note the important significance of "The Twin Trip" section in the text, in that it completely bypasses the equations for time dilation and the relativistic Doppler effect. The reciprocity of relativistic Doppler frequencies for approach and recession stems only from Einstein's 1st and 2nd postulates and is established without the use of a single mathematical formula. This is abbreviated in the long footnote in the chapter and is detailed in the 4-step classroom presentation in the following suggested lecture. [This reciprocal relationship is not valid for sound, where the "moving" frame is not equivalent to the "rest" (relative to air) frame. If the ratio of frequency received to frequency sent for hearing in the rest frame is 2, the ratio for hearing in the moving frame is $^3/_2$ (clearly not 2!). For sound, the speed as well as the frequency depends on the motion of the receiver.] From this and the simple flash-counting sequence, time dilation follows without the use of any mathematical formulas. The results of the twin-trip flash sequence agree with Einstein's time dilation equation. So this treatment is completely independent to the time dilation equation and the relativistic Doppler equation! (Who says that good physics can't be presented without high-powered math?)

If your class is in a more mathematical mood, you may wish to show an alternative approach to The Twin Trip and consider straightforward time dilation plus corrections for the changing positions of the emitting or receiving body between flashes. Instead of bypassing the time dilation equation, use it to show that at 0.6 c, 6-minute flash intervals in the emitting frame compute to be $7^1/_2$-minute flash intervals in the receiving frame. The flashes would *appear* at $7^1/_2$-minute intervals if the spaceship were moving crosswise, neither approaching or receding, such that each flash travels essentially the same distance to the receiver. In our case the spaceship doesn't travel crosswise, but recedes from and then approaches the receiver—so corrections must be made in the time interval due to the extra distance the light travels when the spaceship

is receding and the lesser distance the light travels when the spaceship is approaching. This turns out to be $4^1/2$ minutes; [Δt = (extra distance)/c = (0.6 $c \times 7^1/2$ min)/c = $4^1/2$ min]

So when receding, the flashes are seen at $7^1/2 + 4^1/2$ = 12-min intervals; when approaching, the flashes are seen at $7^1/2 - 4^1/2$ = 3-min intervals. The results of this method are the same as those of the 4-step conceptual presentation in the following suggested lecture.

My 12-minute animated film, *Relativistic Time Dilation*, amplifies the section on The Twin Trip. It is part of the videotape of relativity in the *Conceptual Physics Alive!* series. Contact your Addison-Wesley representative or Arbor Scientific (arborsci.com) for availability.

As in previous editions, relativistic momentum, rather than relativistic mass, is treated. The very early editions of Conceptual Physics, and some other physics textbooks, speak of *relativistic mass*, given by the equation $m = m_0/\sqrt{1 - (v^2/c^2)}$. This idea has lost favor to the somewhat more complex idea of relativistic momentum, rather than mass. One problem with the idea of increased mass is that mass is a scalar: It has no direction. When particles are accelerated to high speeds, their increase in mass is directional. Increase occurs in the direction of motion in a manner similar to the way that length contraction occurs only in the direction of motion. Moving mass is, after all, momentum. So it is more appropriate to speak of increases in momentum rather than mass. Either treatment of relativistic mass or relativistic momentum, however, leads to the same description of rapidly moving objects in accord with observations.

The symbol γ (gamma) simplifies expressions for time dilation and relativistic momentum.

Because of the interest in physics that relativity generates, this chapter may be treated earlier in the course—even to begin your course.

Practicing Physics Book:
• Time Dilation

Problem Solving Book:
There are problems on relativity. Have your math-oriented students have a go at them!

Laboratory Manual:
Not surprisingly, there are no activities or experiments on special relativity

Next-Time Questions:
• Astronaut Travel Time
• Shrinking Spear

Hewitt-Drew-It Screencasts: •*Special Relativity* •*Time Dilation* •*Relativistic Velocities* •*Length Contraction* •*$E = mc^2$* •*Correspondence Principle*

SUGGESTED LECTURE PRESENTATION

After discussing Einstein and a broad overview of what special relativity is and is not, point out somewhere along the line that the theory of relativity is grounded in *experiment*, and in its development it explained some very perplexing experimental facts (constancy of the speed of light, muon decay, solar energy, the nature of mass, etc.). It is not, as some people think, only the speculations of one man's way of thinking.

Motion Is Relative

Ask your class to pretend they are in a parking lot playing ball with someone driving toward them and away from them in an open vehicle. A pitcher in the vehicle tosses a ball at them, always with the same pitching speed—no variation. Ask for the relative speed of catching a ball when the car approaches, and when it recedes. They know there will be a difference. Ask how they would react if the speeds of the ball in

catching were the same, whether the thrower was moving toward them, at rest, or moving away from them. This would be most perplexing. Now discuss the null result of the Michelson-Morley experiment.

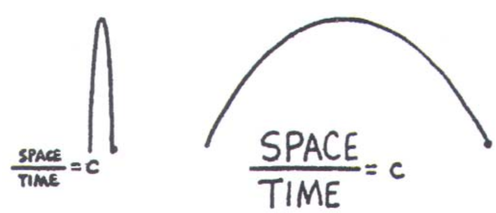
Michelson-Morley Experiment
Treat the Michelson-Morley experiment very briefly, and I suggest you do not delve into the mechanics of the interferometer. Instead direct your students' mental energies to the broad ideas of special relativity. Explain what it means to say the velocity of light is invariant.

First Postulate
The laws of physics are the same in all uniformly moving reference frames. A bee inside a fast-moving jet plane executes the same flying maneuvers regardless of the speed of the plane. If you drop a coin to the floor of the moving plane, it will fall as if the plane were at rest. Physical experiments behave the same in all uniformly moving frames. This leads, most importantly, to the development of special relativity, to the speed of light that is seen to be the same for all observers. There is no violation of common sense in this first postulate. It rules out any effect of uniform motion on any experiment, however. For any observed effect violates this postulate and the foundation of relativity.

Second Postulate
Stand still and toss a pencil up and down, catching it as you would when flipping a coin. Ask the class to suppose that in so doing that all measurements show the pencil to have a constant average speed. Call this constant speed *c* for short. That is, both they and you see only one average speed for the tossed pencil. Then proceed to walk at a fairly brisk pace across the room and again toss the pencil. State that from your frame of reference you again measure the same speed. Ask if the speed looked any different to them. They should respond that the pencil was moving faster this time. Ask them to suppose that their measurement yielded the same previous value. They may be a bit perplexed, which again is similar to the perplexed state of physicists at the turn of the century. On the board, write with uniformly sized letters

$$\boldsymbol{c} = \frac{\text{SPACE}}{\text{TIME}} \ .$$

This is the speed as seen by you in your frame of reference. State that from the frame of reference of the class, the space covered by the tossed pencil appeared to be greater, so write the word SPACE in correspondingly larger letters. Underline it. State that if they see the same speed, that is, the same ratio of space to time, then such can be accounted for if the time is also measured to be greater. Then write the enlarged word TIME beneath the underline, equating it to *c*.



Analogy: Just as all observers will measure the same ratio of circumference to diameter for all sizes of circles, all observers will measure the same ratio of space to time for electromagnetic waves in free space.

Simultaneity
Show by way of Figures 35.9 and 35.10, and the footnoted diagram on page 665 that an interesting result of the constancy of the speed of light in all reference frames is the nonsimultaneity of events in one frame that are simultaneous in another. Contrast this to classical nonsimultaneity, like different observers hearing gun blasts at different time intervals.

Space-time
An interesting way to look at how space and time are related to the speed of light is to think of all things moving through space-time at a constant speed. When movement is maximum through space, movement in

time is minimum. When movement in space is minimum, movement in time is maximum. For example, something at rest relative to us moves not at all in space and moves in time at the maximum rate of 24 hours per day. When something approaches the speed of light relative to us, it moves at its near maximum speed in space, and moves near zero in time—it doesn't age.

The box about clockwatching on a trolley car ride was motivated by remarks made by Jacob Bronowski in his *Accent of Man* series, where he cites the notion of clock information traveling to distant locations, and how that one traveling at the speed of light would see a clock frozen in time.

The Twin Trip

You have a choice of a short treatment of this or a longer more detailed treatment. The short treatment begins without fanfare and as a matter of fact presents the half rate of flashes seen when a spaceship approaches (Figure 35.15) and the doubled rate seen when the spaceship recedes (Figure 35.16). The fact that the half rate and doubled rate are reciprocals is not developed. For the vast majority of my students this is fine. More sophisticated students may be uneasy with this and wish to see this reciprocal relationship developed. This is the longer treatment. This longer treatment is shown by the 4 steps below. For the shorter treatment, jump ahead to paragraph 2, with the * on page 364.

We will in effect bypass the derivation of the relativistic Doppler effect, namely,

$$f = f_0\sqrt{\frac{1 + v/c}{1 - v/c}}$$

with the following four-step conceptual presentation:

Step 1: Consider a person standing on Earth directing brief flashes of light at 3-min intervals to a distant planet at rest relative to the Earth. Some time will elapse before the first of these flashes reaches the planet, but since there is no relative motion between the sender and receiver, successive flashes will be observed at the distant planet at 3-min intervals. While you are making these remarks, make a sketch on the board of Figure 1.

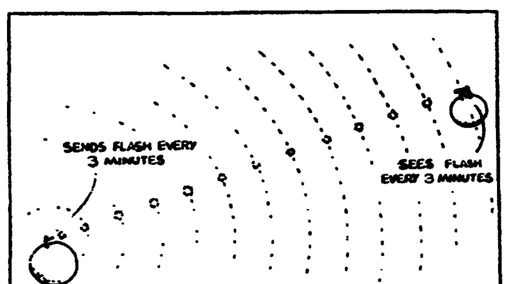


FIGURE 1

Step 2: How frequently would these flashes encounter an observer in a fast-moving spaceship traveling between the Earth and the planet? Although the speed of the flashes would be measured by the spaceship to be *c*, the frequency of flashes would be greater or less than the emitting frequency depending on whether the spaceship were receding or approaching the light source. After supporting this idea with some examples of the Doppler effect (car horns, running into versus away from a slanting rain, etc.) make the supposition that the spaceship recedes from the light source at a speed great enough for the frequency of light flashes to decrease by half—so they're seen from the spaceship only half as often, at 6-min intervals. By now your chalkboard sketch looks like Figure 2.

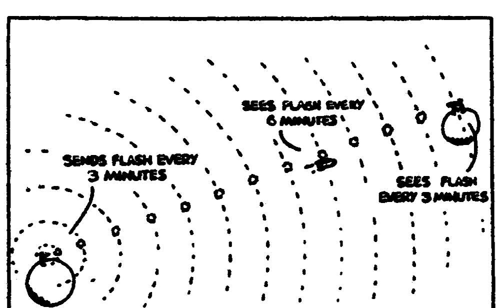


FIGURE 2.

Step 3: Suppose further that each time a flash reaches the spaceship, a triggering device activates a beacon on the spaceship that sends its own flash of light toward the distant planet. According to a clock in the spaceship then, this flash is emitted every 6 min. Since the flashes from Earth and the flashes emitted by the spaceship travel at the same speed *c*, both sets of flashes travel together, and an observer on the distant planet sees not only the Earth flashes at 3-min intervals, but the spaceship flashes at 3-min intervals as well (Figure 3). At this point you have established that 6-min intervals on the approaching spaceship are seen as 3-min intervals on the stationary planet.

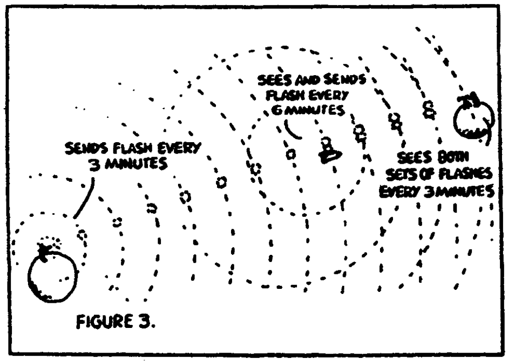


FIGURE 3.

Step 4: To establish that the 6-min flashes emitted by the spaceship are seen at 12-min intervals from the Earth, go back to your earlier supposition that 3-min intervals on Earth are seen as 6-min intervals from the frame of reference of the receding spaceship. Ask your class: If instead of emitting a flash every 3 min, the person on Earth emits a flash every 6 min, then how often would these flashes be seen from the receding spaceship? And then ask if the situation would be any different if the spaceship and Earth were interchanged—if the spaceship were at rest and emitted flashes every 6 min to a receding Earth? After a suitable response erase from your board drawing all the flashes emitted from the Earth. Replace the Earth-twin's light source with a telescope while asking how often the 6-min flashes emitted by the moving spaceship are seen from Earth. Class response should show that you have established the reciprocity of frequencies for the relativistic Doppler effect without a single equation. This is summarized in Fig. 4.

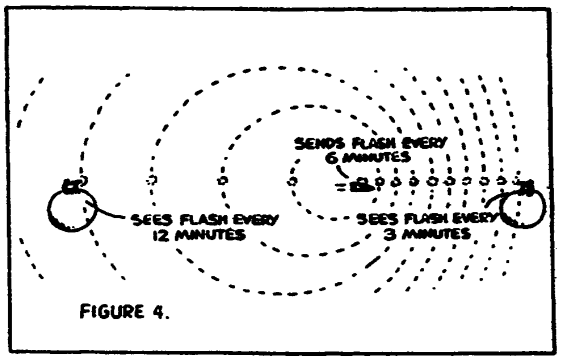


FIGURE 4.

Note that you have employed Einstein's postulates in the last two steps, that is, the second postulate in Step 3 (constancy of the speed of light) and the first postulate in Step 4 (equivalence of the Earth and spaceship frames of reference).

Whether you have established this reciprocity from the Doppler equation or from the preceding four steps, you are now ready to present the twin trip and demonstrate time dilation while also presenting a resolution to the so-called twin paradox.

*With a sketch of Figure 4 above in an upper corner of your board, proceed to make a rendition of textbook Figure 35.17 on the main part of your board. You'll draw only one picture of the Earth and let your eraser be the spaceship which you move away from Earth (to the right as the top part of the figure, *a*, suggests). State the spaceship sends 10 flashes at 6-min intervals. At the 10^{th} flash 1 hour has passed for the spaceship. Ask how these 6-min intervals appear to Earth observers? [At 12 min apart.] What time is it on Earth when the 10^{th} flash is received? [Two hours later!] The spaceship quickly turns around and continues homeward, again sending 10 flashes at 6-min intervals. When the 10^{th} flash is emitted, another hour passes for the spaceship and its total trip time is 2 hours. But ask how often the incoming flashes occurred to Earth types. [At 3-min intervals.] Ten incoming 3-min flashes take only 30 min, Earth time. So from the Earth frame of reference the spaceship took a grand total of $2^1/2$ hours.

During your discussion, summarize this on the board as the lettering of Figure 35.18.

Depending on lecture time, switch frames of reference and repeat the similar sequence suggested by Figures 35.19 and 35.20 for the case where the flashes are emitted from Earth and viewed by the moving spaceship. You get the same results.

Space Travel
Speculate on the idea of "century hopping," the future version of today's "jet hopping." In this scenario future space travelers may take relatively short trips of a few years or less and return in decades, or even centuries. This is, of course, pending the solution to two present problems: rocket engines and sufficient fuel supplies for prolonged voyages, and a means of shielding the radiation that would be produced by impact of interstellar matter.

The Centrifuge
Follow this up with this interesting but fictitious example to show that one needn't go far in space for significant time dilation: Suppose that one could be whirled in a giant centrifuge up to relativistic speeds without physical injury. Of course one would be crushed to death in such a case, but pretend that somehow one is physically unaffected by the crushing centripetal forces (the fictitiousness of this example). Then cite how one taking a "ride" in such a centrifuge might be strapped in his seat and told to press a button on the seat when he or she wishes the ride terminated. And suppose that after being whirled about at rim speeds near the speed of light the occupant decides that 10 minutes is enough. So he or she presses the button, signaling those outside to bring the machine to a halt. After the machine is halted, those outside open the door, peer in, and ask, "Good gosh, what have you been doing in there for the past 3 weeks!" In the laboratory frame of reference, 3 weeks would have elapsed during a ten-minute interval in the rotating centrifuge. Motion in space, rather than space itself is the key factor.

Length Contraction
Hold up a meterstick, horizontally, and state that if your students made accurate measurements of its length, their measurements would agree with your own. Everyone would measure it as 1 meter long. People at the back of the room would have to compensate for it appearing smaller due to distance, but nevertheless, they would agree it is 1 meter long. But now walk across the room holding the meterstick like a spear. State that your measurements and those of your students would differ. If you were to travel at 87% the speed of light, relative to the class, they would measure the meterstick to be half as long, 0.5 m. At 99.5% the speed of light, they would see it as only 10 cm long. At greater speeds, it would be even shorter. At the speed of light it would contract to zero length. Write the length-contraction formula on the board:

$$L = L_o\sqrt{1 - (v^2/c^2)}$$

State that contraction takes place only in the direction of motion. The meterstick moving in spear fashion appears shorter but it doesn't appear thinner.

> CHECK QUESTION: Consider a pair of stars, one on each "edge" of the universe. That's an enormous distance of separation from our frame of reference. Now consider a photon traveling from one star across the entire universe to the other. From the frame of reference of the photon, what is the distance of separation between stars? (How big is the universe?) [Zero! From a frame of reference traveling at *c*, the length contraction reaches zero.]

The implication of the above question is that at high speeds, future space travelers may not face the restrictions of traveling distance that seem formidable without relativity! There is much food for thought on this!

The Mass-Energy Relationship
Write $E = mc^2$ on the board, the most celebrated equation of the previous century. It relates energy and mass. Every material object is composed of energy—"energy of being." This "energy of being" is appropriately called *rest energy*, which is designated by the symbol *E*. (Some instructors label this E_o, to distinguish it from a generalized symbol *E* for total energy. Since we're concerned only with rest energy here, there isn't a need for the subscript. We are here defining rest energy as *E*, which shouldn't pose a problem. If we were to extend our treatment, then such a subscript would be useful.) So the mass of something is actually the internal energy within it. This energy can be converted to other forms—light for example.

On the 4.5 million tons of matter converted to radiant energy by the Sun each second: That tonnage is carried by radiant energy through space, so when we speak of matter being "converted" to energy, we are merely converting from one form to another—from a form with one set of units, to another. Because of the mass and energy equivalence, in any reaction that takes into account the whole system, the total amount of mass + energy does not change.

Discuss the interesting idea that mass, every bit as much as energy, is delivered by the power utilities through the copper wires that run from the power plants to the consumers.

From a long view, the significance of the twentieth century will be most likely seen as a major turning point with the discovery of the $E = mc^2$ relationship. We can speculate about what the equation of this 21st century will turn out to be.

Relativistic Momentum

State that if you push an object that is free to move, it accelerates in accord with Newton's 2nd law, $a = F/m$. As it turns out, Newton originally wrote the 2nd law not in terms of acceleration, but in terms of momentum, $F = \Delta p/\Delta t$, which is equivalent to the familiar $F = ma$. Here we use the symbol p for momentum, $p = mv$. In accord with the momentum version of Newton's 2nd law, push an object that is free to move and we increase its momentum. The acceleration or the change-of-momentum version of the 2nd law produces the same result. But for very high speeds, it turns out that the momentum version is more accurate. $F = \Delta p/\Delta t$ holds for all speeds, from everyday speed to speeds near the speed of light—as long as the relativistic expression of momentum is used.

Write the expression for relativistic momentum on the board: $p = mv/\sqrt{1 - (v^2/c^2)}$. Or $p = \gamma mv$.

Point out that it differs from the classical expression for momentum by γ, or by the denominator $\sqrt{1 - (v^2/c^2)}$. A common interpretation is that of a relativistic mass $m = \gamma\, m_o$, or $m = m_o/\sqrt{1 - (v^2/c^2)}$, multiplied by a velocity v. Because the increase in mass with speed is directional (as is length contraction), and momentum rather than mass is a vector, the concept of momentum increase rather than mass increases is preferred in advanced physics courses. Either treatment of relativistic mass or relativistic momentum, however, leads to the same description of rapidly moving objects in accord with observations.

A good example of the increase of either mass or momentum for different relative speeds is the accelerated electrons and protons in high-energy particle accelerators. In these devices speeds greater than 0.99 c are attained within the first meter, and most of the energy given to the charged particles during the remaining journey goes into increasing mass or momentum, according to your point of view. The particles strike their targets with masses or momentum thousands of times greater than the physics of Newton accounts for. Interestingly enough, if you traveled along with the charged particles, you would note no such increase in the particles themselves (the v in the relativistic mass equation would be zero), but you'd measure a mass or momentum increase in the atoms of the "approaching" target (the crash is the same whether the elephant hits the mouse or the mouse hits the elephant).

Cite how such an increase must be compensated for in the design of circular accelerators such as cyclotrons, bevatrons, and the like, and how such compensation is not required for a linear accelerator (except for the bending magnets at its end).

Point out to your class the similarities of the equations: $t = \gamma\, t_o$; $p = \gamma\, mv$.

Show how for small speeds the relativistic momentum equation reduces to the familiar mv (just as for small speeds $t = t_o$ in time dilation). Then show what happens when v approaches c. The denominator of the equation approaches zero. This means that the momentum approaches infinity! An object pushed to the speed of light would have infinite momentum and would require an infinite impulse (force × time), which is clearly impossible. Nothing material can be pushed to the speed of light. The speed of light c is the upper speed limit in the universe.

Cars, planes, and even the fastest rockets don't approach speeds to merit relativistic considerations, but subatomic particles do. They are routinely pushed to speeds beyond 99% the speed of light where their momenta increase thousands of times more than the classical expression *mv* predicts. This is evidenced when a beam of electrons directed into a magnetic field is appreciably deflected from its normal path. The greater its speed, the greater its "moving inertia"—its momentum, and the greater it resists deflection (Figure 35.26). High-energy physicists must take relativistic momentum into account when working with high-speed subatomic particles in accelerators. In that arena, relativity is an everyday fact of life.

Optional—Relativistic Kinetic Energy

From where did Einstein's equation $E = mc^2$ originate? Einstein was the first to derive the relativistic expression for kinetic energy, KE $=mc^2/\sqrt{1 - v^2/c^2} - mc^2$ and the first to note the term mc^2, which is independent of speed. This term is the basis of the celebrated equation, $E = mc^2$.

Interestingly enough, for ordinary low speeds the relativistic equation for kinetic energy reduces to the familiar KE = $^1/2\ mv^2$ (via the binomial theorem). In many situations where the momentum or energy of high-speed particles is known rather than speed, the expression that relates total energy E to the relativistic momentum p is given by $E^2 = p^2c^2 + (mc^2)^2$. This expression is derived by squaring the relation $E = mc^2$ to obtain $E^2 = m^2c^4 = m^2c^2\ (c^2 + v^2 - v^2)$, and combining the relativistic equation for momentum.

Like the argument for a speed limit via the infinite impulse required to produce infinite momentum, we find that doing more and more work to move an object or particle increases its kinetic energy disproportionately to its increase in speed. The accelerated matter requires more and more kinetic energy for each small increase in speed. An infinite amount of energy would be required to accelerate a material object to the speed of light. Since an infinite amount of energy is unavailable, we again conclude that material particles cannot reach the speed of light.

The Correspondence Principle

Show your students that when small speeds are involved, the relativity formulas reduce to the everyday observation that time, length, and the masses of things do not appear any different when moving. That's because the differences are too tiny to detect.

Answers and Solutions for Chapter 35

Reading Check Questions

1. Speed relative to the ground is 61 km/h.
2. Speed relative to the Sun is only slightly changed.
3. Fitzgerald hypothesized that the experimental apparatus shrunk.
4. Einstein rejected the notion that space and time are independent of each other.
5. The laws of nature are the same in uniformly moving reference frames.
6. The speed of light in free space is constant.
7. The distances are the same as seen in the rocket ship frame of reference.
8. The light traveling to the rear of the compartment moves a shorter distance.
9. Three dimensions for space, a forth dimension for time.
10. You'll share the same spacetime if you're at rest relative to each other. If there is relative motion between you, you'll not share the same spacetime.
11. What is special is that the ratio is a constant, the speed of light.
12. A longer path requires a longer time.
13. The stretching of time is called *time dilation*.
14. Gamma = $\sqrt{1\text{-}v^2/c^2}$, which is never less than 1 because v^2/c^2 is always positive.
15. Measurements of time differ by 1.15 at half the speed of light. At 99.5%, time measurements differ by a factor of 10.
16. Evidence for time dilation comes from many experiments performed in labs and on airplane flights, as well as the accuracy of GPS systems that depend on time dilation.
17. Coming toward you, flashes appear more frequently.
18. Frequency increases, while speed remains constant.
19. For the moving-away source the flashes are seen twice as long in duration.
20. While the stay-at-home twin experiences a single frame of reference, the traveling twin experiences two, one going and one returning.
21. Maximum would be when speeds $v = c$, then $c_1c_2/c^2 = 1$. Smallest would be zero when either v_1 or v_2 equal zero.
22. The rule is consistent with light speed being constant, for no values can add to be greater than c.
23. One obstacle is the energy required, another is shielding the radiation encountered.
24. There is no universal standard of time!
25. Thrown at 99.5% the speed of light, the meterstick would be one-tenth its original length.
26. The same stick traveling perpendicular to velocity would not change in length, because length contraction occurs only in the direction of travel.
27. In your own frame of reference, no local length contraction would occur.
28. At the speed of light, momentum would be infinite.
29. High speed particles exhibit a less-bent trajectory due to relativity.
30. The amount of mass conversion in nuclear reactions is millions of times greater than in chemical reactions.
31. Fissioning a single uranium nucleus produces 10 million times as much energy as combustion of a single carbon atom.
32. Yes, $E = mc^2$ applies to chemical as well as nuclear reactions.
33. $E = mc^2$ tells us that mass is congealed energy.
34. The correspondence principle predicts that for low speed the equations of relativity reduce to the classical equations.
35. The relativity equations hold for everyday speeds, and appreciably differ from classical equations only for speeds near the speed of light.

Think and Do

36. Open ended.

Think and Solve

37. Frequency and period are reciprocals of one another (Chapter 19). If the frequency is doubled, the period is halved. For uniform motion, one senses only half as much time between flashes that are doubled in frequency. For accelerated motion, the situation is different. If the source gains speed in approaching, then each successive flash has even less distance to travel and the frequency increases more, and the period decreases more as well with time.

38. We must use the formula

$$V = \frac{v_1 + v_2}{1 + \frac{v_1 v_2}{c^2}}.$$

Putting $v_1 = 0.80\,c$ and $v_2 = 0.50\,c$, we get $V = (0.80\,c + 0.50\,c)/[1 + (0.80)(0.50)] = 1.30\,c/1.40 = 0.93\,c$. The drone moves at 93% of the speed of light relative to the Earth.

39. $V = \dfrac{c + c}{1 + \frac{c^2}{c^2}} = \dfrac{2c}{1 + 1} = c$

40. The factor $\gamma = 1/\sqrt{[1 - (v^2/c^2)]} = 1/\sqrt{[1 - (0.99)^2]} = 1/\sqrt{(1 - 0.98)} = 1/\sqrt{0.02} = 7.1$. Multiplying 5 min by γ gives 35 min. According to your watch, the nap lasts 35 minutes.

41. In the previous problem we see that for $v = 0.99\,c$, γ is 7.1. The momentum of the bus is more than seven times greater than would be calculated if classical mechanics were valid. The same is true of electrons, or anything traveling at this speed.

42. Gamma, as in the previous two problems, is 7.1. So you measure the length of the bus to be 70 ft /7.1 = 9.9 ft. (Remember, *divide* by γ for length contraction.)

43. Gamma at $v = 0.10\,c$ is $1/\sqrt{[1 - (v^2/c^2)]} = 1/\sqrt{[1 - (0.10)^2]} = 1/\sqrt{(1 - 0.01)} = 1/\sqrt{0.99} = 1.005$. You would measure the passenger's catnap to last 1.005 (5 m) = 5.03 min.

44. Gamma at $v = 0.9999\,c$ is $1/\sqrt{[1 - (v^2/c^2)]} = 1/\sqrt{[1 - (0.9999)^2]} = 1/\sqrt{0.0002} = 70.71$. So you would measure the length of the bus to be 70 ft/70.71 = 0.99 ft.

45. Gamma at $v = 0.5\,c$ is $1/[\sqrt{1 + (v^2/c^2)}] = 1/[\sqrt{1 - 0.5^2}] = 1/[\sqrt{1 - 0.25}] = 1/\sqrt{0.75} = 1.15$. Multiplying 1 h of taxi time by γ gives 1.15 h of Earth time. The drivers' new pay will be (10 hours)(1.15) = 11.5 stellars for this trip.

46. When 1 kg of uranium-235 undergoes fission, the loss of mass is 1 g or 0.001 kg. We note here that c^2 is 9.0×10^{16} J/kg (recall that 1 J = 1 kg m^2/s^2). So the energy released by this loss of mass is $E = mc^2$ = (0.001 kg)(9.0×10^{16} J/kg) = 9.0×10^{13} J, or 9.0×10^{7} MJ (megajoules). Multiply this energy by $0.03 per MJ and you find that the energy in one gram of matter is worth $2.7 million dollars! (Note: Three cents per MJ corresponds to about 11 cents per kWh.)

Think and Rank

47. C, B, A.

48. C, B, A.

Think and Explain

49. Only accelerated motion, and not uniform motion, can be sensed. You could not detect your motion when traveling uniformly, but accelerated motion could be easily detected by observing that the surface of the water in a bowl is not horizontal.

50. (a) The ball is moving faster relative to the ground when the train is moving (forward).
(b) The ball moves at the same speed relative to the freight car whether the train is moving or not.

51. In the case of a light beam shining from atop a moving freight car, the light beam has the same speed relative to the ground as it has relative to the train. The speed of light is the same in all reference frames.

52. When you drive down the highway you are moving through space and also "through time."

53. The *average* speed of light in a transparent medium is less than c, but in the model of light discussed in Chapter 26, the photons that make up the beam travel at c in the void that lies between the atoms of

the material. Hence the speed of individual photons is always *c*. In any event, Einstein's postulate is that the speed of light in *free* space is invariant.

54. It meets them at *c*.

55. No energy or information is carried perpendicular to the swept beam.

56. Yes. No *thing* can move faster than light, but the spot on the face of the tube is not a "thing." No material thing is moving from one spot to the other. The electrons causing the spot, however, move at less than the speed of light. (Also, no information can travel faster than light, but the spot on the screen is not carrying information from one place to another.)

57. It's all a matter of relative velocity. If two frames of reference are in relative motion, events can occur in the order AB in one frame and in the order BA in the other frame. (See the next exercise.)

58. If by now you expect relativity to be surprising, you might want to say yes. But the answer is no. A time difference between two events at the same place in one frame of reference (such as two readings on a given clock) is multiplied by a time-dilation factor to get the time difference in another frame. Similarly, the distance between two points (or two events) at the same time in one frame of reference (for instance, the distance between the ends of a meterstick) is multiplied by a Lorentz-contraction factor to get the distance in another frame of reference. But if the two events are at the same place *and* the same time in one frame, they are also coincident and simultaneous in all frames of reference, for zero time difference multiplied by any factor is still zero, and zero distance multiplied by any factor is still zero. This much of common sense is preserved by relativity!

59. Yes. If the distance the rocket ship moves forward in the time it takes the light to reach the rear is greater than the distance by which the light bulb was shifted, the outside observer will still see the light getting to the rear first. You can see this, too, by considering such a tiny displacement of the light bulb that it makes hardly any difference to the outside observer, who still sees the light reaching the rear first. But to the inside observer, the light will reach the front first no matter how tiny the displacement.

60. There is an upper limit on speed, but no upper limit on the factor we call gamma, and accordingly no upper limit on either the momentum or kinetic energy of a particle. Since momentum is given by $p = \gamma mv$, p can grow without limit as γ grows without limit, even though m is constant and v is limited. Similarly, kinetic energy can grow without limit. As p gets larger, so does KE.

61. When we say that light travels a certain distance in 20,000 years we are talking about distance in our frame of reference. From the frame of reference of a traveling astronaut, this distance may well be far shorter, perhaps even short enough that she could cover it in 20 years of her time (traveling, to be sure, at a speed close to the speed of light). In a distant future, astronauts may travel to destinations many light years away in a matter of months in their frame of reference.

62. Yes. If a person travels at relativistic speeds—that is, very close to the speed of light—distances as far as those that light takes thousands of years to travel (in our frame of reference) could be traversed well within an average lifetime. This is because distance depends on the frame of reference in which it is measured. Distances that are quite long in one frame of reference may be quite short in another.

63. A twin who makes a long trip at relativistic speeds returns younger than his stay-at-home twin sister, but both of them are older than when they separated. If they could watch each other during the trip, there would be no time where either would see a reversal of aging, only a slowing or speeding of aging. A hypothetical reversal would result only for speeds greater than the speed of light.

64. Yes, as strange as it sounds, it is possible for a son or daughter to be biologically older than his or her parents. Suppose, for example, that a woman gives birth to a baby and then departs in a high-speed rocket ship. She could theoretically return from a relativistic trip just a few years older than when she left to find her "baby" 80 or so years older.

65. If you were in a high-speed (or no speed) rocket ship, you would note no changes in your pulse or in your volume. This is because the velocity between the observer, that is, yourself, and the observed is zero. No relativistic effect occurs for the observer and the observed when both are in the same reference frame.

66. In contrast to the previous exercise, if you were monitoring a person who is moving away from you at high speed, you would note both a decrease in pulse and in volume. In this case, there is very definitely a velocity of the observed with respect to the observer.

67. Narrower as well.

68. Your friend sees your watch running as slowly as you see hers.

69. Yes, although only high speeds are significant. Changes at low speeds, although there, are imperceptible.

70. Making such an appointment would not be a good idea because if you and your dentist moved about differently between now and next Thursday, you would not agree on what time it is. If your dentist zipped off to a different galaxy for the weekend, you might not even agree on what day it is!

71. The density of a moving body is measured to increase because of a decrease in volume for the same mass.

72. Elliptical, longer in the direction of motion than perpendicular to that direction. The Lorentz contraction shortens the long axis of the elliptical shape to make it no longer than the short axis.

73. For the speed of light equation, v is c. Before relativity, c might have one value in one frame of reference and a different value in another frame. It depended on the motion of the observer. According to relativity, c is a constant, the same for all observers.

74. Both the frequency and the wavelength of the light change (and, of course, its direction of motion changes). Its speed stays the same.

75. The stick must be oriented in a direction perpendicular to its motion, unlike that of a properly-thrown spear. This is because it is traveling at relativistic speed (actually $0.87c$) as evidenced by its increase in momentum. The fact that its length is unaltered means that its long direction is not in the direction of motion. The thickness of the stick, not the length of the stick, will appear shrunken to half size.

76. The stick will appear to be one-half meter long because for it to have a momentum equal to $2mv$, its speed must be $0.87c$.

77. As with the stick in the preceding exercise, the momentum of the rocket ship will be twice the classical value if its measured length is half its normal length.

78. As speed increases, the increase in momentum is not linear, but increases by γ. Near the speed of light the percentage of momentum increase can be much greater than the percentage of speed increase.

79. For the moving electron, length contraction reduces the apparent length of the 2-mile long tube. Because its speed is nearly the speed of light, the contraction is great.

80. If you were traveling with the electrons, no matter how fast they and you were moving, you would see nothing out of the ordinary. In your frame of reference, the electrons would just be "sitting there." (The v in γ would be zero.) They would have zero momentum and their normal rest energy mc^2. But you would see the target coming toward you at close to the speed of light. (The *relative* speed of two frames of reference is the same for observers in both frames. Someone on the ground measures a certain speed of the electrons moving toward the target. Traveling with the electrons, you measure the same speed of the target moving toward you.)

81. To make the electrons hit the screen with a certain speed, they have to be given more momentum and more energy than if they were nonrelativistic particles. The extra energy is supplied by the power utility. The electric bill is more!

82. The correspondence principle just makes good sense. If a new idea is valid, then it ought to be in harmony with the areas it overlaps. If it doesn't, then either the areas themselves are suspect, or the new idea is suspect. If a new theory is valid, it must account for the verified results of the older theory, whether the theory is or isn't in the field of science.

83. $E = mc^2$ means that energy and mass are two sides of the same coin, mass-energy. The c^2 is the proportionality constant that links the units of energy and mass. In a practical sense, energy and mass are one and the same. When something gains energy, it gains mass. When something loses energy, it loses mass. Mass is simply congealed energy.

84. Both have both the same mass and, hence the same energy.

85. Yes, for it contains more potential energy, which has mass.

86. Just as time is required for knowledge of distant events to reach our eyes, a lesser yet finite time is required for information on nearby things to reach our eyes. So the answer is yes, there is always a finite interval between an event and our perception of that event. If the back of your hand is 30 cm from your eyes, you are seeing it as it was one-billionth of a second ago.

87. Open-ended.

Think and Discuss

88. The effects of relativity become pronounced only at speeds near the speed of light or when energies change by amounts comparable to mc^2. In our "non-relativistic" world, we don't directly perceive such things, whereas we do perceive events governed by classical mechanics. So the mechanics of Newton is consistent with our common sense, based on everyday experience, while the relativity of Einstein is not consistent with common sense. Its effects are outside our everyday experience.

89. Michelson and Morley considered their experiment a failure in the sense that it did not confirm the expected result, namely that differences in the velocity of light would be encountered and measured. No such differences were found. The experiment was successful in that it widened the doors to new insights in physics.

90. Yes, for example, a distant part of a beam sweeping the sky. What it doesn't allow is energy or particles or the transmission of information to exceed c.

91. No, for speed and frequency are entirely different from each other. Frequency, how frequent, is not the same as speed, how fast.

92. The moving points are not material things. No mass or no information can travel faster than c, and the points so described are neither mass nor information. Hence, their faster motion doesn't contradict special relativity.

93. Experimental evidence in accelerators has repeatedly shown that as more and more energy is put into a particle, the particle never reaches the speed of light. Its momentum grows without limit, but not its speed. As the speed of light is approached, the momentum of the particle approaches infinity. There is an infinite resistance to any further increase in momentum, and hence speed. So c is the speed limit for material particles. (Kinetic energy likewise approaches infinity as the speed of light is approached.)

94. The acid bath that dissolved the latched pin will be a little warmer, and a little more massive (in principle). The extra potential energy of the latched pin is transformed into a bit more mass.

95. The mass of the radioactive material decreases, but the mass of the lead container increases. So no net mass change results. There has been a redistribution of energy within the chunk-container system, but no change in total energy and therefore no change in mass.

96. At 0.995c the muon has ten times as much time, or twenty-millionths of a second, to live in our frame of reference. From the stationary Earth, the muon's "clock" is running ten times slower than Earth clocks, allowing sufficient time to make the trip. (Interestingly, from the muon's frame of reference, the distance to Earth is contracted by ten times, so it has sufficient time to get there.)

97. There are two enormous obstacles to the practice of "century hopping" at this time. First, although we have the means to easily accelerate atomic particles to speeds approaching the speed of light, we as yet have no means of propelling a body as massive as an inhabited rocket to relativistic speeds. Second, if we did, we currently have no way of shielding the occupants of such a rocket from the radiation that would result from the high-speed collisions with interstellar matter.

98. Kierkegaard's statement, "Life can only be understood backwards; but it must be lived forwards.," is consistent with special relativity. No matter how much time might be dilated as a result of high speeds, a space traveler can only effectively slow the passage of time relative to various frames of reference, but can never reverse it—the theory does not provide for traveling backward in time. Time, at whatever rate, flows only forward.

99. Rather than say matter can neither be created nor destroyed, it is more accurate to say that mass-energy can neither be created nor destroyed.

100. The decrease is given by $\Delta L = L_0/\gamma$, which is enormously tiny. For speeds near the speed of light, however, decrease in length cannot be ignored.

36 General Relativity

The chapter opens with the now familiar GPS device, and a photo of the NGC 6744 galaxy, which is an intermediate between a barred and unbarred spiral galaxy. This is what our galaxy may look like from afar. And between these photos is Richard Crowe, the late professor and astronomer at the University of Hawaii at Hilo—where "telescope heaven" sits atop Mauna Kea. The bottom photo is my niece Stephanie Hewitt.

The personality profile continues with Albert Einstein.

The three most important theories of physics in the 20th century are the special theory of relativity (1905), the general theory of relativity (1915), and the theory of quantum mechanics (1926). The first and third theories have been focal points of interest and research since their inceptions, yet the second, general relativity, has been largely ignored by physicists—until recently. New interest stems from many of the new astronomical phenomena discovered in recent years—pulsars, quasars, compact X-ray sources, black holes, all of which have indicated the existence of very strong gravitational fields that could be described only by general relativity. The move is now on to a quantum theory of gravitation that will agree with general relativity for macroscopic objects.

One important point to make is that relativity doesn't mean that everything is relative, but rather that no matter how you view a situation, the physical outcome is the same. There is a general misconception about this. Point out that in special and general relativity that fundamental truths of nature look the *same* from every point of view—not different from different points of view!

We measure velocities with rods and clocks; rods for space, and clocks for time. In our local environment, rods and clocks are no different when in different locations. In a larger environment in accord with general relativity, however, we find that space and time are "warped." Rods and clocks at appreciably different distances from the center of the Earth are affected differently. Accordingly, gravitation can be seen as the effects of a curved space-time such that the motion of objects subject to what we call the gravitational force is simply the result of objects moving freely through curved space-time.

So the theories of special and general relativity, quantum mechanics, nuclear power, and the theory of the Big Bang, computers, and DNA are products of the Twentieth Century. In the later part of this 21st century, what will power automobiles? How will electricity be produced? What will the climate be? How will wars be fought? What changes will occur in national borders? We don't have the answers to these questions. What we can do is to educate our students to better orient, anticipate, think, decide, and to act. What they most need to learn most is the process of learning itself.

In my student days we had to think when using slide rules. The decimal point was not given as it is with calculators. Do today's students learn to solve problems, or search for solutions on the internet? Tablets are a mixed blessing at best.

Getting back to the chapter, gravitational lensing is a consequence of general relativity. The gravity of massive objects distorts the fabric of space-time and thereby the pathways of light rays passing the objects. The amount of this bending depends on the mass of the object. By measuring the bending and

having a measure of how much visible matter the object possesses, investigators can infer how much dark matter must also be present in the object.

I presented Figure 36.8 as a Figuring Physics in the May 2005 issue of *The Physics Teacher* magazine, where it gained attention. The question arose as to whether the light would fall twice the distance the hypothetically same-speed ball would fall in the same time. The essence of the equivalence principle, after all, is that what happens in a uniform gravitational field duplicates what happens in an accelerated frame of reference in field-free space. So dropped balls and light move the same in a uniform gravitational field as in an accelerated frame of reference. The Earth's field, however, over a small region, is only approximately uniform—not exactly so for it is an inverse-square field. For nonrelativistic objects like dropped balls, the difference is inconsequential. Does it matter for light? Does light near the Earth, even in a tiny region, "sense" that it is moving in a central inverse-square gravitational field? And in accordance with Einstein's theory, does it "fall" twice as far as in an accelerated frame? So in the hypothetical experiment of Figure 36.8, light would fall 4.9 m in 1 s in a frame accelerating with acceleration g in empty space. But from a rest frame of reference in Earth's gravitational field, would it instead fall 9.8 m in 1 second? Me thinks not.

Einstein applied his thinking to the universe. More recently, Carl Sagan did the same. As Richard Dawkins asks: "Was Carl Sagan a religious man? He was so much more. He left behind the petty, parochial, medieval world of the conventionally religious; left the theologians, priests and mullahs wallowing in their small-minded spiritual poverty. He left them behind, because he had so much more to be religious about. They have their Bronze Age myths, medieval superstitions and childish wishful thinking. He had the universe."

I do not have a suggested lecture presentation for this chapter, and welcome ideas from you that I can incorporate into future printings of this manual.

Next-Time Questions:
• Gravitational Lens
• General Relativity Test
• General Relativity

Hewitt-Drew-It Screencasts: •*General Relativity* •*Principle of Equivalence*

Answers for Chapter 36

Reading Check Questions

1. The principle difference is acceleration in the general theory.
2. Motion of the dropped ball will be the same in both situations.
3. What is equivalent is observations made in an accelerated frame of reference are indistinguishable from observations made in a Newtonian gravitational field.
4. Both bend downward by the same amount in the same time.
5. Only during an eclipse can the stars somewhat behind the Sun be viewed.
6. Strong gravitation slows time.
7. The slower clock is the one on the shore of Lake Michigan.
8. A lower frequency is seen in a spectral line of light from the Sun.
9. We see time slowing.
10. Mercury is in the strongest part of Sun's gravitational field because it's closest.
11. Newton's law of gravity is valid where the gravitational field is relatively weak.
12. Along a radius the stick is not moving parallel to its length, so the meterstick undergoes no length contraction.
13. When rotating, the circumference undergoes length contraction, whereas the diameter does not.
14. Mass produces warps in the geometry of spacetime.
15. A change in motion produces gravitational waves.
16. Gravitational waves, like light, take 10 years to travel a distance of 10 light years.
17. Gravitational waves are difficult to detect because of their weakness.
18. Einstein's gravitation does not invalidate Newton's gravitation for nominal gravitational fields. For huge fields, like near a black hole, Einstein's gravity better describes the physics.
19. Newtonian physics indeed was paramount in getting humans to the Moon.
20. Newtonian physics links with quantum theory where the domain is massive and large, and with relativity theory where speeds are low compared with the speed of light and the gravitational fields aren't relatively strong.

Think and Explain

21. The reference frames of special relativity are of uniform motion—constant velocity. The reference frames of general relativity include accelerated frames.

22. In accord with the principle of equivalence, she cannot discern between accelerated motion and gravitation. The effects of each are identical. So unless she has other clues, she will not be able to tell the difference.

23. When in orbit, an astronaut, although in the grip of Earth gravity is weightless because of no support force (as explained back in Chapter 9). Both the astronaut and the spaceship are in free fall together.

24. You would feel as on Earth if the spaceship accelerates at Earth *g*, or your spaceship rotates at a rate that causes a centripetal acceleration of *g*.

25. The separation distance of two people walking north from the Earth's equator decreases, and if they continue to the North Pole their separation distance will be zero. At the North Pole, a step in any direction is a step south!

26. Bending due to gravity isn't noticed only because it is negligible for short distances.

27. We don't notice the bending of light by gravity in our everyday environment because the gravity we experience is too weak for a noticeable effect. For distances used by surveyors, a beam of light is the best approximation of a straight line known.

28. Practically speaking, and for short distances, we say that a laser beam of light *defines* a straight line.
29. Agree. Starlight bends whether or not the Moon obstructs our view of it. The role of the eclipse is simply to better see the bending effect by comparing displacement of stars on the other side of the Sun.

30. Mercury's mass is much too small for observation of this effect.

31. Distortion of the Sun at sunset is due to atmospheric refraction, which doesn't occur on the Moon due to its absence of an atmosphere. Gravitational deflection of light is too slight to be seen grazing the Moon or the Earth.

32. A beam of light traveling horizontally for one second in a uniform gravitational field of strength 1 g will fall a vertical distance of 4.9 meters, just as a baseball would. This is providing it remains in a 1-g field for one second, for it would travel 300,000 kilometers during this second, nearly 25 Earth diameters away, and well away from the 1-g field strength of the Earth's surface (unless it were confined to the 1-g region as shown in Figure 36.8, with mirrors). If light were to travel in a 1-g region for two seconds, then like a baseball, it would fall $1/2gt^2$ = 19.6 meters.

33. The change in energy for light is evidenced by a change frequency. If the energy of light is lowered, as in traveling against a strong gravitational field, its frequency is lowered, and the light is said to be gravitationally red shifted. If the energy of the light is increased, as when falling in a gravitational field, then the frequency is increased and the light is blue shifted.

34. The clock will run slower at the bottom of a deep well than at the surface because in going down the well, we are moving in the direction that the gravitational force acts, and this results in a slowing of clocks. More correctly we say that the clock is moving toward a lower gravitational potential. (Actually, decrease in gravitational potential, only hinted at in this chapter, results in slowing of the clock.)

35. Events on the Moon, as monitored from the Earth, run a bit faster and are slightly blue shifted. Even though signals escaping the Moon are red shifted in ascending the Moon's gravitational field, they are blue shifted even more in descending through Earth's stronger g field, resulting in a net blue shift.

36. The gravitational field intensity will increase on the surface of a shrinking star because the matter that produces the field is becoming more compact and more localized. This is easiest to see by considering the force on a body of mass m at the surface of the star of mass M via Newton's equation, $F = GmM/d^2$, where the only term that changes is d, which diminishes and therefore results in an increasing F.

37. It will run slightly slower. For observers on Earth, this is because moving a clock from a pole to the equator is moving it in the direction of the centrifugal force, which slows the rate at which clocks run (the same as if it were moving in the direction of a gravitational force). For observers outside in an inertial frame, the slowing of the clock at the equator is an example of time dilation, an effect of special relativity caused by the motion of the clock. (The situation is much like that shown in Figure 36.9.)

38. At the top of the mountain you age faster (see Figure 36.10).

39. Going up in a building is going in a direction opposite to the direction of the gravitational force, and this speeds up time. The person concerned about living a tiny bit longer should live on the ground floor. Strictly speaking, people who live in penthouses live faster lives.

40. Time would run slower at the edge.

41. The photons of light are climbing against the gravitational field and losing energy. Less energy means less frequency. Your friend sees the light red-shifted. The frequency she receives is less than the frequency you sent.

42. Light emitted from the star is red-shifted. This can be understood as the result of gravity slowing down time on the surface of the star, or as gravity taking energy away from the photons as they propagate away from the star.

43. The astronaut falling into the black hole would see the rest of the universe blue shifted. The astronaut's time scale is being slowed, which makes time scales elsewhere look fast to the astronaut. The blue shift can also be understood as the result of the black hole's gravity adding energy to photons that "fall" toward the black hole. The added energy means greater frequency.

44. There are various ways to "see" black holes. If it is the partner of a visible star, we can see its gravitational effect on the visible star's orbit. We could see its effect on light that passes close enough to be deflected but not close enough to be captured. We can see radiation emitted by matter as it is being sucked into a black hole (before it crosses the horizon to oblivion). In the future, perhaps, we will detect gravitational radiation emitted by black holes as they are being formed.

45. Yes. If the star is massive enough and concentrated enough, its gravity could be strong enough to make light follow a circular path. This is what light does at the "event horizon" of a black hole.

46. Mercury follows an elliptical path in its orbit about the Sun, with its perihelion in a stronger part of the Sun's gravitational attraction than its aphelion. If Mercury followed a circular orbit, then there would be no variation of the Sun's gravitational attraction in its orbit.

47. Agree, just as a step in any direction from the North Pole is a step south.

48. Yes. For example, place the Sun just outside one of the legs in Figure 36.14.

49. Binary stars that move about a common center of mass radiate gravitational waves, just as do all accelerating masses.

50. Gravitational waves are extremely long waves.

51. Oscillating mass (or, more generally, accelerated mass) is the mechanism for emission of gravitational waves, just as oscillating or accelerated charge is the mechanism for emission of electromagnetic waves. When it is absorbed, a gravitational wave can set mass into oscillation, just as an absorbed electromagnetic wave can set charge into oscillation. (Scientists seeking to detect gravitational waves try to detect tiny oscillations of matter caused by the absorption of the waves. See Figure 36.16.)

52. Einstein's theory of gravitation predicts the same results as Newton's theory of gravitation in weak gravitational fields such as those of the solar system. In weak fields, Einstein's theory overlaps, corresponds, and gives the same results as Newton's theory, and therefore obeys the correspondence principle.

53. The flat universe expands forever.

54. Open-ended.

55. Open-ended.

Think and Discuss

56. If the spaceship is set into rotation, it will spin of its own rotational inertia like a top, once set spinning. An astronaut in the ship experiences a centrifugal force that provides a simulated "gravity." No fuel is consumed to sustain this effect because the centrifugal (or centripetal) force is perpendicular to rotational motion and does no work on the astronaut.

57. Ole Jules called his shot wrong on this one. Drifting in a spaceship through space, whether under the influence of Moon, Earth, or whatever gravitational field, a ship and its occupants are in a state of free fall—hence there is no sensation of up or down. Occupants of a spaceship would feel weight, or sense an up or down, only if the ship were made to accelerate—say, against their feet. Then they could stand and sense that down is toward their feet, and up away from their feet.

58. The light will be red-shifted. The accelerating car is equivalent to a stationary car standing vertically with its rear end down. The light going from the back to the front of the accelerating car behaves just like light going upward away from the surface of a planet. It is gravitationally red shifted.

59. Prudence is older. Charity's time runs slower during the time she is at the edge of the rotating kingdom (see Figure 36.9).

60. We would need a telescope sensitive to very long wavelength radiation such as radio waves. The light from the astronauts would be red shifted to very long wavelength, eventually infinitely long wavelength.

Appendix E
Exponential Growth and Doubling Time

This material, adapted from papers written by the late Al Bartlett, makes a fine lecture, for the material is not only very important, but is fascinating—and very wide in scope. It can nicely follow Chapter 15, after discussion of climate change and continued industrial growth. Or it can be coupled to a discussion of radioactive half-life as treated in Chapter 33. Or it can be treated in any break—following an exam, perhaps, or on any day that lends itself to a departure from chapter material. As Al admonished, the greatest shortcoming of the human race is our inability to understand the exponential function. I might add, to understand the implications of the exponential function.

The concept of growth rate can be expressed in simple steps:

Step 1: (new amount) = (old amount) + *k* times (old amount).
Step 2: (new amount) becomes (old amount).
Step 3: Keep repeating.

That's it. The mathematics is just arithmetic. Use positive *k* for growth, and negative *k* for decay.

A beginning application is simple 10% annual interest on each dollar that in previous years was in vogue in a savings account. At the end of the 1st year, A = 1 + 0.10(1); 2nd year, A = 1.10 + 0.10(1.10); 3rd year, A = 1.21 + 0.10(1.21); and so on. Suppose your savings are silver dollars and the bank charges 10% annual storage fee.

	INTEREST		RENTAL	
Year	Change	Amount	Change	Amount
0		1.00		1.00
1	+0.100	1.10	-0.100	0.90
2	+0.110	1.21	-0.090	0.81
3	+0.121	1.33	-0.081	0.73
4	+0.133	1.46	-0.073	0.66
5	+0.146	1.61	-0.066	0.59
6	+0.161	1.77	-0.059	0.53
7	+0.177	1.95	-0.053	0.48
8	+0.195	2.14	-0.048	0.43
9	+0.214	2.36	-0.043	0.39
10	+0.236	2.59	-0.039	0.35
20	+0.612	6.73	-0.014	0.12

Note that in 7 years at a 10% rate the amount just about doubles for positive *k* and just about halves for negative *k*.

It is customary to use the decay halving time (half-life) of processes such as radioactive decay as a property of the decaying elements. There is nothing special about doubling-halving time. Tripling-thirding or 3/2ing—2/3ing, or any factor and its reciprocal could be used. As the number of time intervals increases, the process approaches continuity, which leads to the exponential e^{kt}.

The formula for doubling time in the text appears without derivation, which is likely beyond the scope of a nonscience physics class. Its derivation is as follows: Exponential growth may be described by the equation

$$A = A_o e^{kt} .$$

where k is the rate of increase of the quantity A_o. We can re-express this for a time T when $A = 2A_o$,

$$2A_o = A_o e^{kT} .$$

If we take the natural logarithm of each side we get

$$\ln 2 = kT \quad \text{where } T = \frac{\ln 2}{k} = \frac{0.693}{k} .$$

If k is expressed in percent, then

$$T = \frac{69.3}{\%} \sim \frac{70}{\%} .$$

When percentage figures are given for things such as interest rates, population growth, or consumption of nonrenewable resources, conversion to doubling time greatly enhances the meaning of these figures.

Next-Time Questions:
• Growing Beanstalk
• Paper Fold

Hewitt-Drew-It Screencast: •*Exponential Growth*

ANSWERS TO APPENDIX E (Exponential Growth and Doubling Time)

1. Half covered on day 29; one-quarter covered on day 28—the coverage doubles each day.

2. A dollar loses half its value in one doubling time of the inflationary economy; this is 70/3.5% = 20 years.

3. At a steady inflation rate of 3.5%, the doubling time is 70/3.5% = 20 years; so every 20 years the prices of these items will double. This means the $50 dollar theatre ticket in 20 years will cost $100, in 40 years will cost $200, in 60 years will cost $400. The $500 coat will similarly jump each 20 years to $1000, $2000, and $4000. For a $50,000 car the 20-year jumps in price give $100,000, $200,000, and $400,000. For a $500,000 home, the 20-year jumps in price are $1,000,000, $2,000,000, and $4,000,000!

4. For a 5% growth rate, 42 years is three doubling times (70/5% = 14 years; 42/14 = 3). Three doubling times is an eightfold increase. So in 42 years the city would have to have 8 similar sewage treatment plants to service 8 times the population.

5. All things being equal, doubling of food for twice the number of people simply means that twice as many people will be eating, and twice as many will be starving as are starving now.

6. Doubling one penny for 30 days yields a total of $10,737,418.23.

7. On the 30th day your wages will be $5,368,709.12, which is one penny more than the $5,368,709.11 total from all the preceding days.

8. It is generally acknowledged that if the human race is to survive, even from an overheating of the world standpoint, while alleviating even part of the misery that afflicts so much of humankind, the present rates of energy consumption and population growth must be reduced. The chances of achieving reduced growth rates are better in a climate of scarce energy than in a climate of abundant energy. We must hope that by the time we have fusion under control, we will have learned to optimize our numbers and to use energy more wisely.