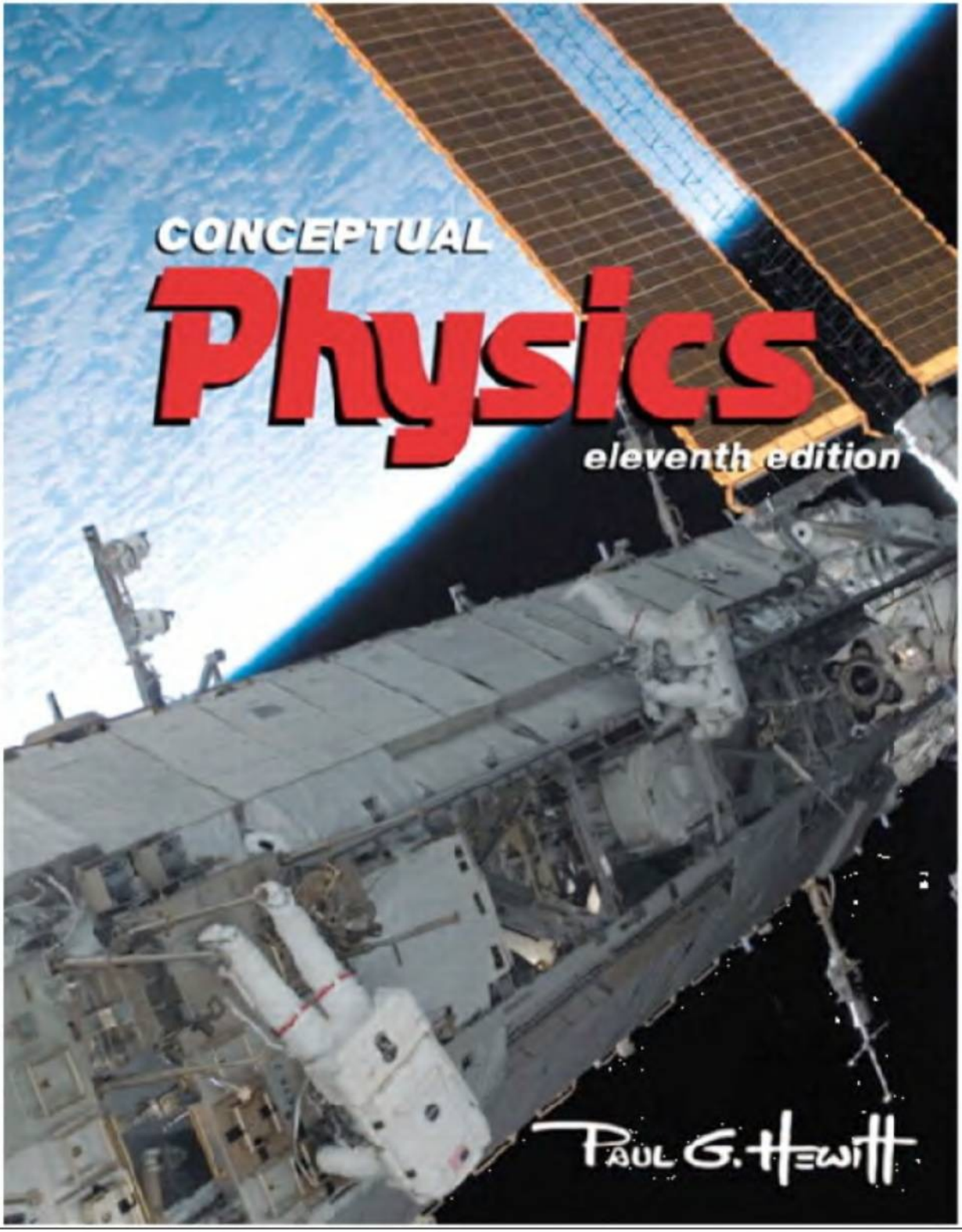
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eleventh edition
PAUL G. HEWITT

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- To Lillian Lee Hewitt, Kenneth W. Ford, and the memory of Ernie Brown

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THE CONCEPTUAL PHYSICS Photo Album

Conceptual Physics is a very personal book, reflected in its many photographs of family and friends, beginning with three people to whom this edition is dedicated—my mentor Ken Ford, my wife Lillian, and my lifelong friend Ernie Brown. A personal profile of Ken, former CEO of the American Institute of Physics, opens Chapter 20 and indicates his passion for gliding. Ken's other passion, teaching with Germantown Academy high-school students in Pennsylvania, is shown on page 620. Lillian is shown on page 1 and various other photos scattered throughout the book. She holds our colorful pet conure, Sneezlee, on page 478. Ernie Brown, Conceptual Physics logo designer, is featured in the photo opener to Chapter 8, with a cartoon likeness in Appendix D, Figure D.7. Sadly, Ernie died in 2008 at the age of 82.

The First Edition of *Conceptual Physical Science* was dedicated to resourceful Charlie Spiegel, shown on page 462. Although Charlie passed away in 1996, his personal touch carries over to this book.

Part opener photos are of family and friends. The book begins on page xxiv with my great nephew Evan Suchocki (pronounced Su-hock-ee, with silent c) holding a pet chickie while sitting on my lap. Part One on page 17 is my Hawaii friend Chiu Man Wu's daughter Andrea, when she was four years old (repeated on pages 120 and 461). Chiu Man is on page 301. Part Two on page 195 is an Egyptian four-year old, Nour Tawfik Diab, niece of friend Mona El Tawil-Nassar (on page 398). Then from Italy, Part Three opens on page 267 with four-year old, Francesco Ming Giovannuzzi, grandson of friends Keith and Tsing Bardin. Keith took several of this book's photos, including Tsing on page 228. Part Four, page 266, is my grandson Alexander Hewitt. Part Five, page 381, is my granddaughter Megan, daughter of Leslie and Bob Abrams. Part Six, page 455, is Lillian's nephew, Joshua Lee. Part Seven, page 565, is Lillian's cousins, Sharon Yee and Leslie Chew. My granddaughter Grace Hewitt begins Part Eight on page 619.

To celebrate this Eleventh Edition, chapter-opening photographs are of teacher friends and colleagues, mostly in their classrooms demonstrating physics typical of the chapter material. Their names, too numerous to list here, appear with their photos.

City College of San Francisco friends and colleagues open Chapters 2, 3, 13, 21, 26, 32, and 33. On page 92 we see Will Maynez with the air track he designed and built, and again burning a peanut on page 299. Diana Lininger Markham, physics department chairperson, is shown on page 75.

Physics instructor friends from other colleges and universities include emeritus University of Hawaii Walter Steiger, profiled in Chapter 30, and again shown on page 588. Mary Beth Monroe demonstrates torque on page 129. Retired physics instructor Evan Jones, in addition to opening Chapter 30, shows the promise of LED light bulbs on page 539. Chuck Stone shows an energy ramp on page 174. Peter Hopkinson, who opens Chapter 28, tosses eggs on page 98. John Hubisz, who opens Chapter 12, appears in the entropy photo on page 327.

Physics teacher friends from high schools include Chicago's finest, Marshall Ellenstein, now retired, who swings the water-filled bucket on page 136 and walks barefoot on broken glass on page 244. His profile begins Chapter 29. Marshall, a longtime contributor to this book has produced the DVDs of my lectures, in San Francisco *(Conceptual Physics Alive!—The San Francisco Years)* and in Hawaii *(Conceptual Physics Alive!)*. He is presently editing 1982 classroom footage saved from CCSF archives by librarian Judith Bergman. Other teachers from Illinois are Ann Brandon, page 250, and Tom Senior, page 378. Dean Baird, author of *Conceptual Physics* and *Conceptual Physical Science* lab manuals is shown and profiled in Chapter 17.

Family photos begin with the touching photo on page 72 of son Paul and his daughter Grace. On page 79 is another photo that links touching to Newton's third law; my brother Steve with his daughter Gretchen at their coffee farm in Costa Rica. Steve's son Travis is seen on page 144, and his oldest daughter Stephanie on page 215. My son Paul is again shown on pages 287 and 319. Daughter-in-law Ludmila Hewitt holds crossed Polaroids on page 523. The endearing girl on page 202 is my daughter Leslie Abrams, earth-science co-author of *Conceptual Physical Science* textbooks. This colorized photo of Leslie has been a trademark of *Conceptual Physics* since the Third Edition. A more recent photo of her with husband Bob is on page 456. Their children, Megan and Emily, along with son Paul's children, make up the colorful set of photos on page 477. Granddaughter Emily is on page 520, and as mentioned, Megan on page 381. Photos of my late son James are on pages 140, 371, and 503. He left me my first grandson, Manuel, seen on pages 219 and 360. Manuel's grandmom, my wife Millie, who passed away in 2004, bravely holds her hand above the active

pressure cooker on page 287. Brother Dave (no, not a twin) and his wife Barbara demonstrate atmospheric pressure on page 251. Their son Dave is on page 418, and grandson John Perry Hewitt is on page 259. Sister Marjorie Hewitt Suchocki, an author and emeritus theologian at Claremont School of Theology, illustrates reflection on page 489. Marjorie's son, John Suchocki, author of *Conceptual Chemistry*, now in its fourth edition, and chemistry co-author of the *Conceptual Physical Science* textbooks, walks fearlessly across hot coals on page 300 (for emphasis, David Willey does the same on page 310). Talented nephew John is also a vocalist and guitarist known as John Andrew in his popular CDs, seen with his guitar on pages 351 and 443. The group listening to music on page 375 are part of John's and Tracy's wedding party; from left to right, late Butch Orr, niece Cathy Candler (on page 124), bride and groom, niece Joan Lucas (on page 35), sister Marjorie, Tracy's parents Sharon and David Hopwood, teachers Kellie Dippel and Mark Werkmeister, and myself.

Photos of Lillian's family include her mom, Siu Bik Lee, who demonstrates solar power on page 295, and her dad Wai Tsan Lee, who shows magnetic induction on page 428. Lillian's niece and nephew, Allison and Erik Wong, dramatically illustrate thermodynamics on page 325.

Personal friends who were my former students begin with Tenny Lim, drawing her bow on page 106, which has appeared in every book since the Sixth Edition. She is presently a rocket engineer at Jet Propulsion Lab in Pasadena and is profiled in Chapter 10. Tenny is seen with husband Mark Clark on page 134. Another of my protégés is rocket-scientist Helen Yan, who develops satellites for Lockheed Martin in Sunnyvale in addition to stints at part-time physics teaching. Her photos and profile open Chapter 16. Helen is again shown on page 511 with Richard Feynman and Marshall Ellenstein. Alexei Cogan demonstrates center of gravity on page 134, and the karate gal on page 87 is Cassy Cosme. On page 140 Cliff Braun is at the far left of my son James in Figure 8.50, with nephew Robert Baruffaldi at the far right.

Three dear friends who go back to my own school days are Dan Johnson on page 315, his wife Sue on page 35 (the first rower in the racing shell), and Howie Brand on page 83. Other cherished friends are Paul Ryan, who drags his finger through molten lead on page 310, and Tim Gardner, demonstrating Bernoulli's principle on page 256. Lori Patterson is electrified on page 399 and her son Ryan resonates on page 359. My science influence from sign-painting days is Burl Grey, page 26 (with a sample sign-painting discussion on page 25). Also from the same era is charismatic and very influential Jacque Fresco, whose profile opens Chapter 8. Larry and Tammy Tunison wear radiation badges on page 582 (Tammy's dogs are on page 301). Suzanne Lyons, co-author of *Conceptual Integrated Science* textbooks poses with her children Tristan and Simone on page 472. Phil Wolf, co-author of the *Problem Solving in Conceptual Physics* book that accompanies this edition, is on page 547. Helping create that book is high school teacher Diane Riendeau, on page 334 (and her son Tim on page 32).

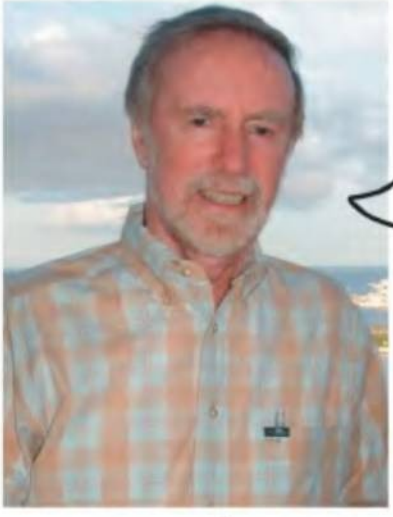
The inclusion of these people who are so dear to me makes *Conceptual Physics* all the more my labor of love.

To the Student

You know you can't enjoy a game unless you know its rules; whether it's a ball game, a computer game, or simply a party game. Likewise, you can't fully appreciate your surroundings until you understand the rules of nature. Physics is the study of these rules, which show how everything in nature is beautifully connected. So the main reason to study physics is to enhance the way you see the physical world. You'll see the mathematical structure of physics in frequent equations, but more than being recipes for computation, you'll see the equations as **guides to thinking**.

I enjoy physics, and you will too — because you'll understand it. So go for comprehension of concepts as you read this book, and if more computation is on your menu, check out *Problem Solving in Conceptual Physics*, the ancillary book by Phil Wolf and me. Your understanding of physics should soar.

Enjoy your physics!



Paul G. Hewitt

To the Instructor

The sequence of chapters in this Eleventh Edition is identical to that of the previous edition. New to this edition are the personality profiles at the outset of every chapter. I was influenced to do this by David Bodanis's popular book, $E = mc^2$, in which the people behind physics discoveries are seen to be so fascinating. So each chapter highlights a scientist, teacher, or historical figure that complements the chapter material. Each chapter also begins with a photo montage of professors, instructors, and teachers, who bring life to physics instruction.

As with the previous edition, Chapter 1, "About Science," begins your course on a high note with coverage on early measurements of the Earth and distances to the Moon and the Sun. It is hoped that the striking photos of wife Lillian surrounded by spots of light on the sidewalk beneath a tall tree will prompt doing the Project at chapter's end that has students investigating the round spot cast by a small hole in a piece of card held in sunlight. And going further to show that simple measurements lead to finding the diameter of the Sun. This project extends to the *Practice Book* and the *Lab Manual*. It's one of my favorites.

Part One, "Mechanics," begins with Chapter 2, which, as in the previous edition, presents a brief historical overview of Aristotle and Galileo, progressing to Newton's first law and to mechanical equilibrium. The high tone of Chapter 1 is maintained as forces are treated before velocity and acceleration. Students get their first taste of physics via a very comprehensible treatment of parallel force vectors. They enter a comfortable part of physics before being introduced to kinematics.

Chapter 3, "Linear Motion," is the only chapter in Part One that is devoid of physics laws. Kinematics has no laws, only definitions, mainly for *speed, velocity,* and *acceleration*—likely the least exciting concepts that your course has to offer. Too often kinematics becomes a pedagogical "black hole" of instruction—too much time for too little physics. Being more math than physics, the kinematics equations can appear to the student as the most intimidating in the book. Although the experienced eye doesn't see them as such, this is how *students* first see them:

$$\varsigma = \varsigma_0 + \delta\mathfrak{z}$$
$$\varsigma = \varsigma_0\mathfrak{z} + \tfrac{1}{2}\delta\mathfrak{z}^2$$
$$\varsigma^2 = \varsigma_0^2 + 2\delta\varsigma$$
$$\varsigma_a = \tfrac{1}{2}(\varsigma_0 + \varsigma)$$

If you wish to reduce class size, display these equations on the first day and announce that class effort for much of the term will be making sense of them. Don't we do much the same with the standard symbols?

Ask any college graduate these two questions: What is the acceleration of an object in free fall? What keeps Earth's interior hot? You'll see where their education was focused, for many more will correctly answer the first question than the second. Traditionally, physics courses have been top-heavy in kinematics with little or no coverage of modern physics. Radioactive decay almost never gets the attention given to falling bodies. So my recommendation is to pass quickly through Chapter 3, making the distinction between velocity and acceleration, and then to move on to Chapter 4, "Newton's Second Law of Motion," where the concepts of velocity and acceleration find their application.

Chapter 5 continues with Newton's third law. The end of the chapter treats the parallelogram rule for combining vectors—first force vectors and then velocity

vectors. It also introduces vector components. More on vectors is found in Appendix D, and especially in the Practice Book.

Chapter 6, "Momentum," is a logical extension of Newton's third law. One reason I prefer teaching it before teaching energy is that students find mv much simpler and easier to grasp than $\frac{1}{2}mv^2$. Another reason for treating momentum first is that the vectors of the previous chapter are employed with momentum but not with energy.

Chapter 7, "Energy," is a longer chapter, rich with everyday examples and current energy concerns. Energy is central to mechanics, so this chapter has the greatest number of exercises (64) in the chapter-end material. Work, energy, and power also get generous coverage in the Practice Book.

After Chapters 8 and 9 (on rotational mechanics and gravity), mechanics culminates with Chapter 10 (on projectile motion and satellite motion). Students are fascinated to learn that any projectile moving fast enough can become an Earth satellite. Moving faster, it can become a satellite of the Sun. Projectile motion and satellite motion belong together.

Part Two, "Properties of Matter," begins with a new chapter on atoms. Chapters on Solids, Liquids, and Gases, are much the same as the previous edition. New applications, some quite enchanting, increase the flavor of these chapters.

Parts Three through Eight continue, like earlier parts, with enriched examples of current technology. New lighting via CFLs and LEDs are introduced in Chapter 23 with more treatment in Chapter 30. The chapters with the fewest changes are Chapters 35 and 36 on special and general relativity, respectively.

At the end of each of the eight parts is a **Practice Exam,** most featuring 30 multiple-choice questions. Answers appear at the end of the book, along with answers to all odd-numbered Exercises, Rankings, and Problems. (Answers to simpler Review Questions and Plug-and-Chugs are not listed.)

As with previous editions, some chapters include short boxed essays on such topics as energy and technology, railroad train wheels, magnetic strips on credit cards, and magnetically levitated trains. Also featured are boxes on pseudoscience, culminating with the public phobia about food irradiation and anything nuclear. To the person who works in the arena of science, who knows about the care, checking, and cross-checking that go into understanding something, pseudoscientific misconceptions are laughable. But to those who don't work in the science arena, including even your best students, pseudoscience can seem compelling when purveyors clothe their wares in the language of science while skillfully sidestepping the tenets of science. Our hope is to help stem this rising tide.

End-of-chapter material begins with a **Summary of Terms.** Following are **Review Questions** that summarize the main points of the chapter. Students can find the answers to these, word for word, in the reading. Unlike the more challenging end-of-chapter material, answers to Review Questions are not given at the end of the book or in the *Instructor Manual*. Likewise, no answers are given for the **Plug and Chug** problems. These require only single-step solutions, a simple plug-in of numerical quantities to familiarize the student with the equations of the chapter. They appear only in more equation-oriented chapters.

New to this edition are **Rankings.** Critical thinking is required in comparing quantities for similar situations. Getting an answer is not enough. The answer must be compared with others and a ranking from most to least is asked for. I consider this the most worthwhile of the chapter-end material.

Exercises are the nuts and bolts of conceptual physics. Many require critical thinking, while some are designed to connect concepts to familiar situations. Most chapters have from 50 to 60 Exercises. Solutions to odd-numbered Exercises are found at the end of the book, and all solutions are in the *Instructor Manual*.

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The most important ancillary to this book is the **Practice Book,** which contains the most creative of my writing and drawings. These work pages guide students step by step toward understanding the central concepts. There are one or more practice pages for nearly every chapter in the book. They can be used inside or outside of class. In my teaching I passed out copies of selected pages as a home tutor.

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All of these innovative, targeted, and effective online learning media are easily integrated in your course using an online gradebook (allowing you to "assign" the tutorials, quizzes, and other activities as out-of-class homework or projects that are automatically graded and recorded), simple icons throughout the text (highlighting for you and your students key tutorials, Interactive Figures, and other online resources), and the Instructor Resource DVD. A chapter guide section on The Physics Place summarizes the media available to you and your students, chapter by chapter.

For more information on the support ancillaries, check out http://www.pearsonhighered.com/physics or contact your Pearson Addison-Wesley representative, or contact me, Pghewitt@aol.com.

What's New in This Edition

Unlike previous editions, every chapter in this Eleventh Edition begins with a several-paragraph profile of a physicist or educator who is linked to the chapter content. By learning more about the people behind the chapter content, the reader gets a more personalized flavor of physics.

For the first time, the chapter-end material has **Ranking Exercises,** which elicit critical student thinking that goes beyond that needed for another new and simpler feature, the **Plug and Chug** exercises. When asked to rank quantities such as momentum or kinetic energy, much more judgment is called for than that needed in providing numerical answers. Also unlike previous editions, a page of multiple-choice practice questions are at the end of each of the eight parts of the book.

The problem sets have been revised for greater success with math-challenged students. In each set of problems, the last one is a challenging one, noted with a •. For the first time, solutions to odd-numbered Exercises and Problems (and now Rankings) are at the end of the book for students to check. More challenging problems are presented in the second edition of the ancillary book, *Problem Solving in Conceptual Physics.*

In addition to these sweeping changes, updates such as wingsuit flying are in Chapter 4, the latest on energy sources and power production are included in Chapter 7, and the fascinating Falkirk Wheel in Scotland is featured in the physics of liquids in Chapter 12. Waves and vibrations in Chapters 19–21 have been updated with current technology, such as blue-ray compact discs. In the chapters on electricity and light, compact fluorescent and light-emitting diodes are now featured.

Acknowledgments

I am enormously grateful to Ken Ford for checking this edition for accuracy and for his many insightful suggestions. Many years ago, I admired Ken's own books, one of which, *Basic Physics*, first inspired me to write *Conceptual Physics*. Today I am honored that he has given so much of his time and energy to assist in making this edition, what he calls, my most beautiful ever. Errors invariably crop up after manuscript is submitted, so I take full responsibility for any errors that have survived his scrutiny.

For insightful additions to this edition I thank my wife Lillian, Marshall Ellenstein, and Evan Jones. Lil made many suggestions for keeping examples updated. She and Marshall convinced me to include the personal profiles of people of science, ala David Bodanis' book $E = mc^2$. Evan helped me update lighting via CFLs and LEDs, and came up with the striking billboard photo that opens Chapter 30. I appreciate the suggestions of Tomas Brage, John Hubisz, Carlton Lane, David Kagan, Sebastian Kuhn, Anne Tabor-Morris, Fred Myers, Chris Thron, and P.O. Zetterberg.

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I remain grateful to the authors of books that initially served as influences and references many years ago: Theodore Ashford, *From Atoms to Stars;* Albert Baez, *The New College Physics: A Spiral Approach;* John N. Cooper and Alpheus W. Smith, *Elements of Physics;* Richard P. Feynman, *The Feynman Lectures on Physics;* Kenneth Ford, *Basic Physics;* Eric Rogers, *Physics for the Inquiring Mind;* Alexander Taffel, *Physics: Its Methods and Meanings;* UNESCO, *700 Science Experiments for Everyone;* and Harvey E. White, *Descriptive College Physics*. I'm thankful to Bob Park, whose book *Voodoo Science* motivated me to include boxes on pseudoscience.

For the *Problem Solving in Conceptual Physics* ancillary, co-authored with Phil Wolf, we both thank Tsing Bardin, Howie Brand, George Curtis, Ken Ford, Herb Gottlieb, Jim Hicks, David Housden, Chelcie Liu, Evan Jones, Fred Myers, Stan Schiocchio, Diane Riendeau, and David Williamson for valuable feedback.

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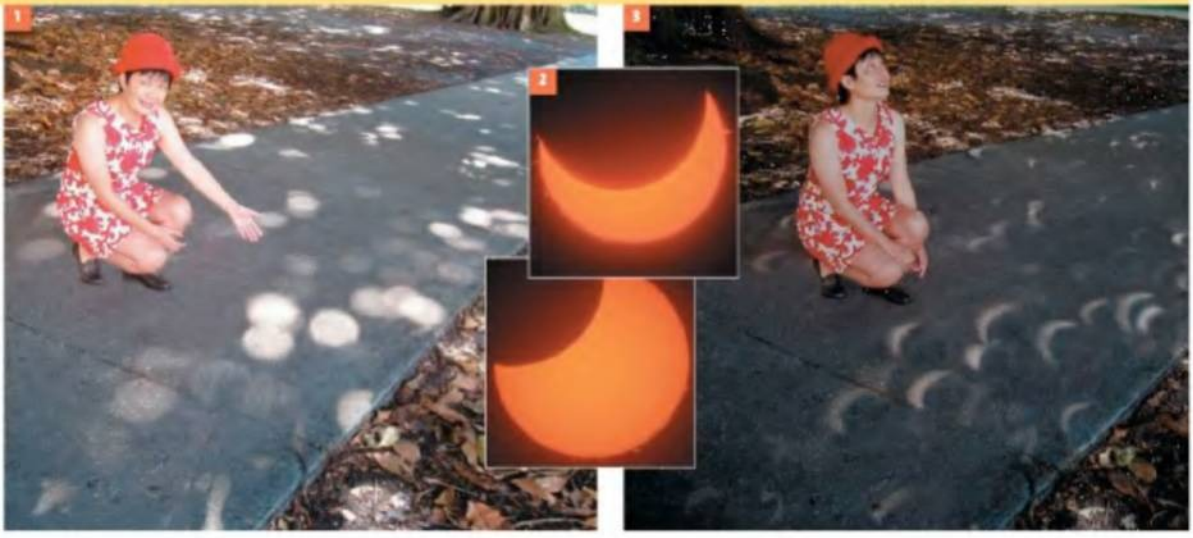
For their dedication to this edition, I am grateful to the staff at Addison Wesley in San Francisco. I am especially thankful to Chandrika Madhavan and Editor-in-Chief

Jim Smith. A note of appreciation is due Claire Masson for the cyberspace components that go back several editions. I thank David Vasquez, my dear friend of many years, and Suzanne Lyons, for their insightful tutorials. And I thank Sylvia Rebert and the production folks at Progressive Publishing Alternatives for their patience with my last-minute changes. I've been blessed with a first-rate team!

Paul G. Hewitt
St. Petersburg, Florida

Wow Great Uncle Paul! Before this chickie exhausted its inner space resources and poked out of its shell, it must have thought it was at its last moments. But what seemed like its end was a new beginning. Are we like chickies, ready to poke through to a new environment and a new understanding of our place in the universe?

1 About Science



1 The circular spots of light surrounding Lillian are "pinhole" images of the Sun, cast through small openings between leaves above. 2 The spots would no longer be full circles as the Moon progresses in front of the Sun. 3 The rendered photo at the right shows that the spots would be crescents during a partial solar eclipse.

Being second best was not all that bad for Greek mathematician Eratosthenes of Cyrene (276–194 BC). He was nicknamed "beta" by his contemporaries who judged him second best in many fields, including mathematics, philosophy, athletics, and astronomy. Perhaps he took second prizes in running or wrestling contests. He was one of the early librarians at the world's then greatest library, the Mouseion, in Alexandria, Egypt, founded by Ptolemy II Soter. Eratosthenes was one of the foremost scholars of his time and wrote on philosophical, scientific, and literary matters. His reputation among his contemporaries was immense—Archimedes dedicated a book to him. As a mathematician, he invented a method for finding prime numbers. As a geographer, he measured the tilt of Earth's axis with great accuracy and wrote *Geography*, the first book to give geography a mathematical basis and to treat Earth as a globe divided by latitudes and into frigid, temperate, and torrid zones.

The classical works of Greek literature were preserved at the Mouseion, which was host to numerous scholars and contained hundreds of thousands of papyrus and vellum scrolls. But this human treasure wasn't appreciated by everybody. Much information in the Mouseion conflicted with cherished beliefs held by others. Threatened by its "heresies," the great library was burned and completely destroyed. Historians are unsure of the culprits—who were likely guided by the certainty of their truths. Being absolutely certain, having absolutely no doubts, is *certitude*—the root cause of much of the destruction, human and otherwise, in the centuries that followed. Eratosthenes didn't witness the destruction of his great library, for it occurred after his lifetime.

Today Eratosthenes is most remembered for his amazing calculation of Earth's size, with remarkable accuracy (two thousand years ago with no computers, no artificial satellites—using only good thinking, geometry, and simple measurements). In this chapter you will see how he accomplished this.

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- Science is the body of knowledge that describes the order within nature and the causes of that order. Science is also an ongoing human activity that represents the collective efforts, findings, and wisdom of the human race, an activity that is dedicated to gathering knowledge about the world and organizing and condensing it into testable laws and theories. Science had its beginnings before recorded history, when people first discovered regularities and relationships in nature, such as star patterns in the night sky and weather patterns—when the rainy season started or when the days grew longer. From these regularities, people learned to make predictions that gave them some control over their surroundings.

  Science made great headway in Greece in the 4th and 3rd centuries BC, and spread throughout the Mediterranean world. Scientific advance came to a near halt in Europe when the Roman Empire fell in the 5th century AD. Barbarian hordes destroyed almost everything in their paths as they overran Europe. Reason gave way to religion, which ushered in what came to be known as the Dark Ages. During this time, the Chinese and Polynesians were charting the stars and the planets and Arab nations were developing mathematics and learning about the production of glass, paper, metals, and various chemicals. Greek science was reintroduced to Europe by Islamic influences that penetrated into Spain during the 10th, 11th, and 12th centuries. Universities emerged in Europe in the 13th century, and the introduction of gunpowder changed the social and political structure of Europe in the 14th century. The 15th century saw art and science beautifully blended by Leonardo da Vinci. Scientific thought was furthered in the 16th century with the advent of the printing press.

Scientific Measurements

Measurements are a hallmark of good science. How much you know about something is often related to how well you can measure it. This was well put by the famous physicist Lord Kelvin in the 19th century: "I often say that when you can measure something and express it in numbers, you know something about it. When you cannot measure it, when you cannot express it in numbers, your knowledge is of a meager and unsatisfactory kind. It may be the beginning of knowledge, but you have scarcely in your thoughts advanced to the stage of science, whatever it may be." Scientific measurements are not something new but go back to ancient times. In the 3rd century BC, for example, fairly accurate measurements were made of the sizes of Earth, Moon, and Sun, as well as of the distances between them.

HOW ERATOSTHENES MEASURED THE SIZE OF EARTH

The size of Earth was first measured in Egypt by Eratosthenes about 235 BC. He calculated the circumference of Earth in the following way. He knew that the Sun is highest in the sky at noon on June 22, the summer solstice. At this time, a vertical stick casts its shortest shadow. If the Sun is directly overhead, a vertical stick casts no shadow at all, which occurs at the summer solstice in Syene, a city south of Alexandria (where the Aswan Dam stands today). Eratosthenes learned that the Sun was directly overhead at the summer solstice in Syene from library information, which reported that, at this particular time, sunlight shines directly down a deep well in Syene and is reflected back up again. Eratosthenes reasoned that, if the Sun's rays were extended into Earth at this point, they would pass through the center. Likewise, a vertical line extended into Earth at Alexandria (or anywhere else) would also pass through Earth's center.

At noon on June 22, Eratosthenes measured the shadow cast by a vertical pillar in Alexandria and found it to be 1/8 the height of the pillar (Figure 1.1). This corresponds to a 7.1° angle between the Sun's rays and the vertical pillar. Since 7.1° is 7.1/360, or about 1/50 of a circle, Eratosthenes reasoned that the distance between Alexandria and Syene must be 1/50 the circumference of Earth. Thus the circumference of Earth becomes 50 times the distance between these two cities. This distance, quite flat and frequently traveled, was measured by surveyors to be about

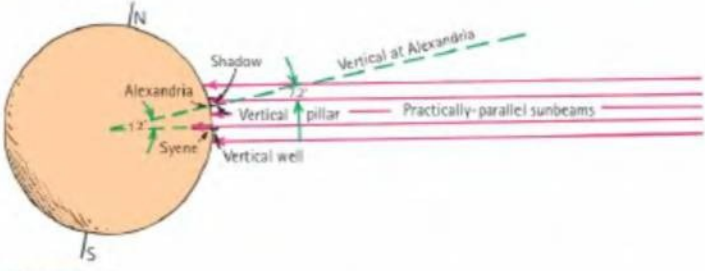

FIGURE 1.1

When the Sun is directly overhead at Syene, it is not directly overhead in Alexandria, 800 km north. When the Sun's rays shine directly down a vertical well in Syene, they cast a shadow of a vertical pillar in Alexandria. The verticals at both locations extend to the center of Earth, and they make the same angle that the Sun's rays make with the pillar at Alexandria. Eratosthenes measured this angle to be 1/50 of a complete circle. Therefore, the distance between Alexandria and Syene is 1/50 Earth's circumference.

5000 stadia (800 kilometers). So Eratosthenes calculated Earth's circumference to be 50 × 5000 stadia = 250,000 stadia. This is very close to the currently accepted value of Earth's circumference.

We get the same result by bypassing degrees altogether and comparing the length of the shadow cast by the pillar to the height of the pillar. Geometrical reasoning shows, to a close approximation, that the ratio *shadow length/pillar height* is the same as the ratio *distance between Alexandria and Syene/Earth's radius.* So just as the pillar is 8 times greater than its shadow, the radius of Earth must be 8 times greater than the distance between Alexandria and Syene.

Since the circumference of a circle is 2π times its radius ($C = 2\pi r$), Earth's radius is simply its circumference divided by 2π. In modern units, Earth's radius is 6370 kilometers and its circumference is 40,000 km.

SIZE OF THE MOON

Aristarchus was perhaps the first to suggest that Earth spins on a daily axis, which accounted for the daily motion of the stars. He also hypothesized that Earth moves around the Sun in a yearly orbit and that the other planets do likewise.[1] He correctly measured the Moon's diameter and its distance from Earth. He did all this in about 240 BC, seventeen centuries before his findings became fully accepted.

Aristarchus compared the size of the Moon with the size of Earth by watching an eclipse of the Moon. Earth, like any body in sunlight, casts a shadow. An eclipse of the Moon is simply the event wherein the Moon passes into this shadow. Aristarchus carefully studied this event and found that the width of Earth's shadow out at the Moon was 2.5 Moon diameters. This would seem to indicate that the Moon's diameter is 2.5 times smaller than Earth's. But because of the huge size of the Sun, Earth's shadow tapers, as evidenced during a solar eclipse. (Figure 1.2 shows this in exaggerated scale.) At that time, Earth intercepts the Moon's

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- The 16th-century Polish astronomer Nicolaus Copernicus caused great controversy when he published a book proposing that the Sun is stationary and that Earth revolves around the Sun. These ideas conflicted with the popular view that Earth was the center of the universe. They also conflicted with Church teachings and were banned for 200 years. The Italian physicist Galileo Galilei was arrested for popularizing the Copernican theory and for some astronomical discoveries of his own. Yet, a century later, the ideas of Copernicus and Galileo were generally accepted.

  This kind of cycle happens age after age. In the early 1800s, geologists met with violent condemnation because they differed with the Genesis account of creation. Later in the same century, geology was accepted, but theories of evolution were condemned and the teaching of them was forbidden. Every age has its groups of intellectual rebels who are condemned and sometimes persecuted at the time but who later seem harmless and often essential to the elevation of human conditions. As Count M. Maeterlinck wisely said, "At every crossway on the road that leads to the future, each progressive spirit is opposed by a thousand men appointed to guard the past."

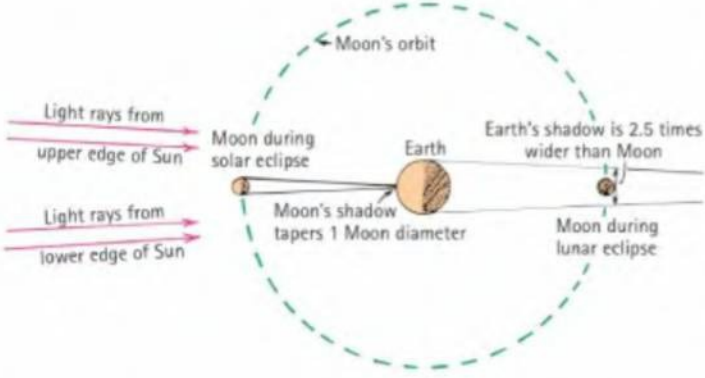

FIGURE 1.2

During a lunar eclipse, Earth's shadow is observed to be 2.5 times as wide as the Moon's diameter. Because of the Sun's large size, Earth's shadow must taper. The amount of taper is evident during a solar eclipse, where the Moon's shadow tapers a whole Moon diameter from Moon to Earth. So Earth's shadow tapers the same amount in the same distance. Therefore, Earth's diameter must be 3.5 Moon diameters.

[1]Aristarchus was unsure of his heliocentric hypothesis, likely because Earth's unequal seasons seemed not to support the idea that Earth circles the Sun. More important, it was noted that the Moon's distance from Earth varies—clear evidence that the Moon does not perfectly circle Earth. If the Moon does not follow a circular path about Earth, it was hard to argue that Earth follows a circular path about the Sun. The explanation, the elliptical paths of planets, was not discovered until centuries later by Johannes Kepler. In the meantime, the epicycles proposed by other astronomers accounted for these discrepancies. It is interesting to speculate about the course of astronomy if the Moon didn't exist. Its irregular orbit would not have contributed to the early discrediting of the heliocentric theory, which might have taken hold centuries earlier.

shadow—but just barely. The Moon's shadow tapers almost to a point at Earth's surface, evidence that the taper of the Moon's shadow at this distance is 1 Moon diameter. So during a lunar eclipse Earth's shadow, covering the same distance, must also taper 1 Moon diameter. Taking the tapering of the Sun's rays into account, Earth's diameter must be (2.5 + 1) times the Moon's diameter. In this way, Aristarchus showed that the Moon's diameter is 1/3.5 that of Earth's. The presently accepted diameter of the Moon is 3640 km, within 5% of the value calculated by Aristarchus.

FIGURE 1.3

Correct scale of solar and lunar eclipses, which shows why eclipses are rare. (They are even rarer because the Moon's orbit is tilted about 5° from the plane of Earth's orbit about the Sun.)

DISTANCE TO THE MOON

Tape a small coin, such as a dime, to a window and view it with one eye so that it just blocks out the full Moon. This occurs when your eye is about 110 coin diameters away. Then the ratio of *coin diameter/coin distance* is about 1/110. Geometrical reasoning of similar triangles shows this is also the ratio of *Moon diameter/Moon distance* (Figure 1.4). So the distance to the Moon is 110 times the Moon's diameter. The early Greeks knew this. Aristarchus's measurement of the Moon's diameter was all that was needed to calculate the Earth–Moon distance. So the early Greeks knew both the size of the Moon and its distance from Earth.

$$\frac{\text{Coin diameter}}{\text{Coin distance}} = \frac{\text{Moon diameter}}{\text{Moon distance}} = \frac{1}{110}$$

FIGURE 1.4

An exercise in ratios: When the coin barely "eclipses" the Moon, then the diameter of the coin to the distance between you and the coin is equal to the diameter of the Moon to the distance between you and the Moon (not to scale here). Measurements give a ratio of 1/110 for both.

With this information, Aristarchus made a measurement of the Earth–Sun distance.

DISTANCE TO THE SUN

If you were to repeat the coin-on-the-window-and-Moon exercise for the Sun (which would be dangerous to do because of the Sun's brightness), guess what: The ratio *Sun diameter/Sun distance* is also 1/110. This is because the size of the Sun and

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Moon are both the same to the eye. They both taper the same angle (about 0.5°). So, although the ratio of diameter to distance was known to the early Greeks, diameter alone or distance alone would have to be determined by some other means. Aristarchus found a method for doing this. Here's what he did.

Aristarchus watched for the phase of the Moon when it was *exactly* half full, with the Sun still visible in the sky. Then the sunlight must be falling on the Moon at right angles to his line of sight. This meant that the lines between Earth and the Moon, between Earth and the Sun, and between the Moon and the Sun form a right triangle (Figure 1.5).

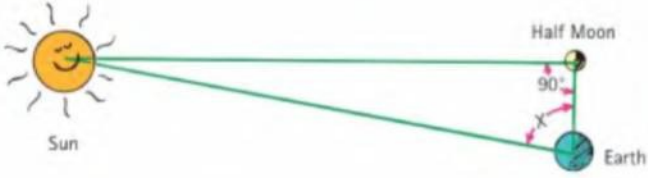


FIGURE 1.5

When the Moon appears exactly half full, the Sun, Moon, and Earth form a right triangle (not to scale). The hypotenuse is the Earth–Sun distance. By simple trigonometry, the hypotenuse of a right triangle can be found if you know the value of either nonright angle and the length of one side. The Earth–Moon distance is a known side. Measure angle *X* and you can calculate the Earth–Sun distance.

A rule of trigonometry states that, if you know all the angles in a right triangle plus the length of any one of its sides, you can calculate the length of any other side. Aristarchus knew the distance from Earth to the Moon. At the time of the half Moon he also knew one of the angles, 90°. All he had to do was measure the second angle between the line of sight to the Moon and the line of sight to the Sun. Then the third angle, a very small one, is 180° minus the sum of the first two angles (the sum of the angles in any triangle = 180°).

Measuring the angle between the lines of sight to the Moon and Sun is difficult to do without a modern transit. For one thing, both the Sun and Moon are not points, but are relatively big. Aristarchus had to sight on their centers (or either edge) and measure the angle between—quite large, almost a right angle itself! By modern-day standards, his measurement was very crude. He measured 87°, while the true value was 89.8°. He figured the Sun to be about 20 times the Moon's distance, when in fact it is about 400 times as distant. So although his method was ingenious, his measurements were crude. Perhaps Aristarchus found it difficult to believe the Sun was so far away, and he erred on the nearer side. We don't know.

Today we know the Sun to be an average of 150,000,000 kilometers away. It is somewhat closer to Earth in December (147,000,000 km), and somewhat farther in June (152,000,000 km).

SIZE OF THE SUN

Once the distance to the Sun is known, the 1/110 ratio of diameter/distance enables a measurement of the Sun's diameter. Another way to measure the 1/110 ratio, besides the method of Figure 1.4, is to measure the diameter of the Sun's image cast through a pinhole opening. You should try this. Poke a hole in a sheet of opaque cardboard and let sunlight shine on it. The round image that is cast on a surface below is actually an image of the Sun. You'll see that the size of the image does not depend on the size of the pinhole, but, rather, on how far away the pinhole is from the image. Bigger holes make brighter images, not bigger ones. Of course, if the hole is very big, no image is formed. Careful measurement will show the ratio of image size to pinhole distance is 1/110—the same as the ratio of *Sun diameter/Sun–Earth distance* (Figure 1.6).

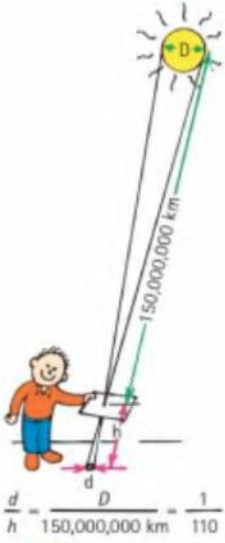


FIGURE 1.6

The round spot of light cast by the pinhole is an image of the Sun. Its *diameter/distance* ratio is the same as the *Sun diameter/Sun distance* ratio, 1/110. The Sun's diameter is 1/110 its distance from Earth.

Interestingly, at the time of a partial solar eclipse, the image cast by the pinhole will be a crescent shape—the same as that of the partially covered Sun. This provides an alternate way to view a partial eclipse without looking at the Sun.

Have you noticed that the spots of sunlight you see on the ground beneath trees are perfectly round when the Sun is overhead and spread into ellipses when the Sun is low in the sky? These are pinhole images of the Sun, where light shines through openings in the leaves that are small compared with the distance to the ground below. A round spot 10 centimeters in diameter is cast by an opening that is 110 × 10 cm above ground. Tall trees make large images; short trees make small images. And, at the time of a partial solar eclipse, the images are crescents (Figure 1.8).

FIGURE 1.7

Renoir accurately painted the spots of sunlight on his subjects' clothing and surroundings—images of the Sun cast by relatively small openings in the leaves above.

FIGURE 1.8

The crescent-shaped spots of sunlight are images of the Sun when it is partially eclipsed.

Mathematics—The Language of Science

Science and human conditions advanced dramatically after science and mathematics became integrated some four centuries ago. When the ideas of science are expressed in mathematical terms, they are unambiguous. The equations of science provide compact expressions of relationships between concepts. They don't have the multiple meanings that so often confuse the discussion of ideas expressed in common language. When findings in nature are expressed mathematically, they are easier to verify or to disprove by experiment. The mathematical structure of physics will be evident in the many equations you will encounter throughout this book. The equations are guides to thinking that show the connections between concepts in nature. The methods of mathematics and experimentation led to enormous success in science.[2]

[2]We distinguish between the mathematical structure of physics and the practice of mathematical problem solving—the focus of most nonconceptual courses. Note the relatively small number of problems at the ends of the chapters in this book, compared with the number of exercises. The focus is on comprehension comfortably before computation. Additional problems for this edition are in the *Problem Solving in Conceptual Physics* booklet.

Scientific Methods

There is no *one* scientific method. But there are common features in the way scientists do their work. This all dates back to the Italian physicist Galileo Galilei (1564–1642) and the English philosopher Francis Bacon (1561–1626). They broke free from the methods of the Greeks, who worked "upward or downward," depending on the circumstances, reaching conclusions about the physical world by reasoning from arbitrary assumptions (axioms). The modern scientist works "upward," first examining the way the world actually works and then building a structure to explain findings.

Although no cookbook description of the **scientific method** is really adequate, some or all of the following steps are likely to be found in the way most scientists carry out their work.

1. Recognize a question or a puzzle—such as an unexplained fact.
2. Make an educated guess—a **hypothesis**—that might resolve the puzzle.
3. Predict consequences of the hypothesis.
4. Perform experiments or make calculations to test the predictions.
5. Formulate the simplest general rule that organizes the three main ingredients: hypothesis, predicted effects, and experimental findings.

Although these steps are appealing, much progress in science has come from trial and error, experimentation without hypotheses, or just plain accidental discovery by a well-prepared mind. The success of science rests more on an attitude common to scientists than on a particular method. This attitude is one of inquiry, integrity, and humility—that is, a willingness to admit error.

The Scientific Attitude

It is common to think of a fact as something that is unchanging and absolute. But, in science, a **fact** is generally a close agreement by competent observers who make a series of observations about the same phenomenon. For example, where it was once a fact that the universe is unchanging and permanent, today it is a fact that the universe is expanding and evolving. A scientific hypothesis, on the other hand, is an educated guess that is only presumed to be factual until supported by experiment. When a hypothesis has been tested over and over again and has not been contradicted, it may become known as a **law** or *principle*.

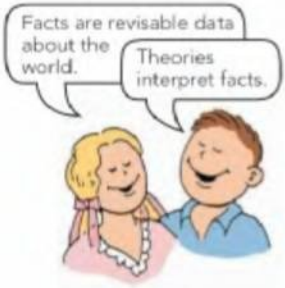
Science is a way of knowing about the world and making sense of it.

If a scientist finds evidence that contradicts a hypothesis, law, or principle, then, in the scientific spirit, it must be changed or abandoned—regardless of the reputation or authority of the persons advocating it (unless the contradicting evidence, upon testing, turns out to be wrong—which sometimes happens). For example, the greatly respected Greek philosopher Aristotle (384–322 BC) claimed that an object falls at a speed proportional to its weight. This idea was held to be true for nearly 2000 years because of Aristotle's compelling authority. Galileo allegedly showed the falseness of Aristotle's claim with one experiment— demonstrating that heavy and light objects dropped from the Leaning Tower of Pisa fell at nearly equal speeds. In the scientific spirit, a single verifiable experiment to the contrary outweighs any authority, regardless of reputation or the number of followers or advocates. In modern science, argument by appeal to authority has little value.[3]

[3]But appeal to *beauty* has value in science. More than one experimental result in modern times has contradicted a lovely theory, which, upon further investigation, proved to be wrong. This has bolstered scientists' faith that the ultimately correct description of nature involves conciseness of expression and economy of concepts—a combination that deserves to be called beautiful.

Scientists must accept their experimental findings even when they would like them to be different. They must strive to distinguish between what they see and what they wish to see, for scientists, like most people, have a vast capacity for fooling themselves.[4] People have always tended to adopt general rules, beliefs, creeds, ideas, and hypotheses without thoroughly questioning their validity and to retain them long after they have been shown to be meaningless, false, or at least questionable. The most widespread assumptions are often the least questioned. Most often, when an idea is adopted, particular attention is given to cases that seem to support it, while cases that seem to refute it are distorted, belittled, or ignored.

Scientists use the word *theory* in a way that differs from its usage in everyday speech. In everyday speech, a theory is no different from a hypothesis—a supposition that has not been verified. A scientific **theory,** on the other hand, is a synthesis of a large body of information that encompasses well-tested and verified hypotheses about certain aspects of the natural world. Physicists, for example, speak of the quark theory of the atomic nucleus, chemists speak of the theory of metallic bonding in metals, and biologists speak of the cell theory.



The theories of science are not fixed; rather, they undergo change. Scientific theories evolve as they go through stages of redefinition and refinement. During the past hundred years, for example, the theory of the atom has been repeatedly refined as new evidence on atomic behavior has been gathered. Similarly, chemists have refined their view of the way molecules bond together, and biologists have refined the cell theory. The refinement of theories is a strength of science, not a weakness. Many people feel that it is a sign of weakness to change their minds. Competent scientists must be experts at changing their minds. They change their minds, however, only when confronted with solid experimental evidence or when a conceptually simpler hypothesis forces them to a new point of view. More important than defending beliefs is improving them. Better hypotheses are made by those who are honest in the face of experimental evidence.

Experiment, not philosophical discussion, decides what is correct in science.

Away from their profession, scientists are inherently no more honest or ethical than most other people. But in their profession they work in an arena that places a high premium on honesty. The cardinal rule in science is that all hypotheses must be testable—they must be susceptible, at least in principle, to being shown to be *wrong*. In science, it is more important that there be a means of proving an idea wrong than that there be a means of proving it right. This is a major factor that distinguishes science from nonscience. At first this may seem strange, for when we wonder about most things, we concern ourselves with ways of finding out whether they are true. Scientific hypotheses are different. In fact, if you want to distinguish whether a hypothesis is scientific or not, check to see if there is a test for proving it wrong. If there is no test for its possible wrongness, then the hypothesis is not scientific. Albert Einstein put it well when he stated, "No number of experiments can prove me right; a single experiment can prove me wrong."

Much learning can occur by asking questions. Socrates preached this, and hence the Socratic method. Questioning has led to some of the most magnificent works of art and science.

Consider the biologist Charles Darwin's hypothesis that life forms evolve from simpler to more complex forms. This could be proved wrong if paleontologists discovered that more complex forms of life appeared before their simpler counterparts. Einstein hypothesized that light is bent by gravity. This might be proved wrong if starlight that grazed the Sun and could be seen during a solar eclipse were undeflected from its normal path. As it turned out, less complex life forms are found to precede their more complex counterparts and starlight is found to bend as it passes close to the Sun, which support the claims. If and when a hypothesis or scientific claim is confirmed, it is regarded as useful and as a stepping-stone to additional knowledge.

Consider the hypothesis "The alignment of planets in the sky determines the best time for making decisions." Many people believe it, but this hypothesis is not

[4]In your education it is not enough to be aware that other people may try to fool you; it is more important to be aware of your own tendency to fool yourself.

scientific. It cannot be proven wrong, nor can it be proven right. It is *speculation*. Likewise, the hypothesis "Intelligent life exists on other planets somewhere in the universe" is not scientific. Although it can be proven correct by the verification of a single instance of intelligent life existing elsewhere in the universe, there is no way to prove it wrong if no intelligent life is ever found. If we searched the far reaches of the universe for eons and found no life, that would not prove that it doesn't exist "around the next corner." On the other hand, the hypothesis "There is no other intelligent life in the universe" *is* scientific. Do you see why?

A hypothesis that is capable of being proved right but not capable of being proved wrong is not a scientific hypothesis. Many such statements are quite reasonable and useful, but they lie outside the domain of science.

The essence of science is expressed in two questions: How would we know? And what evidence would prove this idea wrong? Assertions without evidence are unscientific and can be dismissed without evidence.

CHECK POINT

Which of these is a scientific hypothesis?

a. Atoms are the smallest particles of matter that exist.
b. Space is permeated with an essence that is undetectable.
c. Albert Einstein was the greatest physicist of the 20th century.

Check Your Answer

Only *a* is scientific, because there is a test for falseness. The statement is not only *capable* of being proved wrong but in fact *has* been proved wrong. Statement *b* has no test for possible wrongness and is therefore unscientific. Likewise for any principle or concept for which there is no means, procedure, or test whereby it can be shown to be wrong (if it is wrong). Some pseudoscientists and other pretenders to knowledge will not even consider a test for the possible wrongness of their statements. Statement *c* is an assertion that has no test for possible wrongness. If Einstein was not the greatest physicist, how could we know? It is important to note that because the name Einstein is generally held in high esteem, it is a favorite of pseudoscientists. So we should not be surprised that the name of Einstein, like that of Jesus or of any other highly respected person, is cited often by charlatans who wish to bring respect to themselves and their points of view. In all fields, it is prudent to be skeptical of those who wish to credit themselves by calling upon the authority of others.

None of us has the time, energy, or resources to test every idea, so most of the time we take somebody's word. How do we know whose word to take? To reduce the likelihood of error, scientists accept only the word of those whose ideas, theories, and findings are testable—if not in practice, at least in principle. Speculations that cannot be tested are regarded as "unscientific." This has the long-run effect of compelling honesty—findings widely publicized among fellow scientists are generally subjected to further testing. Sooner or later, mistakes (and deception) are found out; wishful thinking is exposed. A discredited scientist does not get a second chance in the community of scientists. The penalty for fraud is professional excommunication. Honesty, so important to the progress of science, thus becomes a matter of self-interest to scientists. There is relatively little bluffing in a game in which all bets are called. In fields of study where right and wrong are not so easily established, the pressure to be honest is considerably less.

The ideas and concepts most important to our everyday life are often unscientific; their correctness or incorrectness cannot be determined in the laboratory. Interestingly enough, it seems that people honestly believe their own ideas about things to be correct, and almost everyone is acquainted with people who hold completely opposite views—so the ideas of some (or all) must be incorrect. How do you know whether or not *you* are one of those holding erroneous beliefs? There is a test.

Before you can be reasonably convinced that you are right about a particular idea, you should be sure that you understand the objections and the positions of your most articulate antagonists. You should find out whether your views are supported by sound knowledge of opposing ideas or by your *misconceptions* of opposing ideas. You make this distinction by seeing whether or not you can state the objections and positions of your opposition to *their* satisfaction. Even if you can successfully do this, you cannot be absolutely certain of being right about your own ideas, but the probability of being right is considerably higher if you pass this test.

CHECK POINT

Suppose that, in a disagreement between two friends, A and B, you note that friend A only states and restates one point of view, whereas friend B clearly states both her own position and that of friend A. Who is more likely to be correct? *(Think before you read the answer below!)*

Check Your Answer

Who knows for sure? Friend B may have the cleverness of a lawyer who can state various points of view and still be incorrect. We can't be sure about the "other guy." The test for correctness or incorrectness suggested here is not a test of others, but of and for *you*. It can aid your personal development. As you attempt to articulate the ideas of your antagonists, be prepared, like scientists who are prepared to change their minds, to discover evidence contrary to your own ideas—evidence that may alter your views. Intellectual growth often occurs in this way.

We each need a knowledge filter to tell the difference between what is valid and what only pretends to be valid. The best knowledge filter ever invented is science.

Although the notion of being familiar with counter points of view seems reasonable to most thinking people, just the opposite—shielding ourselves and others from opposing ideas—has been more widely practiced. We have been taught to discredit unpopular ideas without understanding them in proper context. With the 20/20 vision of hindsight, we can see that many of the "deep truths" that were the cornerstones of whole civilizations were shallow reflections of the prevailing ignorance of the time. Many of the problems that plagued societies stemmed from this ignorance and the resulting misconceptions; much of what was held to be true simply wasn't true. This is not confined to the past. Every scientific advance is by necessity incomplete and partly inaccurate, for the discoverer sees with the blinders of the day and can only discard a part of that blockage.

Science, Art, and Religion

Art is about cosmic beauty. Science is about cosmic order. Religion is about cosmic purpose.

The search for order and meaning in the world around us has taken different forms: One is science, another is art, and another is religion. Although the roots of all three go back thousands of years, the traditions of science are relatively recent. More important, the domains of science, art, and religion are different, although they often overlap. Science is principally engaged with discovering and recording natural phenomena, the arts are concerned with personal interpretation and creative expression, and religion addresses the source, purpose, and meaning of it all.

Science and the arts are comparable. In the art of literature, we discover what is possible in human experience. We can learn about emotions ranging from anguish to love, even if we haven't experienced them. The arts do not necessarily give us those experiences, but they describe them to us and suggest what may be possible for us. Science tells us what is possible in nature. Scientific knowledge helps us to

Pseudoscience

In prescientific times, any attempt to harness nature meant forcing nature against her will. Nature had to be subjugated, usually with some form of magic or by means that were above nature—that is, supernatural. Science does just the opposite, and it works within nature's laws. The methods of science have largely displaced reliance on the supernatural—but not entirely. The old ways persist, full force in primitive cultures, and they survive in technologically advanced cultures too, sometimes disguised as science. This is fake science—**pseudoscience.** The hallmark of a pseudoscience is that it lacks the key ingredients of evidence and having a test for wrongness. In the realm of pseudoscience, skepticism and tests for possible wrongness are downplayed or flatly ignored.

There are various ways to view cause-and-effect relations in the universe. Mysticism is one view, appropriate perhaps in religion but not applicable to science. Astrology is an ancient belief system that assumes there is a mystical correspondence between individuals and the universe as a whole—that human affairs are influenced by the positions and movements of planets and other celestial bodies. This nonscientific view can be quite appealing. However insignificant we may feel at times, astrologers assure us that we are intimately connected to the workings of the cosmos, which has been created for humans—particularly those humans belonging to one's own tribe, community, or religious group. Astrology as ancient magic is one thing, but astrology in the guise of science is another. When it poses as a science related to astronomy, then it becomes pseudoscience. Some astrologers present their craft in a scientific guise. When they use up-to-date astronomical information and computers that chart the movements of heavenly bodies, astrologers are operating in the realm of science. But when they use these data to concoct astrological revelations, they have crossed over into full-fledged pseudoscience.

Pseudoscience, like science, makes predictions. The predictions of a dowser, who locates underground water with a dowsing stick, have a very high rate of success—nearly 100%. Whenever the dowser goes through his or her ritual and points to a spot on the ground, the well digger is sure to find water. Dowsing works. Of course, the dowser can hardly miss, because there is groundwater within 100 meters of the surface at nearly every spot on Earth. (The real test of a dowser would be finding a place where water wouldn't be found!)

A shaman who studies the oscillations of a pendulum suspended over the abdomen of a pregnant woman can predict the sex of the fetus with an accuracy of 50%. This means that, if he tries his magic many times on many fetuses, half his predictions will be right and half will be wrong—the predictability of ordinary guessing. In comparison, determining the sex of unborns by scientific means gives a 95% success rate via sonograms and 100% by amniocentesis. The best that can be said for the shaman is that the 50% success rate is a lot better than that of astrologers, palm readers, or other pseudoscientists who predict the future.

An example of a pseudoscience that has zero success is provided by energy-multiplying machines. These machines, which are alleged to deliver more energy than they take in, are, we are told, "still on the drawing boards and needing funds for development." They are touted by quacks who sell shares to an ignorant public who succumb to the pie-in-the-sky promises of success. This is junk science. Pseudoscientists are everywhere, are usually successful in recruiting apprentices for money or labor, and can be very convincing even to seemingly reasonable people. Their books greatly outnumber books on science in bookstores. Junk science is thriving.

Four centuries ago, most humans were dominated by superstition, devils, demons, disease, and magic in their short and difficult lives. Life was cruel in medieval times. Only through enormous effort did humans gain scientific knowledge, overthrow superstition, and gain freedom from ignorance. We should rejoice in what we've learned—no longer having to die whenever an infectious disease strikes or to live in fear of demons. Today we have no need to pretend that superstition is anything but superstition, or that junk notions are anything but junk notions—whether voiced by street-corner quacks, by loose thinkers who write promise-heavy health books, by hucksters who sell magnetic therapy, or by demagogues who inflict fear.

Yet there is cause for alarm when the superstitions that people once fought to erase come back in force, enchanting a growing number of people. There are now more than twenty thousand practicing astrologers in the United States who serve millions of credulous believers. A greater percentage of Americans today believe in astrology and occult phenomena than did citizens of medieval Europe. Few newspapers print a daily science column, but nearly all provide daily horoscopes. Although goods and medicines around us have improved with scientific advances, much human thinking has not.

Many believe that the human condition is sliding backward because of growing technology. More likely, however, we'll slide backward because science and technology will bow to the irrationality, superstitions, and demagoguery of the past. "Equal time" will be allotted to irrationality in our classrooms. Watch out for the spokespeople of irrationality. Pseudoscience and irrationality are huge and lucrative businesses.

predict possibilities in nature even before those possibilities have been experienced. It provides us with a way of connecting things, of seeing relationships between and among them, and of making sense of the great variety of natural events around us. Science broadens our perspective of nature. A knowledge of both the arts and the sciences makes for a wholeness that affects the way we view the world and the decisions we make about the world and ourselves. A truly educated person is knowledgeable in both the arts and the sciences.

Science and religion have similarities also, but they are basically different—principally because their domains are different. The domain of science is natural order; the domain of religion is nature's purpose. Religious beliefs and practices usually involve faith in, and worship of, a supreme being and the creation of human community—not the practices of science. In this respect, science and religion are as different as apples and oranges: They are two different yet complementary fields of human activity.

When we study the nature of light later in this book, we will treat light first as a wave and then as a particle. To the person who knows a little bit about science, waves and particles are contradictory; light can be only one or the other, and we have to choose between them. But to the enlightened person, waves and particles complement each other and provide a deeper understanding of light. In a similar way, it is mainly people who are either uninformed or misinformed about the deeper natures of both science and religion who feel that they must choose between believing in religion and believing in science. Unless one has a shallow understanding of either or both, there is no contradiction in being religious and being scientific in one's thinking.[5]

The belief that there is only one truth and that oneself is in possession of it seems to me the deepest root of all the evil that is in the world. —*Max Born*

Many people are troubled about not knowing the answers to religious and philosophical questions. Some avoid uncertainty by uncritically accepting almost any comforting answer. An important message in science, however, is that uncertainty is acceptable. For example, in Chapter 31 you'll learn that it is not possible to know with certainty both the momentum and position of an electron in an atom. The more you know about one, the less you can know about the other. Uncertainty is a part of the scientific process. It's okay not to know the answers to fundamental questions. Why are apples gravitationally attracted to Earth? Why do electrons repel one another? Why do magnets interact with other magnets? Why does energy have mass? At the deepest level, scientists don't know the answers to these questions—at least not yet. We know a lot about where we are, but nothing really about *why* we are. It's okay not to know the answers to such religious questions. Given a choice between a closed mind with comforting answers and an open and exploring mind without answers, most scientists choose the latter. Scientists in general are comfortable with not knowing.

Science and Technology

Science and technology are also different from each other. Science is concerned with gathering knowledge and organizing it. Technology is applied science, used by technologists and engineers for practical purposes. It also provides the tools needed by scientists in their further explorations.

Technology is a double-edged sword that can be both helpful and harmful. We have the technology, for example, to extract fossil fuels from the ground and then to burn the fossil fuels for the production of energy. Energy production from fossil fuels has benefited our society in countless ways. On the flip side, the burning of fossil fuels endangers the environment. It is tempting to blame technology itself for problems such as pollution, resource depletion, and even overpopulation. These problems, however, are not the fault of technology any more than a shotgun wound is the fault of the shotgun. It is humans who use the technology, and humans who are responsible for how it is used.

Remarkably, we already possess the technology to solve many environmental problems. This 21st century is seeing a switch from fossil fuels to more sustainable

[5]Of course, this doesn't apply to religious extremists who steadfastly assert that one cannot embrace both their brand of religion and science.

Risk Assessment

The numerous benefits of technology are paired with risks. When the benefits of a technological innovation are seen to outweigh its risks, the technology is accepted and applied. X-rays, for example, continue to be used for medical diagnosis despite their potential for causing cancer. But when the risks of a technology are perceived to outweigh its benefits, it should be used very sparingly or not at all.

Risk can vary for different groups. Aspirin is useful for adults, but for young children it can cause a potentially lethal condition known as *Reye's syndrome*. Dumping raw sewage into the local river may pose little risk for a town located upstream, but for towns downstream the untreated sewage is a health hazard. Similarly, storing radioactive wastes underground may pose little risk for us today, but for future generations the risks of such storage are greater if there is leakage into groundwater. Technologies involving different risks for different people, as well as differing benefits, raise questions that are often hotly debated. Which medications should be sold to the general public over the counter and how should they be labeled? Should food be irradiated in order to put an end to food poisoning, which kills more than 5000 Americans each year? The risks to all members of society need consideration when public policies are decided.

The risks of technology are not always immediately apparent. No one fully realized the dangers of combustion products when petroleum was selected as the fuel of choice for automobiles early in the last century. From the hindsight of 20/20 vision, alcohols from biomass would have been a superior choice environmentally, but they were banned by the prohibition movements of the day that made alcohol an illegal substance.

Because we are now more aware of the environmental costs of fossil-fuel combustion, biomass fuels are making a slow comeback. An awareness of both the short-term risks and the long-term risks of a technology is crucial.

People seem to have difficulty accepting the impossibility of zero risk. Airplanes cannot be made perfectly safe. Processed foods cannot be rendered completely free of toxicity, for all foods are toxic to some degree. You cannot go to the beach without risking skin cancer, no matter how much sunscreen you apply. You cannot avoid radioactivity, for it's in the air you breathe and the foods you eat, and it has been that way since before humans first walked Earth. Even the cleanest rain contains radioactive carbon-14, not to mention the same in our bodies. Between each heartbeat in each human body, there have always been about 10,000 naturally occurring radioactive decays. You might hide yourself in the hills, eat the most natural of foods, practice obsessive hygiene, and still die from cancer caused by the radioactivity emanating from your own body. The probability of eventual death is 100%. Nobody is exempt.

Science helps to determine the most probable. As the tools of science improve, then assessment of the most probable gets closer to being on target. Acceptance of risk, on the other hand, is a societal issue. Placing zero risk as a societal goal is not only impractical but selfish. Any society striving toward a policy of zero risk would consume its present and future economic resources. Isn't it more noble to accept nonzero risk and to minimize risk as much as possible within the limits of practicality? A society that accepts no risks receives no benefits.

energy sources, such as photovoltaics, solar thermal electric generation, and biomass conversion. Whereas the paper on which this book is printed came from trees, paper will soon come from fast-growing weeds, and less may be needed as small, easy-to-read computer screens gain popularity. We are more and more recycling waste products. In some parts of the world, progress is being made on stemming the human population explosion that aggravates almost every problem faced by humans today. We live on a finite planet and more of us are acknowledging Earth's population carrying capacity. The greatest obstacle to solving today's problems lies more with social inertia than with a lack of technology. Technology is our tool. What we do with this tool is up to us. The promise of technology is a cleaner and healthier world. Wise applications of technology *can* lead to a better world.

No wars are fought over science.

Physics—The Basic Science

Science, once called *natural philosophy*, encompasses the study of living things and nonliving things, the life sciences and the physical sciences. The life sciences include biology, zoology, and botany. The physical sciences include geology, astronomy, chemistry, and physics.

Physics is more than a part of the physical sciences. It is the *basic* science. It's about the nature of basic things such as motion, forces, energy, matter, heat, sound,

light, and the structure of atoms. Chemistry is about how matter is put together, how atoms combine to form molecules, and how the molecules combine to make up the many kinds of matter around us. Biology is more complex and involves matter that is alive. So underneath biology is chemistry, and underneath chemistry is physics. The concepts of physics reach up to these more complicated sciences. That's why physics is the most basic science.

An understanding of science begins with an understanding of physics. The following chapters present physics conceptually so that you can enjoy understanding it.

CHECK POINT

Which of the following activities involves the utmost human expression of passion, talent, and intelligence?

a. painting and sculpture
b. literature
c. music
d. religion
e. science

Check Your Answer

All of them! The human value of science, however, is the least understood by most individuals in our society. The reasons are varied, ranging from the common notion that science is incomprehensible to people of average ability to the extreme view that science is a dehumanizing force in our society. Most of the misconceptions about science probably stem from the confusion between the *abuses* of science and science itself.

Science is an enchanting human activity shared by a wide variety of people who, with present-day tools and know-how, are reaching further and discovering more about themselves and their environment than people in the past were ever able to do. The more you know about science, the more passionate you feel toward your surroundings. There is physics in everything you see, hear, smell, taste, and touch!

In Perspective

Only a few centuries ago the most talented and most skilled artists, architects, and artisans of the world directed their genius and effort to the construction of the great cathedrals, synagogues, temples, and mosques. Some of these architectural structures took centuries to build, which means that nobody witnessed both the beginning and the end of construction. Even the architects and early builders who lived to a ripe old age never saw the finished results of their labors. Entire lifetimes were spent in the shadows of construction that must have seemed without beginning or end. This enormous focus of human energy was inspired by a vision that went beyond worldly concerns—a vision of the cosmos. To the people of that time, the structures they erected were their "spaceships of faith," firmly anchored but pointing to the cosmos.

Today the efforts of many of our most skilled scientists, engineers, artists, and technicians are directed to building the spaceships that already orbit Earth and others that will voyage beyond. The time required to build these spaceships is extremely brief compared with the time spent building the stone and marble structures of the past. Many people working on today's spaceships were alive before the first jetliner carried passengers. Where will younger lives lead in a comparable time?

We seem to be at the dawn of a major change in human growth, for as little Evan suggests in the photo that precedes the beginning of this chapter, we may be like the hatching chicken who has exhausted the resources of its inner-egg environment and is about to break through to a whole new range of possibilities. Earth is our cradle and has served us well. But cradles, however comfortable, are outgrown one day. So with the inspiration that in many ways is similar to the inspiration of those who built the early cathedrals, synagogues, temples, and mosques, we aim for the cosmos.

We live in an exciting time!

SUMMARY OF TERMS

Scientific method Principles and procedures for the systematic pursuit of knowledge involving the recognition and formulation of a problem, the collection of data through observation and experiment, and the formulation and testing of hypotheses.

Hypothesis An educated guess; a reasonable explanation of an observation or experimental result that is not fully accepted as factual until tested over and over again by experiment.

Scientific attitude The scientific method inclined toward inquiry, integrity, and humility.

Fact A statement about the world that competent observers who have made a series of observations agree on.

Law A general hypothesis or statement about the relationship of natural quantities that has been tested over and over again and has not been contradicted. Also known as a *principle*.

Theory A synthesis of a large body of information that encompasses well-tested and verified hypotheses about certain aspects of the natural world.

Pseudoscience Fake science that pretends to be real science.

REVIEW QUESTIONS

1. Briefly, what is science?
2. Throughout the ages, what has been the general reaction to new ideas about established "truths"?

Scientific Measurements

3. When the Sun was directly overhead in Syene, why was it not directly overhead in Alexandria?
4. Earth, like everything else illuminated by the Sun, casts a shadow. Why does this shadow taper?
5. How does the Moon's diameter compare with the distance between Earth and the Moon?
6. How does the Sun's diameter compare with the distance between Earth and the Sun?
7. Why did Aristarchus make his measurements of the Sun's distance at the time of a half Moon?
8. What are the circular spots of light seen on the ground beneath a tree on a sunny day?

Mathematics—The Language of Science

9. What is the role of equations in this book?

Scientific Methods

10. Outline some features of the scientific method.

The Scientific Attitude

11. Distinguish among a scientific fact, a hypothesis, a law, and a theory.
12. In daily life, people are often praised for maintaining some particular point of view, for the "courage of their convictions." A change of mind is seen as a sign of weakness. How is this different in science?
13. What is the test for whether a hypothesis is scientific or not?
14. In daily life, we see many cases of people who are caught misrepresenting things and who soon thereafter are excused and accepted by their contemporaries. How is this different in science?
15. What test can you perform to increase the chance in your own mind that you are right about a particular idea?

Science, Art, and Religion

16. Why are students of the arts encouraged to learn about science and science students encouraged to learn about the arts?
17. Why do many people believe they must choose between science and religion?
18. Psychological comfort is a benefit of having solid answers to religious questions. What benefit accompanies a position of not knowing the answers?

Science and Technology

19. Clearly distinguish between science and technology.

Physics—The Basic Science

20. Why is physics considered to be the basic science?

PROJECTS

1. Poke a hole in a piece of cardboard and hold the cardboard horizontally in the sunlight. Note the image of the Sun that is cast below. To convince yourself that the round spot of light is an image of the round Sun, try holes of different shapes. A square or triangular hole will still cast a round image when the distance to the image is large compared with the size of the hole. When the Sun's rays and the image surface are perpendicular, the image is a circle; when the Sun's rays make an angle with the image surface, the image is a "stretched-out" circle, an ellipse. Let the solar image fall upon a coin, say a dime. Position the cardboard so the image just covers the coin. This is a convenient way to measure the diameter of the image—the same as the diameter of the easy-to-measure coin. Then measure the distance between the cardboard and the coin. Your ratio of image size to image distance should be about 1/110. This is the ratio of solar diameter to solar distance to Earth. Using the information that the Sun is 150,000,000 kilometers distant, calculate the diameter of the Sun. (Interesting questions: How many coins placed end-to-end would fit between the solar image and the cardboard? How many suns would fit between the card and the Sun?)
2. Choose a particular day in the very near future—and during that day carry a small notebook with you and record every time you come in contact with modern technology. After your recording is done, write a short page or two discussing your dependencies on your list of technologies. Make a note of how you'd be affected if each suddenly vanished, and how you'd cope with the loss.

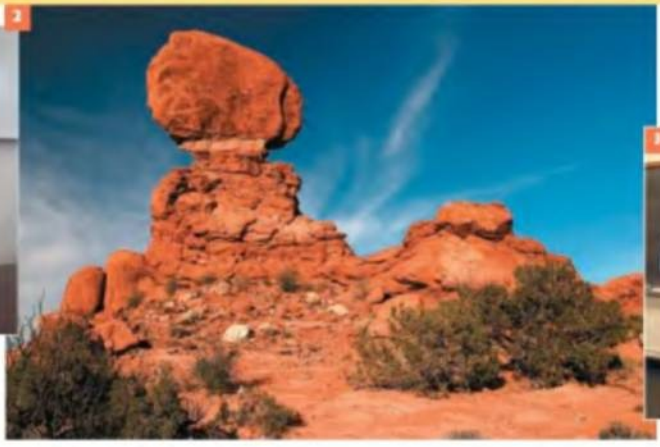
EXERCISES

1. What is the penalty for scientific fraud in the science community?
2. Which of the following are scientific hypotheses? (a) Chlorophyll makes grass green. (b) Earth rotates about its axis because living things need an alternation of light and darkness. (c) Tides are caused by the Moon.
3. In answer to the question, "When a plant grows, where does the material come from?" Aristotle hypothesized by logic that all material came from the soil. Do you consider his hypothesis to be correct, incorrect, or partially correct? What experiments do you propose to support your choice?
4. The great philosopher and mathematician Bertrand Russell (1872–1970) wrote about ideas in the early part of his life that he rejected in the latter part of his life. Do you see this as a sign of weakness or as a sign of strength in Bertrand Russell? (Do you speculate that your present ideas about the world around you will change as you learn and experience more, or do you speculate that further knowledge and experience will solidify your present understanding?)
5. Bertrand Russell wrote, "I think we must retain the belief that scientific knowledge is one of the glories of man. I will not maintain that knowledge can never do harm. I think such general propositions can almost always be refuted by well-chosen examples. What I will maintain—and maintain vigorously—is that knowledge is very much more often useful than harmful and that fear of knowledge is very much more often harmful than useful." Think of examples to support this statement.
6. When you step from the shade into the sunlight, the Sun's heat is as evident as the heat from hot coals in a fireplace in an otherwise cold room. You feel the Sun's heat not because of its high temperature (higher temperatures can be found in some welder's torches), but because the Sun is big. Which do you estimate is larger, the Sun's radius or the distance between the Moon and Earth? Check your answer in the list of physical data on the inside back cover. Do you find your answer surprising?
7. What is probably being misunderstood by a person who says, "But that's only a scientific theory"?
8. The shadow cast by a vertical pillar in Alexandria at noon during the summer solstice is found to be 1/8 the height of the pillar. The distance between Alexandria and Syene is 1/8 Earth's radius. Is there a geometric connection between these two 1-to-8 ratios?
9. If Earth were smaller than it is, but the Alexandria-to-Syene distance were the same, would the shadow of the vertical pillar in Alexandria be longer or shorter at noon during the summer solstice?
10. Scientists call a theory that unites many ideas in a simple way "beautiful." Are unity and simplicity among the criteria of beauty outside of science? Support your answer.

Part One
Mechanics

Like everyone, I'm made of atoms. They're so small and numerous that I inhale billions of trillions of atoms with each breath of air. I exhale some of them right away, but other atoms stay for awhile and become part of me, which I may exhale later. Other people breathe some of these, so they become a part of me. And vice versa. Although I am Egyptian and was born in Cairo, the atoms that make up my body were once in the bodies of people from every country in the world. Furthermore, since there are more atoms in a breath of air than the total number of humans since time zero, in each breath you inhale you recycle atoms that were once a part of every person who ever lived. Hey, in this sense, we're all one!

2 Newton's First Law of Motion–Inertia



1 Theoretical physicist Toby Jacobson, my protégé since age 13, shows a simple demonstration of inertia. 2 The balanced rock more strikingly illustrates inertia. 3 David Yee asks his students which string, the lower or the upper, will break when he suddenly yanks downward on the lower string.

"God said, Let Newton be! and all was light!" *Alexander Pope.*

In this and many other chapters we will study the ideas of Isaac Newton, one of the greatest minds of all time. Newton was born prematurely on Christmas Day, 1642, and barely survived in his mother's farmhouse in England. His father died several months before his birth, and he grew up under the care of his mother and grandmother. As a child, he showed no particular signs of brightness, and, as a young teen, he was taken out of school to help manage his mother's farm. He had little interest in this, preferring to read books he borrowed from a neighbor. An uncle, who sensed the scholarly potential in young Isaac, arranged for him to go back to school for a year and then on to the University of Cambridge, where he stayed for 5 years, graduating without particular distinction.

Isaac Newton (1642–1727)

When a plague swept through England, Newton retreated to his mother's farm—this time to continue his studies. There, at the age of 22 and 23, he laid the foundations for the work that was to make him immortal. Seeing an apple fall to the ground led him to consider the force of gravity extending to the Moon and beyond. He formulated the law of universal gravitation and applied it to solving the centuries-old mysteries of planetary motion and ocean tides; he invented the calculus, an indispensable mathematical tool in science. He extended the work of Italian scientist Galileo, and formulated the three fundamental laws of motion. The first of these laws is the law of inertia, which is the subject of this chapter.

As background to the physics that Newton so clearly presented, we go back to the 3rd century BC to Aristotle, the most outstanding philosopher-scientist of his time in ancient Greece. Aristotle attempted to clarify motion by classification.

Aristotle on Motion

Aristotle divided motion into two main classes: *natural motion* and *violent motion*. We briefly consider each, not as study material, but as a background to present-day ideas about motion.

Aristotle asserted that natural motion proceeds from the "nature" of an object, dependent on the combination of the four elements (earth, water, air, and fire) the object contains. In his view, every object in the universe has a proper place, determined by its "nature"; any object not in its proper place will "strive" to get there. Being of the earth, an unsupported lump of clay will fall to the ground; being of the air, an unimpeded puff of smoke will rise; being a mixture of earth and air but predominantly earth, a feather falls to the ground, but not as rapidly as a lump of clay. He stated that heavier objects would strive harder and argued that objects should fall at speeds proportional to their weights: The heavier the object, the faster it should fall.

Natural motion could be either straight up or straight down, as in the case of all things on Earth, or it could be circular, as in the case of celestial objects. Unlike up-and-down motion, circular motion has no beginning or end, repeating itself without deviation. Aristotle believed that different rules apply to the heavens and asserted that celestial bodies are perfect spheres made of a perfect and unchanging substance, which he called *quintessence*.[1] (The only celestial object with any detectable variation on its face was the Moon. Medieval Christians, still under the sway of Aristotle's teaching, ignorantly explained that lunar imperfections were due to the closeness of the Moon and contamination by human corruption on Earth.)

Violent motion, Aristotle's other class of motion, resulted from pushing or pulling forces. Violent motion was imposed motion. A person pushing a cart or lifting a heavy weight imposed motion, as did someone hurling a stone or winning a tug of war. The wind imposed motion on ships. Floodwaters imposed it on boulders and tree trunks. The essential thing about violent motion was that it was externally caused and was imparted to objects; they moved not of themselves, not by their "nature," but because of pushes or pulls.

The concept of violent motion had its difficulties, for the pushes and pulls responsible for it were not always evident. For example, a bowstring moved an arrow until the arrow left the bow; after that, further explanation of the arrow's motion seemed to require some other pushing agent. Aristotle imagined, therefore, that a parting of the air by the moving arrow resulted in a squeezing effect on the rear of the arrow as the air rushed back to prevent a vacuum from forming. The arrow was propelled through the air as a bar of soap is propelled in the bathtub when you squeeze one end of it.

To sum up, Aristotle taught that all motions are due to the nature of the moving object, or due to a sustained push or pull. Provided that an object is in its proper place, it will not move unless subjected to a force. Except for celestial objects, the normal state is one of rest.

Aristotle's statements about motion were a beginning in scientific thought, and, although he did not consider them to be the final words on the subject, his followers for nearly 2000 years regarded his views as beyond question. Implicit in the thinking of ancient, medieval, and early Renaissance times was the notion that the normal state of objects is one of rest. Since it was evident to most thinkers until the 16th century that Earth must be in its proper place, and since a force capable of moving Earth was inconceivable, it seemed quite clear to them that Earth does not move.

[1]Quintessence is the *fifth* essence, the other four being earth, water, air, and fire.

CHECK POINT

Isn't it common sense to think of Earth in its proper place and that a force to move it *is* inconceivable, as Aristotle held, and that Earth *is* at rest in this universe?

Check Your Answer

Aristotle's views were logical and consistent with everyday observations. So, unless you become familiar with the physics to follow in this book, Aristotle's views about motion *do* make common sense. But, as you acquire new information about nature's rules, you'll likely find your common sense progressing beyond Aristotelian thinking.

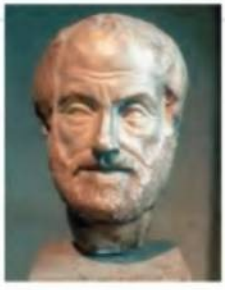
Copernicus and the Moving Earth

Nicolaus Copernicus (1473–1543)

It was in this intellectual climate that the Polish astronomer Nicolaus Copernicus (1473–1543) formulated his theory of the moving Earth. Copernicus reasoned that the simplest way to account for the observed motions of the Sun, Moon, and planets through the sky was to assume that Earth (and other planets) circle around the Sun. For years he worked without making his thoughts public—for two reasons. The first was that he feared persecution; a theory so completely different from common opinion would surely be taken as an attack on established order. The second reason was that he had grave doubts about it himself; he could not reconcile the idea of a moving Earth with the prevailing ideas of motion. Finally, in the last days of his life, at the urging of close friends, he sent his *De Revolutionibus* to the printer. The first copy of his famous exposition reached him on the day he died—May 24, 1543.

Most of us know about the reaction of the medieval Church to the idea that Earth travels around the Sun. Because Aristotle's views had become so formidably a part of Church doctrine, to contradict them was to question the Church itself. For many Church leaders, the idea of a moving Earth threatened not only their authority but the very foundations of faith and civilization as well. For better or for worse, this new idea was to overturn their conception of the cosmos—although eventually the Church embraced it.

Aristotle (384–322 BC)



Greek philosopher, scientist, and educator, Aristotle was the son of a physician who personally served the king of Macedonia. At 17, he entered the Academy of Plato, where he worked and studied for 20 years until Plato's death. He then became the tutor of young Alexander the Great. Eight years later, he formed his own school. Aristotle's aim was to systematize existing knowledge. Just as Euclid had systematized geometry, Aristotle made critical observations, collected specimens, and gathered together, summarized, and classified almost all existing knowledge of the physical world. His systematic approach became the method from which Western science later arose. After his death, his voluminous notebooks were preserved in caves near his home and were later sold to the library at Alexandria. Scholarly activity ceased in most of Europe through the Dark Ages, and the works of Aristotle were forgotten and lost in the scholarship that continued in the Byzantine and Islamic empires. Various texts were reintroduced to Europe during the 11th and 12th centuries and translated into Latin. The Church, the dominant political and cultural force in Western Europe, first prohibited the works of Aristotle and then accepted and incorporated them into Christian doctrine.

Galileo and the Leaning Tower

It was Galileo, the foremost scientist of the early 17th century, who gave credence to the Copernican view of a moving Earth. He accomplished this by discrediting the Aristotelian ideas about motion. Although he was not the first to point out difficulties in Aristotle's views, Galileo was the first to provide conclusive refutation through observation and experiment.

Galileo easily demolished Aristotle's falling-body hypothesis. Galileo is said to have dropped objects of various weights from the top of the Leaning Tower of Pisa to compare their falls. Contrary to Aristotle's assertion, Galileo found that a stone twice as heavy as another did not fall twice as fast. Except for the small effect of air resistance, he found that objects of various weights, when released at the same time, fell together and hit the ground at the same time. On one occasion, Galileo allegedly attracted a large crowd to witness the dropping of two objects of different weight from the top of the tower. Legend has it that many observers of this demonstration who saw the objects hit the ground together scoffed at the young Galileo and continued to hold fast to their Aristotelian teachings.

FIGURE 2.1
Galileo's famous demonstration.

Galileo's Inclined Planes

Galileo was concerned with *how* things move rather than *why* they move. He showed that experiment rather than logic is the best test of knowledge. Aristotle was an astute observer of nature, and he dealt with problems around him rather than with abstract cases that did not occur in his environment. Motion always involved a resistive medium such as air or water. He believed a vacuum to be impossible and therefore did not give serious consideration to motion in the absence of an interacting medium. That's why it was basic to Aristotle that an object requires a push or pull to keep it moving. And it was this basic principle that Galileo rejected when he stated that, if there is no interference with a moving object, it will keep moving in a straight line forever; no push, pull, or force of any kind is necessary.

Galileo was concerned with how things move rather than why they move. He showed that experiment rather than logic is the best test of knowledge.

Galileo Galilei (1564–1642)

Galileo was born in Pisa, Italy, in the same year Shakespeare was born and Michelangelo died. He studied medicine at the University of Pisa and then changed to mathematics. He developed an early interest in motion and was soon at odds with his contemporaries, who held to Aristotelian ideas on falling bodies. Galileo's experiments with falling bodies discredited Aristotle's assertion that the speed of a falling object was proportional to its weight, as discussed above. But quite importantly, Galileo's findings also threatened the authority of the Church, who held that the teachings of Aristotle were part of Church doctrine. Galileo went on to report his telescopic observations, which got him further in trouble with the Church. He told of his sightings of moons that orbited the planet Jupiter. The Church, however, taught that everything in the heavens revolved around Earth. Galileo also reported dark spots on the Sun, but according to Church doctrine, God created the Sun as a perfect source of light, without blemish. Under pressure, Galileo recanted his discoveries and avoided the fate of Giordano Bruno, who held firm to his belief in the Copernican model of the solar system and was burned at the stake in 1600. Nevertheless, Galileo was sentenced to perpetual house arrest. Earlier, he had damaged his eyes while investigating the Sun in his telescopic studies, which led to blindness at the age of 74. He died 4 years later. Every age has intellectual rebels, some of whom push the frontiers of knowledge further. Among them is certainly Galileo.

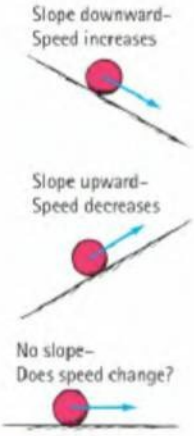


FIGURE 2.2
Motion of balls on various planes.

Galileo tested this hypothesis by experimenting with the motion of various objects on plane surfaces tilted at various angles. He noted that balls rolling on downward-sloping planes picked up speed, while balls rolling on upward-sloping planes lost speed. From this he reasoned that balls rolling along a horizontal plane would neither speed up nor slow down. The ball would finally come to rest not because of its "nature," but because of friction. This idea was supported by Galileo's observation of motion along smoother surfaces: When there was less friction, the motion of objects persisted for a longer time; the less the friction, the more the motion approached constant speed. He reasoned that, in the absence of friction or other opposing forces, a horizontally moving object would continue moving indefinitely.

This assertion was supported by a different experiment and another line of reasoning. Galileo placed two of his inclined planes facing each other. He observed that a ball released from a position of rest at the top of a downward-sloping plane rolled down and then up the slope of the upward-sloping plane until it almost reached its initial height. He reasoned that only friction prevented it from rising to exactly the same height, for the smoother the planes, the closer the ball rose to the same height. Then he reduced the angle of the upward-sloping plane. Again the ball rose to the same height, but it had to go farther. Additional reductions of the angle yielded similar results; to reach the same height, the ball had to go farther each time. He then asked the question, "If I have a long horizontal plane, how far must the ball go to reach the same height?" The obvious answer is "Forever—it will never reach its initial height."[2]

Galileo analyzed this in still another way. Because the downward motion of the ball from the first plane is the same for all cases, the speed of the ball when it begins moving up the second plane is the same for all cases. If it moves up a steep slope, it loses its speed rapidly. On a lesser slope, it loses its speed more slowly and rolls for a longer time. The less the upward slope, the more slowly it loses its speed. In the extreme case in which there is no slope at all—that is, when the plane is horizontal—the ball should not lose any speed. In the absence of retarding forces, the tendency of the ball is to move forever without slowing down. We call this property of an object to resist changes in motion **inertia.**

fyi

- Galileo published the first mathematical treatment of motion in 1632—12 years after the Pilgrims landed at Plymouth Rock.

Galileo's concept of inertia discredited the Aristotelian theory of motion. Aristotle did not recognize the idea of inertia because he failed to imagine what motion would be like without friction. In his experience, all motion was subject to

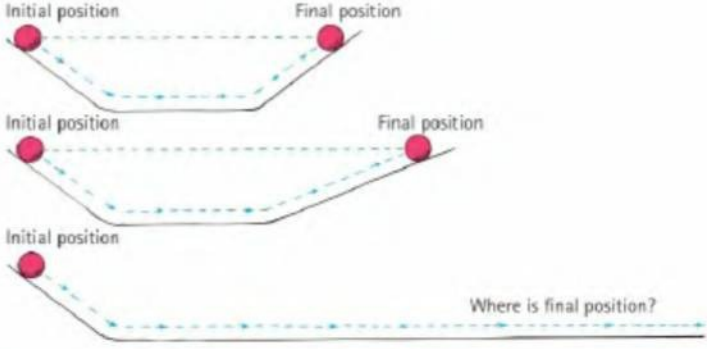


FIGURE 2.3
A ball rolling down an incline on the left tends to roll up to its initial height on the right. The ball must roll a greater distance as the angle of incline on the right is reduced.

[2]From Galileo's *Dialogues Concerning the Two New Sciences.*

resistance, and he made this fact central to his theory of motion. Aristotle's failure to recognize friction for what it is—namely, a force like any other—impeded the progress of physics for nearly 2000 years, until the time of Galileo. An application of Galileo's concept of inertia would show that no force is required to keep Earth moving forward. The way was open for Isaac Newton to synthesize a new vision of the universe.

CHECK POINT

Would it be correct to say that inertia is the *reason* a moving object continues in motion when no force acts upon it?

Check Your Answer

In the strict sense, no. We don't know the reason for objects persisting in their motion when no forces act upon them. We refer to the property of material objects to behave in this predictable way as *inertia*. We understand many things and have labels and names for these things. There are many things we do not understand, and we have labels and names for these things also. Education consists not so much in acquiring new names and labels, but in learning which phenomena we understand and which we don't.

In 1642, several months after Galileo died, Isaac Newton was born. By the time Newton was 23, he developed his famous laws of motion, which completed the overthrow of the Aristotelian ideas that had dominated the thinking of the best minds for nearly two millennia. In this chapter, we will consider the first of Newton's laws. It is a restatement of the concept of inertia as proposed earlier by Galileo. (Newton's three laws of motion first appeared in one of the most important books of all time, Newton's *Principia*.)

Inertia isn't a kind of force; it's a property of all matter to resist changes in motion.

Newton's First Law of Motion

Aristotle's idea that a moving object must be propelled by a steady force was completely turned around by Galileo, who stated that, in the *absence* of a force, a moving object will continue moving. The tendency of things to resist changes in motion was what Galileo called *inertia*. Newton refined Galileo's idea and made it his first law, appropriately called the **law of inertia.** From Newton's *Principia* (translated from the original Latin):

Every object continues in a state of rest or of uniform speed in a straight line unless acted on by a nonzero net force.

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Toilet Paper Roll
Inertia of a Cylinder
Inertia of an Anvil

The key word in this law is *continues:* An object *continues* to do whatever it happens to be doing unless a force is exerted upon it. If it is at rest, it *continues* in a state of rest. This is nicely demonstrated when a tablecloth is skillfully whipped from under dishes on a tabletop, leaving the dishes in their initial state of rest. This property of objects to resist changes in motion is called inertia.

If an object is moving, it *continues* to move without turning or changing its speed. This is evident in space probes that continually move in outer space. Changes in motion must be imposed against the tendency of an object to retain its state of motion. In the absence of net forces, a moving object tends to move along a straight-line path indefinitely.

FIGURE 2.4
Inertia in action.

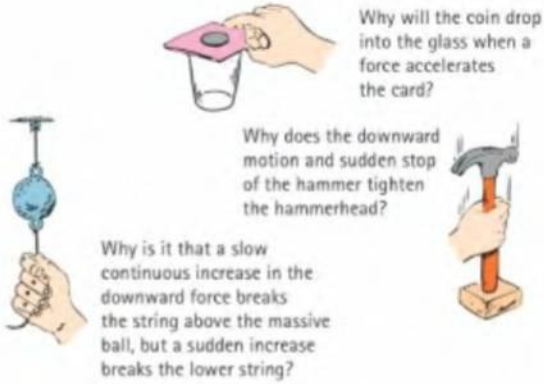

FIGURE 2.5
Examples of inertia.

You can think of inertia as another word for *laziness* (or resistance to change).

CHECK POINT

A hockey puck sliding across the ice finally comes to rest. How would Aristotle have interpreted this behavior? How would Galileo and Newton have interpreted it? How would you interpret it? *(Think before you read the answers below!)*

Check Your Answers

Aristotle would probably say that the puck slides to a stop because it seeks its proper and natural state, one of rest. Galileo and Newton would probably say that, once in motion, the puck would continue in motion and that what prevents continued motion is not its nature or its proper rest state, but the friction the puck encounters. This friction is small compared with the friction between the puck and a wooden floor, which is why the puck slides so much farther on ice. Only you can answer the last question.

Net Force

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Definition of a Newton

Changes in motion are produced by a force or combination of forces (in the next chapter we'll refer to changes in motion as *acceleration*). A **force,** in the simplest sense, is a push or a pull. Its source may be gravitational, electrical, magnetic, or simply muscular effort. When more than a single force acts on an object, we consider the ***net* force.** For example, if you and a friend pull in the same direction with equal forces on an object, the forces combine to produce a net force twice as great as your single force. If each of you pull with equal forces in *opposite* directions, the net force is zero. The equal but oppositely directed forces cancel each other. One of the forces can be considered to be the negative of the other, and they add algebraically to zero, with a resulting net force of zero.

Figure 2.6 shows how forces combine to produce a net force. A pair of 5-newton forces in the same direction produce a net force of 10 newtons (the newton, N, is the scientific unit of force). If the 5-newton forces are in opposite directions, the net force is zero. If 10 newtons of force is exerted to the right and 5 newtons to the left, the net force is 5 newtons to the right. The forces are shown by arrows. A quantity such as force that has both magnitude and direction is called a *vector quantity.* Vector quantities can be represented by arrows whose length and direction show the magnitude and direction of the quantity. (More about vectors in Chapter 4.)

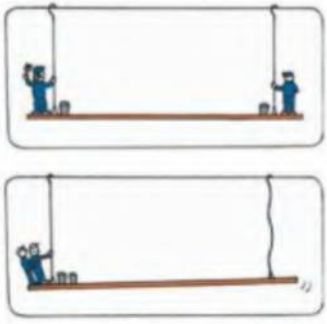
Personal Essay

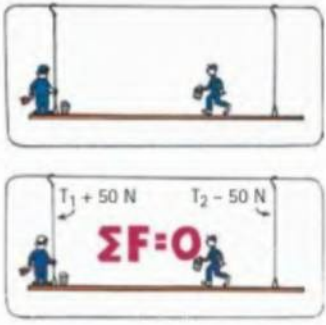
When I was in high school, my counselor advised me not to enroll in science and math classes and instead to focus on what seemed to be my gift for art. I took this advice. I was then interested in drawing comic strips and in boxing, neither of which earned me much success. After a stint in the Army, I tried my luck at sign painting, and the cold Boston winters drove me south to warmer Miami, Florida. There, at age 26, I got a job painting billboards and met a man who became a great intellectual influence on me, Burl Grey. Like me, Burl had never studied physics in high school. But he was passionate about science in general, and he shared his passion with many questions as we painted together. I remember Burl asking me about the tensions in the ropes that held up the scaffold we were on. The scaffold was simply a heavy horizontal plank suspended by a pair of ropes. Burl twanged the rope nearest his end of the scaffold and asked me to do the same with mine. He was comparing the tensions in both ropes—to determine which was greater. Burl was heavier than I was, and he reasoned that the tension in his rope was greater. Like a more tightly stretched guitar string, the rope with greater tension twangs at a higher pitch. The finding that Burl's rope had a higher pitch seemed reasonable because his rope supported more of the load.

When I walked toward Burl to borrow one of his brushes, he asked if the tensions in the ropes had changed. Did tension in his rope increase as I moved closer? We agreed that it should have, because even more of the load was supported by Burl's rope. How about my rope? Would its tension decrease? We agreed that it would, for it would be supporting less of the total load. I was unaware at the time that I was discussing physics. Burl and I used exaggeration to bolster our reasoning (just as physicists do). If we both stood at an extreme end of the scaffold and leaned outward, it was easy to imagine the opposite end of the scaffold rising like the end of a seesaw—with the opposite rope going limp. Then there would be no tension in that rope. We then reasoned the tension in my rope would gradually decrease as I walked toward Burl. It was fun posing such questions and seeing if we could answer them.

A question that we couldn't answer was whether or not the decrease in tension in my rope when I walked away from it would be *exactly* compensated by a tension increase in Burl's rope. For example, if my rope underwent a decrease of 50 newtons, would Burl's rope gain 50 newtons? (We talked pounds back then, but here we use the scientific unit of force, the *newton*—abbreviated N.) Would the gain be *exactly* 50 N? And, if so, would this be a grand coincidence? I didn't know the answer until more than a year later, when Burl's stimulation resulted in my leaving full-time painting and going to college to learn more about science.[1]

At college, I learned that any object at rest, such as the sign-painting scaffold that supported us, is said to be in equilibrium. That is, all the forces that act on it balance to zero. So the sums of the upward forces supplied by the supporting ropes indeed do add up to our weights plus the weight of the scaffold. A 50-N loss in one would be accompanied by a 50-N gain in the other.





I tell this true story to make the point that one's thinking is very different when there is a rule to guide it. Now when I look at any motionless object I know immediately that all the forces acting on it cancel out. We view nature differently when we know its rules. Without the rules of physics, we tend to be superstitious and to see magic where there is none. Quite wonderfully, everything is connected to everything else by a surprisingly small number of rules, and in a beautifully simple way. The rules of nature are what the study of physics is about.

[1] I am forever indebted to Burl Grey for the stimulation he provided, for when I continued with formal education, it was with enthusiasm. I lost touch with Burl for 40 years. A student in my class at the Exploratorium in San Francisco, Jayson Wechter, who was a private detective, located him in 1998 and put us in contact. Friendship renewed, we once again continue in spirited conversations.

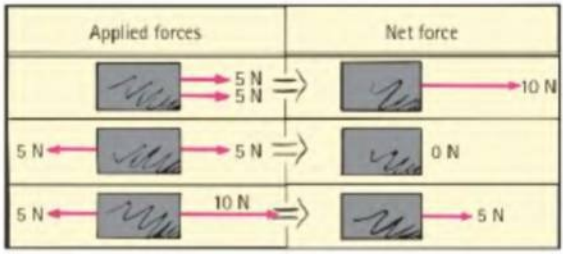


FIGURE 2.6
Net force (a force of 5 N is about 1.1 lb).

The Equilibrium Rule

If you tie a string around a 2-pound bag of flour and hang it on a weighing scale (Figure 2.7), a spring in the scale stretches until the scale reads 2 pounds. The stretched spring is under a "stretching force" called *tension*. The same scale in a science lab is likely calibrated to read the same force as 9 newtons. Both pounds and newtons are units of weight, which in turn are units of *force*. The bag of flour is attracted to Earth with a gravitational force of 2 pounds—or, equivalently, 9 newtons. Hang twice as much flour from the scale and the reading will be 18 newtons.

FIGURE 2.7
Burl Grey, who first introduced the author to tension forces, suspends a 2-lb bag of flour from a spring scale, showing its weight and the tension in the string of about 9 N.

Note that there are two forces acting on the bag of flour—tension force acting upward and weight acting downward. The two forces on the bag are equal and opposite, and they cancel to zero. Hence, the bag remains at rest. In accord with Newton's first law, no net force acts on the bag. We can look at Newton's first law in a different light—*mechanical equilibrium*.

When the net force on something is zero, we say that something is in **mechanical equilibrium.**[4] In mathematical notation, the **equilibrium rule** is

$$\Sigma \mathbf{F} = 0$$

The symbol Σ stands for "the vector sum of" and $\mathbf{F}$ stands for "forces." For a suspended object at rest, like the bag of flour, the rule says that the forces acting upward on the object must be balanced by other forces acting downward to make the vector sum equal zero. (Vector quantities take direction into account, so if upward forces are +, downward ones are −, and, when added, they actually subtract.)

Everything not undergoing changes in motion is in mechanical equilibrium. That's when $\Sigma \mathbf{F} = 0$.

In Figure 2.8, we see the forces involved for Burl and Hewitt on their sign-painting scaffold. The sum of the upward tensions is equal to the sum of their weights plus the weight of the scaffold. Note how the magnitudes of the two upward vectors equal the magnitude of the three downward vectors. Net force on the scaffold is zero, so we say it is in mechanical equilibrium.

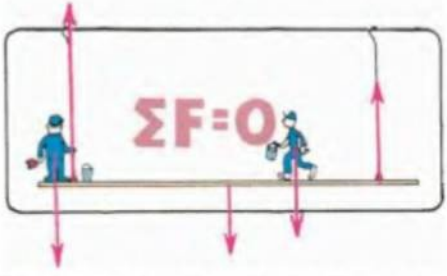


FIGURE 2.8
The sum of the upward vectors equals the sum of the downward vectors. $\Sigma \mathbf{F} = 0$ and the scaffold is in equilibrium.

[4]Something in equilibrium is without a change in its state of motion. When we study rotational motion in Chapter 8, we'll see that another condition for mechanical equilibrium is that the net *torque* equals zero.

CHECK POINT

Consider the gymnast hanging from the rings.

1. If she hangs with her weight evenly divided between the two rings, how would scale readings in both supporting ropes compare with her weight?
2. Suppose she hangs with slightly more of her weight supported by the left ring. How will the right scale read?

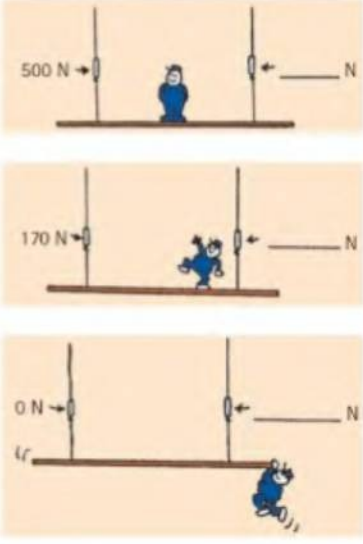
Check Your Answers

(Are you reading this before you have formulated reasoned answers in your thinking? If so, do you also exercise your body by watching others do push-ups? Exercise your thinking. When you encounter the many Check Point questions throughout this book, think before you check the answers!)

1. The reading on each scale will be half her weight. The sum of the readings on both scales then equals her weight.
2. When more of her weight is supported by the left ring, the reading on the right scale will be less. For vertical or near-vertical ropes, the sum of the upward pulls of both scales will equal her weight. (The upward pulls provided by the rope tensions for nonparallel ropes is treated in Figure 5.25 on page 75.)

Practicing Physics

1. When Burl stands alone in the exact middle of his scaffold, the left scale reads 500 N. Fill in the reading on the right scale. The total weight of Burl and the scaffold must be _____ N.
2. Burl stands farther from the left. Fill in the reading on the right scale.
3. In a silly mood, Burl dangles from the right end. Fill in the reading on the right scale.



Practicing Physics Answers

Do your answers illustrate the equilibrium rule? In Question 1, the right rope must be under **500 N** of tension because Burl is in the middle and both ropes support his weight equally. Since the sum of upward tensions is 1000 N, the total weight of Burl and the scaffold must be **1000 N.** Let's call the upward tension forces +1000 N. Then the downward weights are −1000 N. What happens when you add +1000 N and −1000 N? The answer is that they equal zero. So we see that $\Sigma F = 0$.

For Question 2, did you get the correct answer of **830 N?** Reasoning: We know from Question 1 that the sum of the rope tensions equals 1000 N, and since the left rope has a tension of 170 N, the other rope must make up the difference—that 1000 N − 170 N = 830 N. Get it? If so, great. If not, talk about it with your friends until you do. Then read further.

The answer to Question 3 is **1000 N.** Do you see that this illustrates $\Sigma F = 0$.

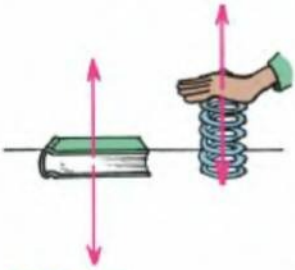


FIGURE 2.9

(Left) The table pushes up on the book with as much force as the downward force of gravity on the book. (Right) The spring pushes up on your hand with as much force as you exert to push down on the spring.

Support Force

Consider a book lying at rest on a table. It is in equilibrium. What forces act on the book? One force is that due to gravity—the *weight* of the book. Since the book is in equilibrium, there must be another force acting on the book to produce a net force of zero—an upward force opposite to the force of gravity. The table exerts this upward force. We call this the upward *support force*. This upward support force, often called the *normal force*, must equal the weight of the book.[5] If we call the upward force positive, then the downward weight is negative, and the two add to become zero. The net force on the book is zero. Another way to say the same thing is $\Sigma \mathbf{F} = 0$.

To understand better that the table pushes up on the book, compare the case of compressing a spring (Figure 2.9). If you push the spring down, you can feel the spring pushing up on your hand. Similarly, the book lying on the table compresses atoms in the table, which behave like microscopic springs. The weight of the book squeezes downward on the atoms, and they squeeze upward on the book. In this way, the compressed atoms produce the support force.

When you step on a bathroom scale, two forces act on the scale. One is your downward push on the scale—the result of gravity pulling on you—and the other is the upward support force of the floor. These forces squeeze a mechanism (in effect, a spring) within the scale that is calibrated to show the magnitude of the support force (Figure 2.10). It is this support force that shows your weight. When you weigh yourself on a bathroom scale at rest, the support force and the force of gravity pulling you down have the same magnitude. Hence we can say that your weight is the force of gravity acting on you.

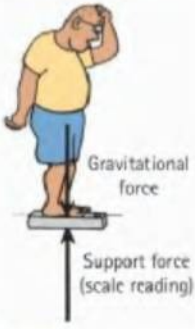


FIGURE 2.10

The upward support is as much as the downward gravitational force.

CHECK POINT

1. What is the net force on a bathroom scale when a 150-pound person stands on it?
2. Suppose you stand on two bathroom scales with your weight evenly divided between the two scales. What will each scale read? What happens when you stand with more of your weight on one foot than the other?

Check Your Answers

1. Zero, as evidenced by the scale remaining at rest. The scale reads the *support force*, which has the same magnitude as weight—not the net force.
2. The reading on each scale is half your weight. Then the sum of the scale readings will balance your weight and the net force on you will be zero. If you lean more on one scale than the other, more than half your weight will be read on that scale but less on the other, so they will still add up to your weight. Like the example of the gymnast hanging by the rings, if one scale reads two-thirds your weight, the other scale will read one-third your weight.

Equilibrium of Moving Things

Rest is only one form of equilibrium. An object moving at constant speed in a straight-line path is also in equilibrium. Equilibrium is a state of no change. A bowling ball rolling at constant speed in a straight line is in equilibrium—until it hits the pins. Whether at rest (static equilibrium) or steadily rolling in a straight-line path (dynamic equilibrium), $\Sigma \mathbf{F} = 0$.

A zero net force on an object doesn't mean the object must be at rest, but that its state of motion remains unchanged. It can be at rest or moving uniformly in a straight line.

[5]This force acts at right angles to the surface. When we say "normal to," we are saying "at right angles to," which is why this force is called a normal force.

It follows from Newton's first law that an object under the influence of only one force cannot be in equilibrium. Net force couldn't be zero. Only when two or more forces act on it can it be in equilibrium. We can test whether or not something is in equilibrium by noting whether or not it undergoes changes in its state of motion.

Consider a crate being pushed horizontally across a factory floor. If it moves at a steady speed in a straight-line path, it is in dynamic equilibrium. This tells us that more than one force acts on the crate. Another force exists—likely the force of friction between the crate and the floor. The fact that the net force on the crate equals zero means that the force of friction must be equal and opposite to our pushing force.

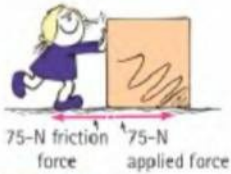


FIGURE 2.11
When the push on the crate is as great as the force of friction between the crate and the floor, the net force on the crate is zero and it slides at an unchanging speed.

The equilibrium rule, $\Sigma \mathbf{F} = 0$, provides a reasoned way to view all things at rest—balancing rocks, objects in your room, or the steel beams in bridges or in building construction. Whatever their configuration, if in static equilibrium, all acting forces always balance to zero. The same is true of objects that move steadily, not speeding up, slowing down, or changing direction. For dynamic equilibrium, all acting forces also balance to zero. The equilibrium rule is one that allows you to see more than meets the eye of the casual observer. It's nice to know the reasons for the stability of things in our everyday world.

There are different forms of equilibrium. In Chapter 8, we'll talk about rotational equilibrium, and, in Part 4, we'll discuss thermal equilibrium associated with heat. Physics is everywhere.

CHECK POINT

An airplane flies at constant speed in a horizontal straight path. In other words, the flying plane is in equilibrium. Two horizontal forces act on the plane. One is the thrust of the propellers that push it forward, and the other is the force of air resistance that acts in the opposite direction. Which force is greater?

Check Your Answer

Both forces have the same magnitude. Call the forward force exerted by the propellers positive. Then the air resistance is negative. Since the plane is in dynamic equilibrium, can you see that the two forces combine to equal zero? Hence it neither gains nor loses speed.

The Moving Earth

When Copernicus announced the idea of a moving Earth in the 16th century, the concept of inertia was not understood. There was much arguing and debate about whether or not Earth moved. The amount of force required to keep Earth moving was beyond imagination. Another argument against a moving Earth was the following: Consider a bird sitting at rest at the top of a tall tree. On the ground below is a fat, juicy worm. The bird sees the worm and drops vertically below and catches it. This would be impossible, it was argued, if Earth moved as Copernicus suggested. If Copernicus were correct, Earth would have to travel at a speed of 107,000 kilometers per hour to circle the Sun in one year. Convert this speed to kilometers per second and you'll get 30 kilometers per second. Even if the bird could descend from its branch in 1 second, the worm would have been swept by the moving Earth a distance of 30 kilometers away. It would be impossible for a bird to drop straight down and catch a worm. But birds in fact *do* catch worms from high tree branches, which seemed to be clear evidence that Earth must be at rest.

FIGURE 2.12
Can the bird drop down and catch the worm if Earth moves at 30 km/s?

Can you refute this argument? You can if you invoke the idea of inertia. You see, not only is Earth moving at 30 kilometers per second but so are the tree, the branch of the tree, the bird that sits on it, the worm below, and even the air in between. All

FIGURE 2.13
When you flip a coin in a high-speed airplane, it behaves as if the airplane were at rest. The coin keeps up with you—inertia in action!

are moving at 30 kilometers per second. Things in motion remain in motion if no unbalanced forces are acting upon them. So, when the bird drops from the branch, its initial sideways motion of 30 kilometers per second remains unchanged. It catches the worm, quite unaffected by the motion of its total environment.

Stand next to a wall. Jump up so that your feet are no longer in contact with the floor. Does the 30-kilometer-per-second wall slam into you? It doesn't, because you are also traveling at 30 kilometers per second—before, during, and after your jump. The 30 kilometers per second is the speed of Earth relative to the Sun, not the speed of the wall relative to you.

People 400 years ago had difficulty with ideas like these, not only because they failed to acknowledge the concept of inertia but because they were not accustomed to moving in high-speed vehicles. Slow, bumpy rides in horsedrawn carriages did not lend themselves to experiments that would reveal the effect of inertia. Today we flip a coin in a high-speed car, bus, or plane, and we catch the vertically moving coin as we would if the vehicle were at rest. We see evidence for the law of inertia when the horizontal motion of the coin before, during, and after the catch is the same. The coin keeps up with us. The vertical force of gravity affects only the vertical motion of the coin.

Our notions of motion today are very different from those of our ancestors. Aristotle did not recognize the idea of inertia because he did not see that all moving things follow the same rules. He imagined that rules for motion in the heavens were very different from the rules of motion on Earth. He saw vertical motion as natural but horizontal motion as unnatural, requiring a sustained force. Galileo and Newton, on the other hand, saw that all moving things follow the same rules. To them, moving things require *no* force to keep moving if there are no opposing forces, such as friction. We can only wonder how differently science might have progressed if Aristotle had recognized the unity of all kinds of motion.

SUMMARY OF TERMS

Inertia The property of things to resist changes in motion.

Newton's first law of motion (the law of inertia) Every object continues in a state of rest or of uniform speed in a straight line unless acted on by a nonzero net force.

Force In the simplest sense, a push or a pull.

Net force The vector sum of forces that act on an object.

Mechanical equilibrium The state of an object or system of objects for which there are no changes in motion. In accord with Newton's first law, if at rest, the state of rest persists. If moving, motion continues without change.

Equilibrium rule For any object or system of objects in equilibrium, the sum of the forces acting equals zero. In equation form, $\Sigma \mathbf{F} = 0$.

REVIEW QUESTIONS

Each chapter in this book concludes with a set of review questions, exercises, and, for some chapters, ranking exercises, and problems. The ***Review Questions*** *are designed to help you comprehend ideas and catch the essentials of the chapter material. You'll notice that answers to the questions can be found within the chapters. In some chapters, there is a set of single-step numerical problems—****Plug and Chug****—that are meant to acquaint you with equations in the chapter. In some chapters* ***Ranking*** *tasks prompt you to compare the magnitudes of various concepts. All chapters have* ***Exercises*** *that stress thinking rather than mere recall of information. Unless you cover only a few chapters in your course, you will likely be expected to tackle only a few exercises for each chapter. Answers should be in complete sentences, with an explanation or sketch when applicable. The large number of exercises is to allow your instructor a wide choice of assignments.* ***Problems*** *go further than Plug and Chugs and feature concepts that are more clearly understood with more challenging computations. Challenging problems are indicated with a bullet (•). Solutions to odd-numbered Rankings, Exercises, and Problems are shown at the back of this book. Additional problems are in the supplement* ***Problem Solving in Conceptual Physics.***

Aristotle on Motion

1. Contrast Aristotle's ideas of natural motion and violent motion.
2. What class of motion, natural or violent, did Aristotle attribute to motion of the Moon?
3. What state of motion did Aristotle attribute to Earth?

Copernicus and the Moving Earth

4. What relationship between the Sun and Earth did Copernicus formulate?

Galileo and the Leaning Tower

5. What did Galileo discover in his legendary experiment on the Leaning Tower of Pisa?

Galileo's Inclined Planes

6. What did Galileo discover about moving bodies and force in his experiments with inclined planes?
7. What does it mean to say that a moving object has inertia? Give an example.
8. Is inertia the *reason* for moving objects maintaining motion or the *name* given to this property?

Newton's First Law of Motion

9. Cite Newton's first law of motion.

Net Force

10. What is the net force on a cart that is pulled to the right with 100 pounds and to the left with 30 pounds?
11. Why do we say that force is a vector quantity?

The Equilibrium Rule

12. Can force be expressed in units of pounds and also in units of newtons?
13. What is the net force on an object that is pulled with 80 newtons to the right and 80 newtons to the left?
14. What is the net force on a bag pulled down by gravity with 18 newtons and pulled upward by a rope with 18 newtons?
15. What does it mean to say something is in mechanical equilibrium?
16. State the equilibrium rule in symbolic notation.

Support Force

17. Consider a book that weighs 15 N at rest on a flat table. How many newtons of support force does the table provide? What is the net force on the book in this case?
18. When you stand at rest on a bathroom scale, how does your weight compare with the support force by the scale?

Equilibrium of Moving Things

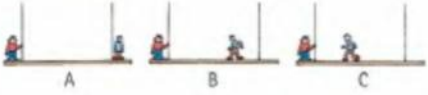
19. A bowling ball at rest is in equilibrium. Is the ball in equilibrium when it moves at constant speed in a straight-line path?
20. What is the test for whether or not a moving object is in equilibrium?
21. If you push on a crate with a force of 100 N and it slides at constant velocity, how much is the friction acting on the crate?

The Moving Earth

22. What concept was missing in people's minds in the 16th century when they couldn't believe Earth was moving?
23. A bird sitting in a tree is traveling at 30 km/s relative to the faraway Sun. When the bird drops to the ground below, does it still go 30 km/s, or does this speed become zero?
24. Stand next to a wall that travels at 30 km/s relative to the Sun. With your feet on the ground, you also travel the same 30 km/s. Do you maintain this speed when your feet leave the ground? What concept supports your answer?
25. What did Aristotle fail to recognize about the rules of nature for objects on Earth and in the heavens?

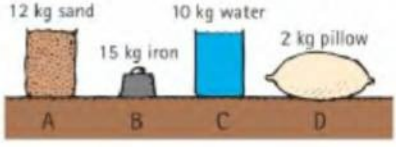
RANKING

1. The weights of Burl, Paul, and the scaffold produce tensions in the supporting ropes. Rank the tension in the *left* rope, from most to least, in the three situations, A, B, and C.

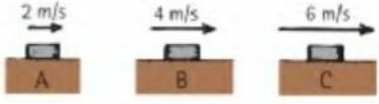


2. Rank the net force on the block from least to most in the four situations, A, B, C, and D.

3. Different materials, A, B, C, and D, rest on a table.
   a. From greatest to least, rank them by how much they resist being set into motion.
   b. From greatest to least, rank them by the support (normal) force the table exerts on them.



4. Three pucks, A, B, and C, are shown sliding across ice at the noted speeds. Air and ice friction forces are negligible.



   a. Rank them, from greatest to least, by the force needed to keep them moving.
   b. Rank them, from greatest to least, by the force needed to stop them in the same time interval.

EXERCISES

Please do not be intimidated by the large number of exercises in this book. As mentioned earlier, if your course work is to cover many chapters, your instructor will likely assign only a few exercises from each.

1. A ball rolling along a floor doesn't continue rolling indefinitely. Is it because it is seeking a place of rest or because some force is acting upon it? If the latter, identify the force.
2. Copernicus postulated that Earth moves around the Sun (rather than the other way around), but he was troubled about the idea. What concepts of mechanics was he missing (concepts later introduced by Galileo and Newton) that would have eased his doubts?
3. What Aristotelian idea did Galileo discredit in his fabled Leaning Tower demonstration?
4. What Aristotelian idea did Galileo demolish with his experiments with inclined planes?
5. Was it Galileo or Newton who first proposed the concept of inertia?
6. Asteroids have been moving through space for billions of years. What keeps them moving?
7. A space probe may be carried by a rocket into outer space. What keeps the probe moving after the rocket no longer pushes it?
8. In answer to the question "What keeps Earth moving around the Sun?" a friend asserts that inertia keeps it moving. Correct your friend's erroneous assertion.
9. Your friend says that inertia is a force that keeps things in their place, either at rest or in motion. Do you agree? Why or why not?
10. Why is it important that Tim pull slightly downward when he attempts to whip the cloth from beneath the dishes? (What occurs if he pulls slightly upward?)

11. Consider a ball at rest in the middle of a toy wagon. When the wagon is pulled forward, the ball rolls against the back of the wagon. Interpret this observation in terms of Newton's first law.
12. In tearing a paper towel or plastic bag from a roll, why is a sharp jerk more effective than a slow pull?
13. If you're in a car at rest that gets hit from behind, you can suffer a serious neck injury called whiplash. What does whiplash have to do with Newton's first law?
14. In terms of Newton's first law (the law of inertia), how does a car headrest help to guard against whiplash in a rear-end collision?
15. Why do you lurch forward in a bus that suddenly slows? Why do you lurch backward when it picks up speed? What law applies here?
16. Suppose that you're in a moving car and the motor stops running. You step on the brakes and slow the car to half speed. If you release your foot from the brakes, will the car speed up a bit, or will it continue at half speed and slow due to friction? Defend your answer.
17. When you push a cart, it moves. When you stop pushing, it comes to rest. Does this violate Newton's law of inertia? Defend your answer.
18. Each bone in the chain of bones forming your spine is separated from its neighbors by disks of elastic tissue. What happens, then, when you jump heavily onto your feet from an elevated position? (*Hint:* Think about the hammerhead in Figure 2.5.) Can you think of a reason why you are a little taller in the morning than at night?
19. Start a ball rolling down a bowling alley and you'll find that it moves slightly slower with time. Does this violate Newton's law of inertia? Defend your answer.
20. Consider a pair of forces, one having a magnitude of 20 N and the other a magnitude of 12 N. What maximum net force is possible for these two forces? What is the minimum net force possible?
21. When any object is in mechanical equilibrium, what can be correctly said about all the forces that act on it? Must the net force necessarily be zero?
22. A monkey hangs stationary at the end of a vertical vine. What two forces act on the monkey? Which, if either, is greater?
23. Can an object be in mechanical equilibrium when only a single force acts on it? Explain.
24. When a ball is tossed straight up, it momentarily comes to a stop at the top of its path. Is it in equilibrium during this brief moment? Why or why not?
25. A hockey puck slides across the ice at a constant speed. Is it in equilibrium? Why or why not?
26. Can you say that no force acts on a body at rest? Or is it correct to say that no *net* force acts on it? Defend your answer.
27. Nellie Newton hangs at rest from the ends of the rope as shown. How does the reading on the scale compare with her weight?

28. Harry the painter swings year after year from his bosun's chair. His weight is 500 N and the rope, unknown to him, has a breaking point of 300 N. Why doesn't the rope break when he is supported as shown at the left? One day, Harry is painting near a flagpole, and, for a change, he ties the free end of the rope to the flagpole instead of to his chair, as shown

at the right. Why did Harry end up taking his vacation early?

29. For the pulley system shown, what is the upper limit of weight the strong man can lift?

30. If the strong man in the previous exercise exerts a downward force of 800 N on the rope, how much upward force is exerted on the block?

31. A force of gravity pulls downward on a book on a table. What force prevents the book from accelerating downward?

32. How many significant forces act on a book at rest on a table? Identify the forces.

33. Consider the normal force on a book at rest on a tabletop. If the table is tilted so that the surface forms an inclined plane, will the magnitude of the normal force change? If so, how?

34. When you push downward on a book at rest on a table, you feel an upward force. Does this force depend on friction? Defend your answer.

35. Place a heavy book on a table and the table pushes up on the book. Why doesn't this upward push cause the book to rise from the table?

36. As you stand on a floor, does the floor exert an upward force against your feet? How much force does it exert? Why are you not moved upward by this force?

37. An empty jug of weight W rests on a table. What is the support force exerted on the jug by the table? What is the support force when water of weight w is poured into the jug?

38. If you pull horizontally on a crate with a force of 200 N, it slides across the floor in dynamic equilibrium. How much friction is acting on the crate?

39. In order to slide a heavy cabinet across the floor at constant speed, you exert a horizontal force of 600 N. Is the force of friction between the cabinet and the floor greater than, less than, or equal to 600 N? Defend your answer.

40. Consider a crate at rest on a factory floor. As a pair of workmen begin lifting it, does the support force on the crate provided by the floor increase, decrease, or remain unchanged? What happens to the support force on the workmen's feet?

41. Two people each pull with 300 N on a rope in a tug of war. What is the net force on the rope? How much force is exerted on each person by the rope?

42. Two forces act on a parachutist falling in air: weight and air drag. If the fall is steady, with no gain or loss of speed, then the parachutist is in dynamic equilibrium. How do the magnitudes of weight and air drag compare?

43. A child learns in school that Earth is traveling faster than 100,000 kilometers per hour around the Sun and, in a frightened tone, asks why we aren't swept off. What is your explanation?

44. Before the time of Galileo and Newton, some learned scholars thought that a stone dropped from the top of a tall mast of a moving ship would fall vertically and hit the deck behind the mast by a distance equal to how far the ship had moved forward while the stone was falling. In light of your understanding of Newton's first law, what do you think about this?

45. Because Earth rotates once every 24 hours, the west wall in your room moves in a direction toward you at a linear speed that is probably more than 1000 kilometers per hour (the exact speed depends on your latitude). When you stand facing the wall, you are carried along at the same speed, so you don't notice it. But when you jump upward, with your feet no longer in contact with the floor, why doesn't the high-speed wall slam into you?

46. If you toss a coin straight upward while riding in a train, where does the coin land when the motion of the train is uniform along a straight-line track? When the train slows while the coin is in the air? When the train is turning?

47. The smokestack of a stationary toy train consists of a vertical spring gun that shoots a steel ball a meter or so straight into the air—so straight that the ball always falls back into the smokestack. Suppose the train moves at constant speed along the straight track. Do you think the ball will still return to the smokestack if shot from the moving train? What if the train gains speed along the straight track? What if it moves at a constant speed on a circular track? Why do your answers differ?

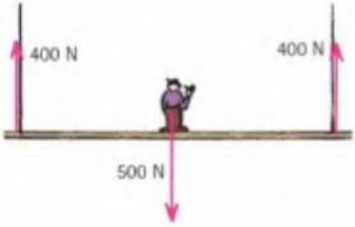
48. Consider an airplane that flies due east on a trip, then returns flying due west. Flying in one direction, the plane flies with Earth's rotation, and in the opposite direction, against Earth's rotation. But, in the absence of winds, the times of flight are equal either way. Why is this so?

PROBLEMS

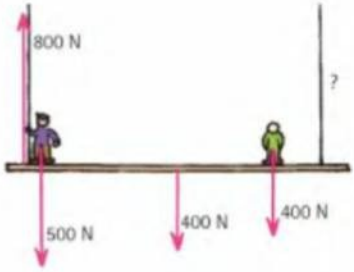
1. Lucy Lightfoot stands with one foot on one bathroom scale and her other foot on a second bathroom scale. Each scale reads 350 N. What is Lucy's weight?

2. Henry Heavyweight weighs 1200 N and stands on a pair of bathroom scales so that one scale reads twice as much as the other. What are the scale readings?

3. The sketch shows a painter's scaffold in mechanical equilibrium. The person in the middle weighs 500 N, and the tensions in each rope are 400 N. What is the weight of the scaffold?



4. A different scaffold that weighs 400 N supports two painters, one 500 N and the other 400 N. The reading in the left scale is 800 N. What is the reading in the right-hand scale?



CHAPTER 2 ONLINE RESOURCES

PhysicsPlace.com

Videos

- Newton's Law of Inertia
- The Old Tablecloth Trick
- Toilet Paper Roll
- Inertia of a Cylinder
- Inertia of an Anvil
- Definition of a Newton

Quizzes

Flashcards

Links

3 Linear Motion

1 Joan Lucas moves with increasing speed when the distance her horse travels each second increases. 2 Likewise for Sue Johnson and her crew who win medals for high speed in their racing shell. 3 Chelcie Liu asks his students to check their thinking with neighbors and predict which ball will first reach the end of the equal-length tracks.

In this chapter we continue with the ideas of a man who was subjected to house arrest because of his ideas, the Italian scientist Galileo Galilei, who died in the same year that Newton was born. These ideas were to be a foundation for Isaac Newton, who, when asked about his success in science, replied that he stood on the shoulders of giants. Most notable of these was Galileo.

Galileo developed an early interest in motion and was soon at odds with his contemporaries, who held to Aristotelian ideas on falling bodies and generally believed that the Sun goes around Earth. He left Pisa to teach at the University of Padua and became an advocate of the new Copernican theory of the solar system. He was the first man to discover mountains on the moon and to find the moons of Jupiter. Because he published his findings in Italian, the language of the people, instead of in Latin, the language of scholars, and because of the recent invention of the printing press, his ideas reached a wide readership. He soon ran afoul of the Church, and he was warned not to teach or hold to Copernican views. He restrained himself publicly for nearly 15 years and then defiantly published his observations and conclusions, which were counter to Church doctrine. The outcome was a trial in which he was found guilty, and he was forced to renounce his discovery that Earth moves. As he walked out of the court, it is said that he whispered, "But it moves." By then an old man, broken in health and spirit, he was sentenced to perpetual house arrest. Nevertheless, he completed his studies on motion, and his writings were smuggled from Italy and published in Holland. His ideas on motion are the subject of this chapter.

FIGURE 3.1
When you sit on a chair, your speed is zero relative to Earth but 30 km/s relative to the Sun.

Motion Is Relative

Everything moves—even things that appear to be at rest. They move relative to the Sun and stars. As you're reading this, you're moving at about 107,000 kilometers per hour relative to the Sun, and you're moving even faster relative to the center of our galaxy. When we discuss the motion of something, we describe the motion relative to something else. If you walk down the aisle of a moving bus, your speed relative to the floor of the bus is likely quite different from your speed relative to the road. When we say a racing car reaches a speed of 300 kilometers per hour, we mean relative to the track. Unless stated otherwise, when we discuss the speeds of things in our environment, we mean relative to the surface of Earth. Motion is relative.

CHECK POINT

A hungry mosquito sees you resting in a hammock in a 3-m/s breeze. How fast and in what direction should the mosquito fly in order to hover above you for lunch?

Check Your Answer

The mosquito should fly toward you into the breeze. When just above you, it should fly at 3 m/s in order to hover at rest. Unless its grip on your skin is strong enough after landing, it must continue flying at 3 m/s to keep from being blown off. That's why a breeze is an effective deterrent to mosquito bites.

If you look out an airplane window and view another plane flying at the same speed in the opposite direction, you'll see it flying twice as fast—nicely illustrating relative motion.

Speed

Before the time of Galileo, people described moving things as simply "slow" or "fast." Such descriptions were vague. Galileo is credited with being the first to measure speed by considering the distance covered and the time it takes. He defined **speed** as the distance covered per unit of time. Interestingly, Galileo could easily measure distance, but in his day measuring short times was no easy matter. He sometimes used his own pulse and sometimes the dripping of drops from a "water clock" he devised.

$$\text{Speed} = \frac{\text{distance}}{\text{time}}$$

A cyclist who covers 16 meters in a time of 2 seconds, for example, has a speed of 8 meters per second.

Any combination of distance and time units is legitimate for measuring speed; for motor vehicles (or long distances), the units kilometers per hour (km/h) or miles per hour (mi/h or mph) are commonly used. For shorter distances, meters per second (m/s) is more useful. The slash symbol (/) is read as *per* and means "divided by." Throughout this book, we'll primarily use meters per second (m/s). Table 3.1 shows some comparative speeds in different units.[1]

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Videos
Definition of Speed
Average Speed

TABLE 3.1
Approximate Speeds in Different Units

12 mi/h = 20 km/h = 6 m/s
25 mi/h = 40 km/h = 11 m/s
37 mi/h = 60 km/h = 17 m/s
50 mi/h = 80 km/h = 22 m/s
62 mi/h = 100 km/h = 28 m/s
75 mi/h = 120 km/h = 33 m/s
100 mi/h = 160 km/h = 44 m/s

INSTANTANEOUS SPEED

Things in motion often have variations in speed. A car, for example, may travel along a street at 50 km/h, slow to 0 km/h at a red light, and speed up to only 30 km/h because of traffic. You can tell the speed of the car at any instant by looking at its

[1]Conversion is based on 1 h = 3600 s, 1 mi = 1609.344 m.

speedometer. The speed at any instant is the **instantaneous speed.** A car traveling at 50 km/h usually goes at that speed for less than 1 hour. If it did go at that speed for a full hour, it would cover 50 km. If it continued at that speed for half an hour, it would cover half that distance: 25 km. If it continued for only 1 minute, it would cover less than 1 km.

FIGURE 3.2
A speedometer gives readings in both miles per hour and kilometers per hour.

AVERAGE SPEED

In planning a trip by car, the driver often wants to know the time of travel. The driver is concerned with the **average speed** for the trip. Average speed is defined as

$$\text{Average speed} = \frac{\text{total distance covered}}{\text{time interval}}$$

Average speed can be calculated rather easily. For example, if we drive a distance of 80 kilometers in a time of 1 hour, we say our average speed is 80 kilometers per hour. Likewise, if we travel 320 kilometers in 4 hours,

$$\text{Average speed} = \frac{\text{total distance covered}}{\text{time interval}} = \frac{320\ \text{km}}{4\ \text{h}} = 80\ \text{km/h}$$

We see that, when a distance in kilometers (km) is divided by a time in hours (h), the answer is in kilometers per hour (km/h).

Since average speed is the whole distance covered divided by the total time of travel, it doesn't indicate the different speeds and variations that may have taken place during shorter time intervals. On most trips, we experience a variety of speeds, so the average speed is often quite different from the instantaneous speed.

If we know average speed and time of travel, distance traveled is easy to find. A simple rearrangement of the definition above gives

$$\text{Total distance covered} = \text{average speed} \times \text{time}$$

If your average speed is 80 kilometers per hour on a 4-hour trip, for example, you cover a total distance of 320 kilometers (80 km/h × 4 h).

If you're cited for speeding, which does the police officer write on your ticket, your *instantaneous speed* or your *average speed?*

CHECK POINT

1. What is the average speed of a cheetah that sprints 100 meters in 4 seconds? If it sprints 50 m in 2 s?
2. If a car moves with an average speed of 60 km/h for an hour, it will travel a distance of 60 km.
   a. How far would it travel if it moved at this rate for 4 h?
   b. For 10 h?
3. In addition to the speedometer on the dashboard of every car is an odometer, which records the distance traveled. If the initial reading is set at zero at the beginning of a trip and the reading is 40 km one-half hour later, what has been your average speed?
4. Would it be possible to attain this average speed and never go faster than 80 km/h?

Check Your Answers

(Are you reading this before you have reasoned answers in your mind? As mentioned in the previous chapter, when you encounter Check Yourself questions throughout this book, check your ***thinking*** *before you read the answers. You'll not only learn more, you'll enjoy learning more.)*

1. In both cases the answer is 25 m/s:

$$\text{Average speed} = \frac{\text{distance covered}}{\text{time interval}} = \frac{100\ \text{meters}}{4\ \text{seconds}} = \frac{50\ \text{meters}}{2\ \text{seconds}} = 25\ \text{m/s}$$

2. The distance traveled is the average speed × time of travel, so
   a. Distance = 60 km/h × 4 h = 240 km
   b. Distance = 60 km/h × 10 h = 600 km
3. Average speed $= \frac{\text{total distance covered}}{\text{time interval}} = \frac{40\ \text{km}}{0.5\ \text{h}} = 80\ \text{km/h}$
4. No, not if the trip starts from rest and ends at rest. There are times in which the instantaneous speeds are less than 80 km/h, so the driver must drive at speeds of greater than 80 km/h during one or more time intervals in order to average 80 km/h. In practice, average speeds are usually much lower than high instantaneous speeds.

Velocity

When we know both the speed and the direction of an object, we know its **velocity.** For example, if a car travels at 60 km/h, we know its speed. But if we say it moves at 60 km/h to the north, we specify its *velocity.* Speed is a description of how fast; velocity is how fast *and* in what direction. A quantity such as velocity that specifies direction as well as magnitude is called a **vector quantity.** Recall from Chapter 2 that force is a vector quantity, requiring both magnitude and direction for its description. Likewise, velocity is a vector quantity. In contrast, a quantity that requires only magnitude for a description is called a **scalar quantity.** Speed is a scalar quantity.

Velocity is "directed" speed.

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Velocity
Changing Velocity

CONSTANT VELOCITY

Constant speed means steady speed. Something with constant speed doesn't speed up or slow down. Constant velocity, on the other hand, means both constant speed *and* constant direction. Constant direction is a straight line—the object's path doesn't curve. So constant velocity means motion in a straight line at a constant speed.

FIGURE 3.3
The car on the circular track may have a constant speed, but its velocity is changing every instant. Why?

CHANGING VELOCITY

If either the speed or the direction changes (or if both change), then the velocity changes. A car on a curved track, for example, may have a constant speed, but, because its direction is changing, its velocity is not constant. We'll see in the next section that it is *accelerating.*

CHECK POINT

1. "She moves at a constant speed in a constant direction." Rephrase the same sentence in fewer words.
2. The speedometer of a car moving to the east reads 100 km/h. It passes another car that moves to the west at 100 km/h. Do both cars have the same speed? Do they have the same velocity?
3. During a certain period of time, the speedometer of a car reads a constant 60 km/h. Does this indicate a constant speed? A constant velocity?

Check Your Answers

1. "She moves at a constant velocity."
2. Both cars have the same speed, but they have opposite velocities because they are moving in opposite directions.
3. The constant speedometer reading indicates a constant speed but not a constant velocity, because the car may not be moving along a straight-line path, in which case it is accelerating.

Acceleration

We can change the velocity of something by changing its speed, by changing its direction, or by changing both its speed *and* its direction. How quickly velocity changes is **acceleration:**

$$\text{Acceleration} = \frac{\text{change of velocity}}{\text{time interval}}$$

We are familiar with acceleration in an automobile. When the driver depresses the gas pedal (appropriately called the accelerator), the passengers then experience acceleration (or "pickup," as it is sometimes called) as they are pressed against their seats. The key idea that defines acceleration is *change*. Suppose we are driving and, in 1 second, we steadily increase our velocity from 30 kilometers per hour to 35 kilometers per hour, and then to 40 kilometers per hour in the next second, to 45 in the next second, and so on. We change our velocity by 5 kilometers per hour each second. This change in velocity is what we mean by acceleration.

$$\text{Acceleration} = \frac{\text{change of velocity}}{\text{time interval}} = \frac{5\ \text{km/h}}{1\ \text{s}} = 5\ \text{km/h}\cdot\text{s}$$

In this case, the acceleration is 5 kilometers per hour second (abbreviated as 5 km/h·s). Note that a unit for time enters twice: once for the unit of velocity and again for the interval of time in which the velocity is changing. Also note that acceleration is not just the total change in velocity; it is the *time rate of change*, or *change per second*, in velocity.

FIGURE 3.4

We say that a body undergoes acceleration when there is a *change* in its state of motion.

CHECK POINT

1. A particular car can go from rest to 90 km/h in 10 s. What is its acceleration?
2. In 2.5 s, a car increases its speed from 60 km/h to 65 km/h while a bicycle goes from rest to 5 km/h. Which undergoes the greater acceleration? What is the acceleration of each?

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Definition of Acceleration
Numerical Example of Acceleration

Check Your Answers

1. Its acceleration is 9 km/h·s. Strictly speaking, this would be its average acceleration, for there may have been some variation in its rate of picking up speed.
2. The accelerations of both the car and the bicycle are the same: 2 km/h·s.

$$\text{Acceleration}_{car} = \frac{\text{change of velocity}}{\text{time interval}} = \frac{65\ \text{km/h} - 60\ \text{km/h}}{2.5\ \text{s}} = \frac{5\ \text{km/h}}{2.5\ \text{s}} = 2\ \text{km/h}\cdot\text{s}$$

$$\text{Acceleration}_{bike} = \frac{\text{change of velocity}}{\text{time interval}} = \frac{5\ \text{km/h} - 0\ \text{km/h}}{2.5\ \text{s}} = \frac{5\ \text{km/h}}{2.5\ \text{s}} = 2\ \text{km/h}\cdot\text{s}$$

Although the velocities are quite different, the rates of *change* of velocity are the same. Hence, the accelerations are equal.

The term *acceleration* applies to decreases as well as to increases in velocity. We say the brakes of a car, for example, produce large retarding accelerations; that is, there is a large decrease per second in the velocity of the car. We often call this *deceleration*. We experience deceleration when the driver of a bus or car applies the brakes and we tend to lurch forward.

FIGURE 3.5

Rapid deceleration is sensed by the driver, who lurches forward (in accord with Newton's first law).

Can you see that a car has three controls that change velocity—the gas pedal (accelerator), the brakes, and the steering wheel?

We accelerate whenever we move in a curved path, even if we are moving at constant speed, because our direction is changing—hence, our velocity is changing. We experience this acceleration as we tend to lurch toward the outer part of the curve. We distinguish speed and velocity for this reason and define *acceleration* as the rate at which velocity changes, thereby encompassing changes both in speed and in direction.

Anyone who has stood in a crowded bus has experienced the difference between velocity and acceleration. Except for the effects of a bumpy road, you can stand with no extra effort inside a bus that moves at constant velocity, no matter how fast it is going. You can flip a coin and catch it exactly as if the bus were at rest. It is only when the bus accelerates—speeds up, slows down, or turns—that you experience difficulty standing.

In much of this book, we will be concerned only with motion along a straight line. When straight-line motion is being considered, it is common to use *speed* and *velocity* interchangeably. When direction doesn't change, acceleration may be expressed as the rate at which *speed* changes.

$$\text{Acceleration (along a straight line)} = \frac{\text{change in speed}}{\text{time interval}}$$

CHECK POINT

1. What is the acceleration of a race car that whizzes past you at a constant velocity of 400 km/h?
2. Which has the greater acceleration, an airplane that goes from 1000 km/h to 1005 km/h in 10 seconds or a skateboard that goes from zero to 5 km/h in 1 second?

Check Your Answers

1. Zero, because its velocity doesn't change.
2. Both gain 5 km/h, but the skateboard does so in one-tenth the time. The skateboard therefore has the greater acceleration—in fact, ten times greater. A little figuring will show that the acceleration of the airplane is 0.5 km/h·s, whereas acceleration of the slower-moving skateboard is 5 km/h·s. Velocity and acceleration are very different concepts. Distinguishing between them is very important.

ACCELERATION ON GALILEO'S INCLINED PLANES

Galileo developed the concept of acceleration in his experiments on inclined planes. His main interest was falling objects, and, because he lacked accurate timing devices, he used inclined planes effectively to slow accelerated motion and to investigate it more carefully.

Galileo found that a ball rolling down an inclined plane picks up the same amount of speed in successive seconds; that is, the ball rolls with unchanging acceleration. For example, a ball rolling down a plane inclined at a certain angle might be found to pick up a speed of 2 meters per second for each second it rolls. This gain per second is its acceleration. Its instantaneous velocity at 1-second intervals, at this acceleration, is then 0, 2, 4, 6, 8, 10, and so forth, meters per second. We can see that the instantaneous speed or velocity of the ball at any given time after being released from rest is simply equal to its acceleration multiplied by the time:[2]

$$\text{Velocity acquired} = \text{acceleration} \times \text{time}$$

[2]Note that this relationship follows from the definition of acceleration. From $a = v/t$, simple rearrangement (multiplying both sides of the equation by t) gives $v = at$.

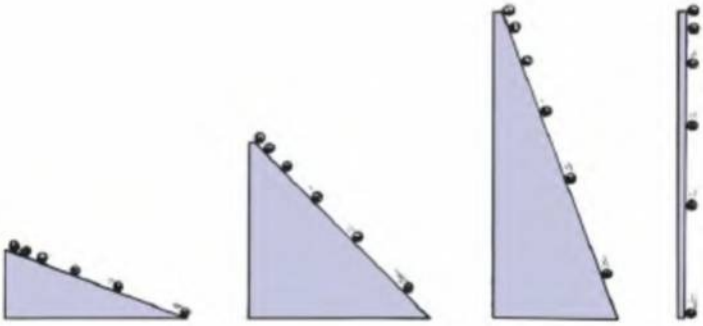

FIGURE 3.6
INTERACTIVE FIGURE
The greater the slope of the incline, the greater the acceleration of the ball. What is its acceleration if the ball falls vertically?

If we substitute the acceleration of the ball in this relationship (2 meters per second squared), we can see that, at the end of 1 second, the ball is traveling at 2 meters per second; at the end of 2 seconds, it is traveling at 4 meters per second; at the end of 10 seconds, it is traveling at 20 meters per second; and so on. The instantaneous speed or velocity at any time is simply equal to the acceleration multiplied by the number of seconds it has been accelerating.

Galileo found greater accelerations for steeper inclines. The ball attains its maximum acceleration when the incline is tipped vertically. Then it falls with the acceleration of a falling object (Figure 3.6). Regardless of the weight or size of the object, Galileo discovered that, when air resistance is small enough to be neglected, all objects fall with the same unchanging acceleration.

How nice, the acceleration due to gravity is 10 m/s each second all the way down. Why this is so, for any mass, awaits you in Chapter 4.

Free Fall

HOW FAST

Things fall because of the force of gravity. When a falling object is free of all restraints—no friction, with the air or otherwise—and falls under the influence of gravity alone, the object is in a state of **free fall.** (We'll consider the effects of air resistance on falling objects in Chapter 4.) Table 3.2 shows the instantaneous speed of a freely falling object at 1-second intervals. The important thing to note in these numbers is the way in which the speed changes. *During each second of fall, the object gains a speed of 10 meters per second.* This gain per second is the acceleration. Free-fall acceleration is approximately equal to 10 meters per second each second, or, in shorthand notation, 10 m/s^2 (read as 10 meters per second squared). Note that the unit of time, the second, enters twice—once for the unit of speed and again for the time interval during which the speed changes.

In the case of freely falling objects, it is customary to use the letter g to represent the acceleration (because the acceleration is due to *gravity*). The value of g is very different on the surface of the Moon and on the surfaces of other planets. Here on Earth, g varies slightly in different locations, with an average value equal to 9.8 meters per second each second, or, in shorter notation, 9.8 m/s^2. We round this off to 10 m/s^2 in our present discussion and in Table 3.2 to establish the ideas involved more clearly; multiples of 10 are more obvious than multiples of 9.8. Where accuracy is important, the value of 9.8 m/s^2 should be used.

Note in Table 3.2 that the instantaneous speed or velocity of an object falling from rest is consistent with the equation that Galileo deduced with his inclined planes:

$$\text{Velocity acquired} = \text{acceleration} \times \text{time}$$

TABLE 3.2
Free-Fall from Rest

Time of Fall (seconds)	Velocity Acquired (meters/second)
0	0
1	10
2	20
3	30
4	40
5	50
.	.
.	.
.	.
t	$10t$

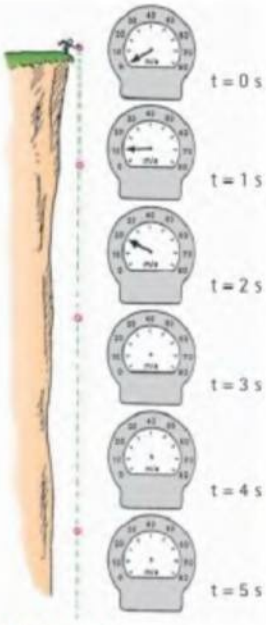

FIGURE 3.7
Pretend that a falling rock is equipped with a speedometer. In each succeeding second of fall, you'd find the rock's speed increasing by the same amount: 10 m/s. Sketch in the missing speedometer needle at t = 3 s, 4 s, and 5 s. (Table 3.2 shows the speeds we would read at various seconds of fall.)

The instantaneous velocity v of an object falling from rest[3] after a time t can be expressed in shorthand notation as

$$v = gt$$

To see that this equation makes good sense, take a moment to check it with Table 3.2. Note that the instantaneous velocity or speed in meters per second is simply the acceleration $g = 10\ \text{m/s}^2$ multiplied by the time t in seconds.

Free-fall acceleration is clearer when we consider a falling object equipped with a speedometer (Figure 3.7). Suppose a rock is dropped from a high cliff and you witness it with a telescope. If you focus the telescope on the speedometer, you'd note increasing speed as time progresses. By how much? The answer is, by 10 m/s each succeeding second.

CHECK POINT

What would the speedometer reading on the falling rock shown in Figure 3.7 be 5 s after it drops from rest? How about 6 s after it is dropped? 6.5 s after it is dropped?

Check Your Answer

The speedometer readings would be 50 m/s, 60 m/s, and 65 m/s, respectively. You can reason this from Table 3.2 or use the equation $v = gt$, where g is 10 m/s^2.

So far, we have been considering objects moving straight downward in the direction of the pull of gravity. How about an object thrown straight upward? Once released, it continues to move upward for a time and then comes back down. At its highest point, when it is changing its direction of motion from upward to downward, its instantaneous speed is zero. Then it starts downward *just as if it had been dropped from rest at that height.*

During the upward part of this motion, the object slows as it rises. It should come as no surprise that it slows at the rate of 10 meters per second each second—the same acceleration it experiences on the way down. So, as Figure 3.8 shows, the instantaneous speed at points of equal elevation in the path is the same whether the object is moving upward or downward. The velocities are opposite, of course, because they are in opposite directions. Note that the downward velocities have a negative sign, indicating the downward direction (it is customary to call *up* positive, and *down* negative.) Whether moving upward or downward, the acceleration is 10 m/s^2 the whole time.

CHECK POINT

A ball is thrown straight upward and leaves your hand at 20 m/s. What predictions can you make about the ball? (Please think about this *before* reading the suggested predictions!)

Check Your Answer

There are several. One prediction is that it will slow to 10 m/s 1 second after it leaves your hand and will come to a momentary stop 2 seconds after leaving your hand, when it reaches the top of its path. This is because it loses 10 m/s each second going up. Another prediction is that 1 second later, 3 seconds total, it will be moving downward at 10 m/s. In another second, it will return to its starting point and be moving at 20 m/s. So the time each way is 2 seconds, and its total time in flight takes 4 seconds. We'll now treat how far it travels up and down.

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Free Fall: How Fast?
$v = gt$
Free Fall: How Far?

[3]If, instead of being dropped from rest, the object is thrown downward at speed v_0, the speed v after any elapsed time t is $v = v_0 + gt$. We will not be concerned with this added complication here; we will instead learn as much as we can from the simplest cases. That will be a lot!

HOW FAR

How *far* an object falls is altogether different from how *fast* it falls. With his inclined planes, Galileo found that the distance a uniformly accelerating object travels is proportional to the *square of the time*. The distance traveled by a uniformly accelerating object starting from rest is

$$\text{Distance traveled} = \frac{1}{2}\,(\text{acceleration} \times \text{time} \times \text{time})$$

This relationship applies to the distance something falls. We can express it, for the case of a freely falling object, in shorthand notation as

$$d = \frac{1}{2}gt^2$$

in which d is the distance something falls when the time of fall in seconds is substituted for t and squared.[4] If we use 10 m/s^2 for the value of g, the distance fallen for various times will be as shown in Table 3.3.

Note that an object falls a distance of only 5 meters during the first second of fall, although its speed is then 10 meters per second. This may be confusing, for we may think that the object should fall a distance of 10 meters. But for it to fall 10 meters in its first second of fall, it would have to fall at an *average* speed of 10 meters per second for the entire second. It starts its fall at 0 meters per second, and its speed is 10 meters per second only in the last instant of the 1-second interval. Its average speed during this interval is the average of its initial and final speeds, 0 and 10 meters per second. To find the average value of these or any two numbers, we simply add the two numbers and divide by 2. This equals 5 meters per second, which, over a time interval of 1 second, gives a distance of 5 meters. As the object continues to fall in succeeding seconds, it will fall through ever-increasing distances because its speed is continuously increasing.

CHECK POINT

A cat steps off a ledge and drops to the ground in 1/2 second.

a. What is its speed on striking the ground?
b. What is its average speed during the 1/2 second?
c. How high is the ledge from the ground?

Check Your Answers

a. Speed: $v = gt = 10\ \text{m/s}^2 \times 1/2\ \text{s} = 5\ \text{m/s}$

b. Average speed: $\bar{v} = \dfrac{\text{initial } v + \text{final } v}{2} = \dfrac{0\ \text{m/s} + 5\ \text{m/s}}{2} = 2.5\ \text{m/s}$

We put a bar over the symbol to denote average speed: $\bar{v}$.

c. Distance: $d = \bar{v}t = 2.5\ \text{m/s} \times 1/2\ \text{s} = 1.25\ \text{m}$

Or equivalently,

$$d = \frac{1}{2}gt^2 = \frac{1}{2} \times 10\ \text{m/s}^2 \times \left(\frac{1}{2}\ \text{s}\right)^2 = 1.25\ \text{m}$$

Notice that we can find the distance by either of these equivalent relationships.

[4]Distance fallen from rest: d = average velocity × time

$$d = \frac{\text{initial velocity} + \text{final velocity}}{2} \times \text{time}$$

$$d = \frac{0 + gt}{2} \times t$$

$$d = \frac{1}{2}gt^2$$

(See Appendix B for further explanation.)

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Air Resistance and Falling Objects
Falling Distance

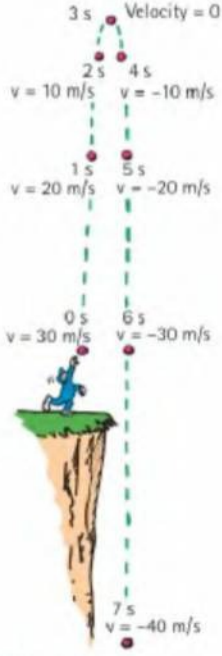


FIGURE 3.8

INTERACTIVE FIGURE

The rate at which the velocity changes each second is the same.

TABLE 3.3

Distance Fallen in Free Fall

Time of Fall (seconds)	Distance Fallen (meters)
0	0
1	5
2	20
3	45
4	80
5	125
.	.
.	.
.	.
t	$\frac{1}{2}10t^2$

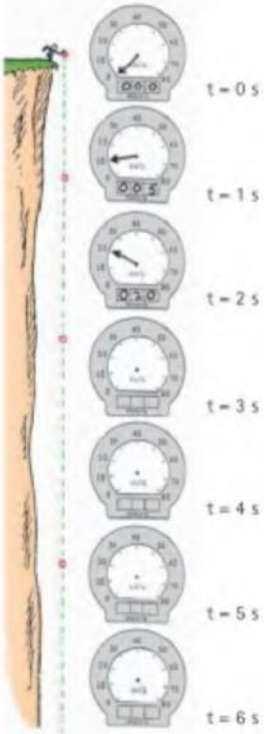


FIGURE 3.9
Pretend that a falling rock is equipped with a speedometer and an odometer. Speed readings increase by 10 m/s and distance readings by $1/2\,gt^2$. Can you complete the speedometer positions and odometer readings?

It is a common observation that many objects fall with unequal accelerations. A leaf, a feather, or a sheet of paper may flutter to the ground slowly. The fact that air resistance is responsible for these different accelerations can be shown very nicely with a closed glass tube containing light and heavy objects—a feather and a coin, for example. In the presence of air, the feather and coin fall with quite different accelerations. But, if the air in the tube is removed by a vacuum pump and the tube is quickly inverted, the feather and coin fall with the same acceleration (Figure 3.10). Although air resistance appreciably alters the motion of things like falling feathers, the motion of heavier objects like stones and baseballs at ordinary low speeds is not appreciably affected by the air. The relationships $v = gt$ and $d = 1/2\,gt^2$ can be used to a very good approximation for most objects falling in air from an initial position of rest.

FIGURE 3.10
A feather and a coin fall at equal accelerations in a vacuum.

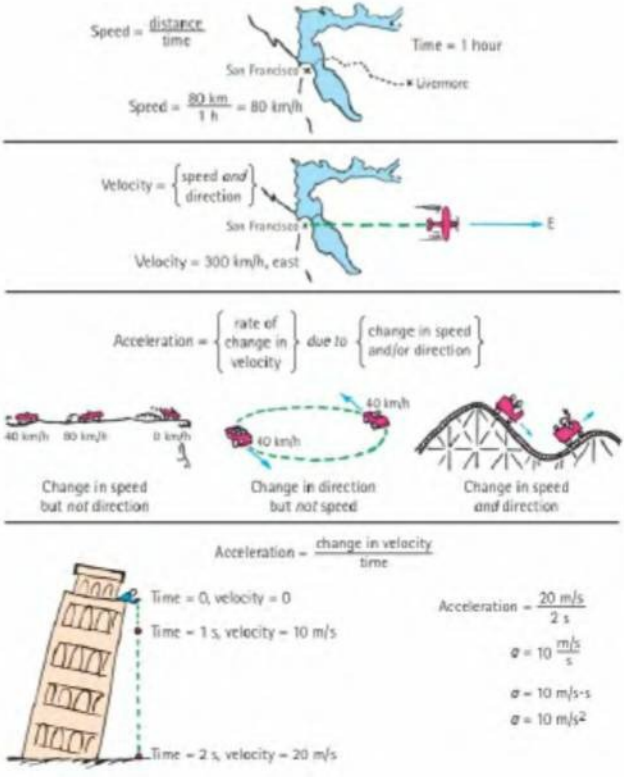


FIGURE 3.11
Motion analysis.

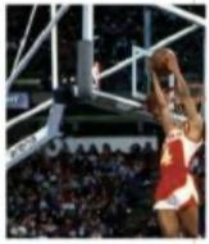
Hang Time

Some athletes and dancers have great jumping ability. Leaping straight up, they seem to "hang in the air," defying gravity. Ask your friends to estimate the "hang time" of the great jumpers—the time a jumper is airborne with feet off the ground. They may say 2 or 3 seconds. But, surprisingly, the hang time of the greatest jumpers is almost always less than 1 second! A longer time is one of many illusions we have about nature.

A related illusion is the vertical height a human can jump. Most of your classmates probably cannot jump higher than 0.5 meter. They can step over a 0.5-meter fence, but, in doing so, their body rises only slightly. The height of the barrier is different than the height a jumper's "center of gravity" rises. Many people can leap over a 1-meter fence, but only rarely does anybody raise the "center of gravity" of their body 1 meter. Even basketball stars Michael Jordan and Kobe Bryant in their prime couldn't raise their body 1.25 meters high, although they could easily reach considerably above the more-than-3-meter-high basket.

Jumping ability is best measured by a standing vertical jump. Stand facing a wall with feet flat on the floor and arms extended upward. Make a mark on the wall at the top of your reach. Then make your jump and, at the peak, make another mark. The distance between these two marks measures your vertical leap. If it's more than 0.6 meter (2 feet), you're exceptional.

Here's the physics. When you leap upward, jumping force is applied only while your feet make contact with the ground. The greater the force, the greater your launch speed and the higher the jump. When your feet leave the ground, your upward speed immediately decreases at the steady rate of g—10 m/s². At the top of your jump, your upward speed decreases to zero. Then you begin to fall, gaining speed at exactly the same rate, g. If you land as you took off, upright with legs extended, then time rising equals time falling; hang time is time up plus time down. While airborne, no amount of leg or arm pumping or other bodily motions can change your hang time.



The relationship between time up or down and vertical height is given by

$$d = \frac{1}{2}gt^2$$

If we know the vertical height d, we can rearrange this expression to read

$$t = \sqrt{\frac{2d}{g}}$$

The world-record vertical standing jump is 1.25 meters.[5] Let's use this jumping height of 1.25 meters for d, and use the more precise value of 9.8 m/s² for g. Solving for t, half the hang time, we get

$$t = \sqrt{\frac{2d}{g}} = \sqrt{\frac{2(1.25\ \text{m})}{9.8\ \text{m/s}^2}} = 0.50\ \text{s}$$

Double this (because this is the time for one way of an up-and-down round-trip) and we see that the record-breaking hang time is 1 second.

We're discussing vertical motion here. How about running jumps? We'll see in Chapter 10 that hang time depends only on the jumper's vertical speed at launch. While airborne, the jumper's horizontal speed remains constant and only the vertical speed undergoes acceleration. Interesting physics!

[5]For a running jump, liftoff speed can be increased and hang time extended as the foot bounds off the floor. We'll discuss this in Chapter 8.

HOW QUICKLY "HOW FAST" CHANGES

Much of the confusion that arises in analyzing the motion of falling objects comes about because it is easy to get "how fast" mixed up with "how far." When we wish to specify how fast something is falling, we are talking about *speed* or *velocity*, which is expressed as $v = gt$. When we wish to specify how far something falls, we are talking about *distance*, which is expressed as $d = 1/2\ gt^2$. Speed or velocity (how fast) and distance (how far) are entirely different from each other.

A most confusing concept, and probably the most difficult encountered in this book, is "how quickly does how fast change"—acceleration. What makes acceleration so complex is that it is *a rate of a rate*. It is often confused with velocity, which is itself a rate (the rate of change of position). Acceleration is not velocity, nor is it even a change in velocity. Acceleration is the rate at which velocity itself changes.

Please remember that it took people nearly 2000 years from the time of Aristotle to reach a clear understanding of motion, so be patient with yourself if you find that you require a few hours to achieve as much!

SUMMARY OF TERMS

Speed How fast something moves; the distance traveled per unit of time.
Instantaneous speed The speed at any instant.
Average speed The total distance traveled divided by the time of travel.
Velocity The speed of an object and a specification of its direction of motion.
Vector quantity Quantity in physics that has both magnitude and direction.
Scalar quantity Quantity that can be described by magnitude without direction.
Acceleration The rate at which velocity changes with time; the change in velocity may be in magnitude, or direction, or both.
Free fall Motion under the influence of gravity only.

SUMMARY OF EQUATIONS

$$\text{Speed} = \frac{\text{distance}}{\text{time}}$$

$$\text{Average speed} = \frac{\text{total distance covered}}{\text{time interval}}$$

$$\text{Acceleration} = \frac{\text{change of velocity}}{\text{time interval}}$$

$$\text{Acceleration (along a straight line)} = \frac{\text{change in speed}}{\text{time interval}}$$

Velocity acquired in free fall, from rest: $v = gt$

Distance fallen in free fall, from rest: $d = \frac{1}{2}gt^2$

REVIEW QUESTIONS

Motion Is Relative

1. As you read this, how fast are you moving relative to the chair you are sitting on? Relative to the Sun?

Speed

2. What two units of measurement are necessary for describing speed?

Instantaneous Speed

3. What kind of speed is registered by an automobile speedometer—average speed or instantaneous speed?

Average Speed

4. Distinguish between instantaneous speed and average speed.
5. What is the average speed in kilometers per hour for a horse that gallops a distance of 15 km in a time of 30 min?
6. How far does a horse travel if it gallops at an average speed of 25 km/h for 30 min?

Velocity

7. Distinguish between speed and velocity.

Constant Velocity

8. If a car moves with a constant velocity, does it also move with a constant speed?

Changing Velocity

9. If a car is moving at 90 km/h and it rounds a corner, also at 90 km/h, does it maintain a constant speed? A constant velocity? Defend your answer.

Acceleration

10. Distinguish between velocity and acceleration.
11. What is the acceleration of a car that increases its velocity from 0 to 100 km/h in 10 s?
12. What is the acceleration of a car that maintains a constant velocity of 100 km/h for 10 s? (Why do some of your classmates who correctly answer the previous question get this question wrong?)
13. When are you most aware of motion in a moving vehicle—when it is moving steadily in a straight line or when it is accelerating? If a car moved with absolutely constant velocity (no bumps at all), would you be aware of motion?
14. Acceleration is generally defined as the time rate of change of velocity. When can it be defined as the time rate of change of speed?

Acceleration on Galileo's Inclined Planes

15. What did Galileo discover about the amount of speed a ball gained each second when rolling down an inclined plane? What did this say about the ball's acceleration?
16. What relationship did Galileo discover for the velocity acquired on an incline?

17. What relationship did Galileo discover about a ball's acceleration and the steepness of an incline? What acceleration occurs when the plane is vertical?

Free Fall—How Fast

18. What exactly is meant by a "freely falling" object?
19. What is the gain in speed per second for a freely falling object?
20. What is the velocity acquired by a freely falling object 5 s after being dropped from a rest position? What is the velocity 6 s after?
21. The acceleration of free fall is about 10 m/s^2. Why does the seconds unit appear twice?
22. When an object is thrown upward, how much speed does it lose each second?

How Far

23. What relationship between distance traveled and time did Galileo discover for accelerating objects?
24. What is the distance fallen for a freely falling object 1 s after being dropped from a rest position? What is it 4 s after?
25. What is the effect of air resistance on the acceleration of falling objects? What is the acceleration with no air resistance?

How Quickly "How Fast" Changes

26. Consider these measurements: 10 m, 10 m/s, and 10 m/s^2. Which is a measure of distance, which of speed, and which of acceleration?

PROJECTS

1. Grandma is interested in your educational progress. She perhaps has little science background and may be mathematically challenged. Write a letter to Grandma, without using equations, and explain to her the difference between velocity and acceleration. Tell her why some of your classmates confuse the two, and state some examples that clear up the confusion.
2. Stand flatfooted next to a wall. Make a mark at the highest point you can reach. Then jump vertically and mark this highest point. The distance between the marks is your vertical jumping distance. Use this data to calculate your personal hang time.

PLUG AND CHUG

These are "plug-in-the-number" type activities to familiarize you with the equations that link the concepts of physics. They are mainly one-step substitutions and are less challenging than the Problems.

$$\text{Speed} = \frac{\text{distance}}{\text{time}}$$

1. Calculate your walking speed when you step 1 meter in 0.5 second.
2. Calculate the speed of a bowling ball that travels 4 meters in 2 seconds.

$$\text{Average speed} = \frac{\text{total distance covered}}{\text{time interval}}$$

3. Calculate your average speed if you run 50 meters in 10 seconds.
4. Calculate the average speed of a tennis ball that travels the full length of the court, 24 meters, in 0.5 second.
5. Calculate the average speed of a cheetah that runs 140 meters in 5 seconds.
6. Calculate the average speed (in km/h) of Larry, who runs to the store 4 kilometers away in 30 minutes.

$$\text{Distance} = \text{average speed} \times \text{time}$$

7. Calculate the distance (in km) that Larry runs if he maintains an average speed of 8 km/h for 1 hour.
8. Calculate the distance you will travel if you maintain an average speed of 10 m/s for 40 seconds.
9. Calculate the distance you will travel if you maintain an average speed of 10 km/h for one-half hour.

$$\text{Acceleration} = \frac{\text{change of velocity}}{\text{time interval}}$$

10. Calculate the acceleration of a car (in km/h·s) that can go from rest to 100 km/h in 10 s.
11. Calculate the acceleration of a bus that goes from 10 km/h to a speed of 50 km/h in 10 seconds.
12. Calculate the acceleration of a ball that starts from rest, rolls down a ramp, and gains a speed of 25 m/s in 5 seconds.
13. On a distant planet, a freely falling object gains speed at a steady rate of 20 m/s during each second of fall. Calculate its acceleration.

$$\text{Instantaneous speed} = \text{acceleration} \times \text{time}$$

14. Calculate the instantaneous speed (in m/s) at the 10-second mark for a car that accelerates at 2 m/s^2 from a position of rest.
15. Calculate the speed (in m/s) of a skateboarder who accelerates from rest for 3 s down a ramp at an acceleration of 5 m/s^2.

Velocity acquired in free fall, from rest:

$$v = gt \text{ (where } g = 10 \text{ m/s}^2\text{)}$$

16. Calculate the instantaneous speed of an apple that falls freely from a rest position and accelerates at 10 m/s^2 for 1.5 s.

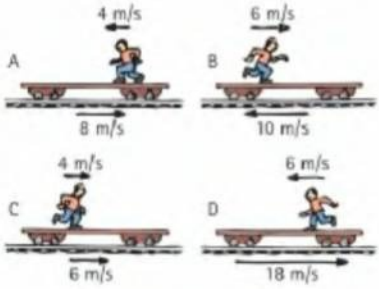
17. An object is dropped from rest and falls freely. After 7 s, calculate its instantaneous speed.
18. A skydiver steps from a high-flying helicopter. In the absence of air resistance, how fast would she be falling at the end of a 12-s jump?
19. On a distant planet, a freely falling object has an acceleration of 20 m/s^2. Calculate the speed that an object dropped from rest on this planet acquires in 1.5 s.

Distance fallen in free fall, from rest: $d = \frac{1}{2}gt^2$

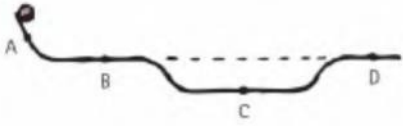
20. An apple drops from a tree and hits the ground in 1.5 s. Calculate how far it falls.
21. Calculate the vertical distance an object dropped from rest covers in 12 s of free fall.
22. On a distant planet a freely falling object has an acceleration of 20 m/s^2. Calculate the vertical distance an object dropped from rest on this planet covers in 1.5 s.

RANKING

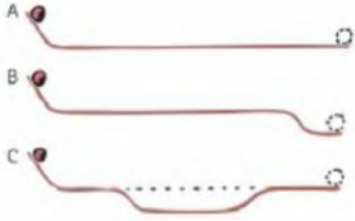
1. Jogging Jake runs along a train flatcar that moves at the velocities shown in positions A–D. From greatest to least, rank the velocity of Jake relative to a stationary observer on the ground. (Call the direction to the right positive.)



2. A track is made of a piece of channel iron bent as shown. A ball released at the left end of the track continues past the various points. Rank the speed of the ball at points A, B, C, and D, from fastest to slowest. (Watch for tie scores.)

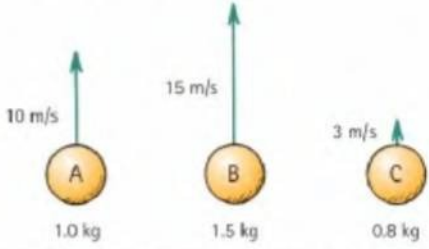


3. A ball is released at the left end of these different tracks. The tracks are bent from equal-length pieces of channel iron.



a. From fastest to slowest, rank the speed of the ball at the right end of the track.
b. From longest to shortest, rank the tracks in terms of the *time* for the ball to reach the end.
c. From greatest to least, rank the tracks in terms of the *average speed* of the ball. Or do all balls have the same average speed on all three tracks?

4. Three balls of different masses are thrown straight upward with initial speeds as indicated.

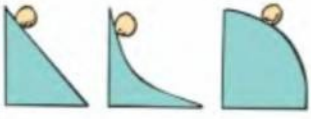


a. From fastest to slowest, rank the speeds of the balls 1 s after being thrown.
b. From greatest to least, rank the accelerations of the balls 1 s after being thrown. (Or are the accelerations the same?)

EXERCISES

1. What is the impact speed when a cat moving at 100 km/h bumps into the rear of another car traveling in the same direction at 98 km/h?
2. Suzie Surefoot can paddle a canoe in still water at 8 km/h. How successful will she be at canoeing upstream in a river that flows at 8 km/h?

3. Is a fine for speeding based on one's average speed or one's instantaneous speed? Explain.
4. One airplane travels due north at 300 km/h while another travels due south at 300 km/h. Are their speeds the same? Are their velocities the same? Explain.
5. Light travels in a straight line at a constant speed of 300,000 km/s. What is the acceleration of light?
6. Can an automobile with a velocity toward the north simultaneously have an acceleration toward the south? Explain.
7. You're in a car traveling at some specified speed limit. You see a car moving at the same speed coming toward you. How fast is the car approaching you, compared with the speed limit?
8. Can an object reverse its direction of travel while maintaining a constant acceleration? If so, give an example. If not, provide an explanation.
9. For straight-line motion, how does a speedometer indicate whether or not acceleration is occurring?
10. Correct your friend who says, "The dragster rounded the curve at a constant velocity of 100 km/h."
11. You are driving north on a highway. Then, without changing speed, you round a curve and drive east. (a) Does your velocity change? (b) Do you accelerate? Explain.
12. Jacob says acceleration is how fast you go. Emily says acceleration is how fast you get fast. They look to you for confirmation. Who's correct?
13. Starting from rest, one car accelerates to a speed of 50 km/h, and another car accelerates to a speed of 60 km/h. Can you say which car underwent the greater acceleration? Why or why not?
14. Cite an example of something with a constant speed that also has a varying velocity. Can you cite an example of something with a constant velocity and a varying speed? Defend your answers.
15. Cite an instance in which your speed could be zero while your acceleration is nonzero.
16. Cite an example of something that undergoes acceleration while moving at constant speed. Can you also give an example of something that accelerates while traveling at constant velocity? Explain.
17. (a) Can an object be moving when its acceleration is zero? If so, give an example. (b) Can an object be accelerating when its speed is zero? If so, give an example.
18. Can you cite an example in which the acceleration of a body is opposite in direction to its velocity? If so, what is your example?
19. On which of these hills does the ball roll down with increasing speed and decreasing acceleration along the path? (Use this example if you wish to explain to someone the difference between speed and acceleration.)



20. Suppose that the three balls shown in Exercise 19 start simultaneously from the tops of the hills. Which one reaches the bottom first? Explain.
21. What is the acceleration of a car that moves at a steady velocity of 100 km/h for 100 s? Explain your answer.
22. Which is greater, an acceleration from 25 km/h to 30 km/h or one from 96 km/h to 100 km/h if both occur during the same time?
23. Galileo experimented with balls rolling on inclined planes of various angles. What is the range of accelerations from angles 0° to 90° (from what acceleration to what)?
24. Be picky and correct your friend who says, "In free fall, air resistance is more effective in slowing a feather than a coin."
25. Suppose that a freely falling object were somehow equipped with a speedometer. By how much would its reading in speed increase with each second of fall?
26. Suppose that the freely falling object in the preceding exercise were also equipped with an odometer. Would the readings of distance fallen each second indicate equal or different falling distances for successive seconds?
27. For a freely falling object dropped from rest, what is the acceleration at the end of the fifth second of fall? At the end of the tenth second of fall? Defend your answers.
28. If air resistance can be neglected, how does the acceleration of a ball that has been tossed straight upward compare with its acceleration if simply dropped?
29. When a ballplayer throws a ball straight up, by how much does the speed of the ball decrease each second while ascending? In the absence of air resistance, by how much does it increase each second while descending? How much time is required for rising compared to falling?
30. Someone standing at the edge of a cliff (as in Figure 3.8) throws a ball nearly straight up at a certain speed and another ball nearly straight down with the same initial speed. If air resistance is negligible, which ball will have the greater speed when it strikes the ground below?
31. Answer the previous question for the case where air resistance is *not* negligible—where air drag affects motion.
32. If you drop an object, its acceleration toward the ground is 10 m/s^2. If you throw it down instead, would its acceleration after throwing be greater than 10 m/s^2? Why or why not?
33. In the preceding exercise, can you think of a reason why the acceleration of the object thrown downward through the air might be appreciably less than 10 m/s^2?
34. While rolling balls down an inclined plane, Galileo observes that the ball rolls 1 cubit (the distance from elbow to fingertip) as he counts to 10. How far will the ball have rolled from its starting point when he has counted to 20?
35. Consider a vertically launched projectile when air drag is negligible. When is the acceleration due to gravity greater? When ascending, at the top, or when descending? Defend your answer.
36. Extend Tables 3.2 and 3.3 to include times of fall of 6 to 10 s, assuming no air resistance.
37. If it were not for air resistance, why would it be dangerous to go outdoors on rainy days?
38. As speed increases for an object in free fall, does acceleration increase also?
39. A ball tossed upward will return to the same point with the same initial speed when air resistance is negligible. When air resistance is not negligible, how does the return speed compare with its initial speed?

40. Two balls are released simultaneously from rest at the left end of equal-length tracks A and B as shown. Which ball reaches the end of its track first?

41. Refer to the pair of tracks in Exercise 40. (a) On which track is the average speed greater? (b) Why is the speed of the ball at the end of the tracks the same?

42. In this chapter, we studied idealized cases of balls rolling down smooth planes and objects falling with no air resistance. Suppose a classmate complains that all this attention focused on idealized cases is worthless because idealized cases simply don't occur in the everyday world. How would you respond to this complaint? How do you suppose the author of this book would respond?

43. A person's hang time would be considerably greater on the Moon. Why?

44. Why does a stream of water get narrower as it falls from a faucet?

45. Make up two multiple-choice questions that would check a classmate's understanding of the distinction between velocity and acceleration.

PROBLEMS

1. You toss a ball straight up with an initial speed of 30 m/s. How high does it go, and how long is it in the air (neglecting air resistance)?

2. A ball is tossed with enough speed straight up so that it is in the air several seconds. (a) What is the velocity of the ball when it reaches its highest point? (b) What is its velocity 1 s before it reaches its highest point? (c) What is the change in its velocity during this 1-s interval? (d) What is its velocity 1 s after it reaches its highest point? (e) What is the change in velocity during this 1-s interval? (f) What is the change in velocity during the 2-s interval? (Careful!) (g) What is the acceleration of the ball during any of these time intervals and at the moment the ball has zero velocity?

3. What is the instantaneous velocity of a freely falling object 10 s after it is released from a position of rest? What is its average velocity during this 10-s interval? How far will it fall during this time?

4. A car takes 10 s to go from $v = 0$ m/s to $v = 25$ m/s at constant acceleration. If you wish to find the distance traveled using the equation $d = 1/2\,at^2$, what value should you use for a?

5. Surprisingly, very few athletes can jump more than 2 feet (0.6 m) straight up. Use $d = 1/2gt^2$ and solve for the time one spends moving upward in a 0.6-m vertical jump. Then double it for the "hang time"—the time one's feet are off the ground.

• **6.** A dart leaves the barrel of a blowgun at a speed v. The length of the blowgun barrel is L. Assume that the acceleration of the dart in the barrel is uniform.

a. Show that the dart moves inside the barrel for a time of $\frac{2L}{v}$.

b. If the dart's exit speed is 15.0 m/s and the length of the blowgun is 1.4 m, show that the time the dart is in the barrel is 0.19 s.

CHAPTER 3 ONLINE RESOURCES

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Interactive Figures

- 3.6, 3.8

Videos

- Definition of Speed
- Average Speed
- Velocity
- Changing Velocity
- Definition of Acceleration
- Numerical Example of Acceleration
- Free Fall: How Fast?
- $v = gt$
- Free Fall: How Far?
- Air Resistance and Falling Objects
- Falling Distance

Quizzes

Flashcards

Links

4 Newton's Second Law of Motion

1 Efrain Lopez shows that when the forces on the blue block balance to zero, no acceleration occurs. 2 Wingsuit skydivers do what flying squirrels have always done, but faster. They jump from mountains or airplanes and after high terminal speeds use a parachute to safely land. 3 When Emily Abrams kicks the ball, it undergoes acceleration.

Galileo introduced the concept of acceleration, the rate at which velocity changes with time—$a = \Delta v/\Delta t$. But what produces acceleration? That question is answered in Newton's second law. It is *force*. (Newton himself dealt first with momentum and impulse, topics we address in Chapter 6, but nowadays we like to start with acceleration and force.) Newton's second law links these fundamental concepts of acceleration and force to one more profound concept, *mass*, as given by the famous equation, $a = F/m$. Interestingly, although Newton's insights of nature bloomed before he was 24 years of age, he was 42 when he included his three laws of motion in what is generally acknowledged as the greatest scientific book ever written, the *Principia Mathematica Philosophiae Naturalis*. He wrote the work in Latin and completed it in 18 months. It appeared in print in 1687, but it wasn't printed in English until 1729, two years after his death. When asked how he was able to make so many discoveries, Newton replied that he found his solutions to problems not by sudden insight but by continually thinking very long and hard about them until he worked them out. We've treated his first law in Chapter 2, defined acceleration in Chapter 3, and in this chapter we combine what we've learned—Newton's second law of motion.

Isaac Newton (1642–1727)

FIGURE 4.1
Kick the ball and it accelerates.

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Video
Force Causes Acceleration

Force Causes Acceleration

Consider a hockey puck at rest on ice. Apply a force, and it starts to move—it accelerates. When the hockey stick is no longer pushing it, the puck moves at constant velocity. Apply another force by striking the puck again, and again the motion changes. Applied force produces acceleration.

Most often, the applied force is not the only force acting on an object. Other forces may act as well. Recall, from Chapter 2, that the combination of forces acting on an object is the *net force*. Acceleration depends on the *net force*. To increase the acceleration of an object, you must increase the net force acting on it. If you double the net force on an object, its acceleration doubles; if you triple the net force, its acceleration triples; and so on. This makes good sense. We say an object's acceleration is directly proportional to the net force acting on it. We write

$$\text{Acceleration} \sim \text{net force}$$

The symbol ~ stands for "is directly proportional to." That means, for instance, that if one doubles, the other also doubles.

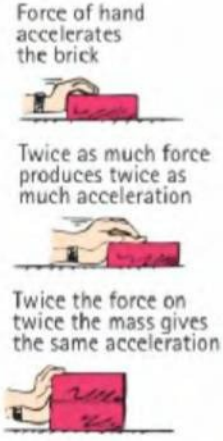

FIGURE 4.2
Acceleration is directly proportional to force.

CHECK POINT

1. You push on a crate that sits on a smooth floor, and it accelerates. If you apply four times the net force, how much greater will be the acceleration?
2. If you push with the same increased force on the same crate, but it slides on a very rough floor, how will the acceleration compare with pushing the crate on a smooth floor? *(Think before you read the answer below!)*

Check Your Answers

1. It will have four times as much acceleration.
2. It will have less acceleration because friction will reduce the net force.

Friction

When surfaces slide or tend to slide over one another, a force of friction acts. When you apply a force to an object, friction usually reduces the net force and the resulting acceleration. Friction is caused by the irregularities in the surfaces in mutual contact, and it depends on the kinds of material and how much they are pressed together. Even surfaces that appear to be very smooth have microscopic irregularities that obstruct motion. Atoms cling together at many points of contact. When one object slides against another, it must either rise over the irregular bumps or else scrape atoms off. Either way requires force.

The direction of the friction force is always in a direction opposing motion. An object sliding *down* an incline experiences friction directed *up* the incline; an object that slides to the *right* experiences friction toward the *left*. Thus, if an object is to move at constant velocity, a force equal to the opposing force of friction must be applied so that the two forces exactly cancel each other. The zero net force then results in zero acceleration and constant velocity.

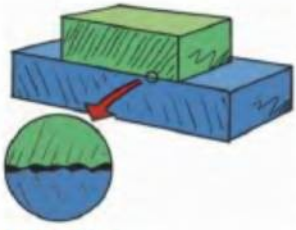

FIGURE 4.3
Friction results from the mutual contact of irregularities in the surfaces of sliding objects. Even surfaces that appear to be smooth have irregular surfaces when viewed at the microscopic level.

No friction exists on a crate that sits at rest on a level floor. But, if you push the crate horizontally, you'll disturb the contact surfaces and friction is produced. How much? If the crate is still at rest, then the friction that opposes motion is just enough to cancel your push. If you push horizontally with, say, 70 newtons, friction builds up to become 70 newtons. If you push harder—say, 100 newtons—and the crate is on the verge of sliding, the friction between the crate and floor opposes your push

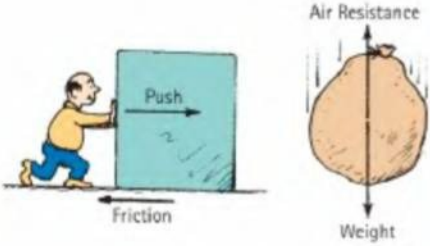

FIGURE 4.4
The direction of the force of friction always opposes the direction of motion. (Left) Push the crate to the right, and friction acts toward the left. (Right) The sack falls downward, and air friction (air resistance) acts upward. (What is the acceleration of the sack when air resistance equals the sack's weight?)

with 100 newtons. If 100 newtons is the most the surfaces can muster, then, when you push a bit harder, the clinging gives way and the crate slides.[1]

Interestingly, the friction of sliding is somewhat less than the friction that builds up before sliding takes place. Physicists and engineers distinguish between *static friction* and *sliding friction*. For given surfaces, static friction is somewhat greater than sliding friction. If you push on a crate, it takes more force to get it going than it takes to keep it sliding. Before the time of antilock brake systems, slamming on the brakes of a car was quite problematic. When tires lock, they slide, providing less friction than if they are made to roll to a stop. A rolling tire does not slide along the road surface, and friction is static friction, with more grab than sliding friction. But once the tires start to slide, the frictional force is reduced—not a good thing. An antilock brake system keeps the tires below the threshold of breaking loose into a slide.

PhysicsPlace.com™
Video
Friction

It's also interesting that the force of friction does not depend on speed. A car skidding at low speed has approximately the same friction as the same car skidding at high speed. If the friction force of a crate that slides against a floor is 90 newtons at low speed, to a close approximation it is 90 newtons at a greater speed. It may be more when the crate is at rest and on the verge of sliding, but, once the crate is sliding, the friction force remains approximately the same.

Tires have treads not to increase friction, but to displace and redirect water from between the road surface and the underside of the tire. Many racing cars use tires without treads because they race on dry days.

More interesting still, friction does not depend on the area of contact. If you slide the crate on its smallest surface, all you do is concentrate the same weight on a smaller area with the result that the friction is the same. So those extra wide tires you see on some cars provide no more friction than narrower tires. The wider tire simply spreads the weight of the car over more surface area to reduce heating and wear. Similarly, the friction between a truck and the ground is the same whether the truck has four tires or eighteen! More tires spread the load over more ground area and reduce the pressure per tire. Interestingly, stopping distance when brakes are applied is not affected by the number of tires. But the wear that tires experience very much depends on the number of tires.

FIGURE 4.5
Friction between the tire and the ground is nearly the same whether the tire is wide or narrow. The purpose of the greater contact area is to reduce heating and wear.

Friction is not restricted to solids sliding over one another. Friction occurs also in liquids and gases, both of which are called *fluids* (because they flow). Fluid friction occurs as an object pushes aside the fluid it is moving through. Have you ever attempted a 100-m dash through waist-deep water? The friction of fluids is appreciable, even at low speeds. So unlike the friction between solid surfaces, fluid friction depends on speed. A very common form of fluid friction for something moving through air is *air resistance*, also called *air drag*. You usually aren't aware of air resistance when walking or jogging, but you notice it at higher speeds when riding a bicycle or when skiing downhill. Air resistance increases with increasing speed.

[1]Even though it may not seem so yet, most of the concepts in physics are not really complicated. But friction is different. Unlike most concepts in physics, it is a very complicated phenomenon. The findings are empirical (gained from a wide range of experiments) and the predictions approximate (also based on experiment).

The falling sack shown in Figure 4.4 will reach a constant velocity when air resistance balances the sack's weight.

CHECK POINT

What net force does a sliding crate experience when you exert a force of 110 N and friction between the crate and the floor is 100 N?

Check Your Answer

10 N in the direction of your push (110 N − 100 N).

Mass and Weight

The acceleration imparted to an object depends not only on applied forces and friction forces but on the inertia of the object. How much inertia an object possesses depends on the amount of matter in the object—the more matter, the more inertia. In speaking of how much matter something has, we use the term *mass*. The greater the mass of an object, the greater its inertia. Mass is a measure of the inertia of a material object.

Mass corresponds to our intuitive notion of weight. We casually say that something has a lot of matter if it weighs a lot. But there is a difference between mass and weight. We can define each as follows:

Mass: ***The quantity of matter in an object. It is also the measure of the inertia or sluggishness that an object exhibits in response to any effort made to start it, stop it, or change its state of motion in any way.***

Weight: ***The force upon an object due to gravity.***

In the absence of acceleration, mass and weight are directly proportional to each other.[2] If the mass of an object is doubled, its weight is also doubled; if the mass is halved, the weight is halved. Because of this, mass and weight are often interchanged. Also, mass and weight are sometimes confused because it is customary to measure the quantity of matter in things (mass) by their gravitational attraction to Earth (weight). But mass is more fundamental than weight; it is a fundamental quantity that completely escapes the notice of most people.

There are times when weight corresponds to our unconscious notion of inertia. For example, if you are trying to determine which of two small objects is the heavier one, you might shake them back and forth in your hands or move them in some way instead of lifting them. In doing so, you are judging which of the two is more difficult to get moving, feeling which of the two is more resistant to a change in motion. You are really comparing the inertias of the objects.

FIGURE 4.6
An anvil in outer space—between Earth and the Moon, for example—may be weightless, but it is not massless.

In the United States, the quantity of matter in an object is commonly described by the gravitational pull between it and Earth, or its *weight*, usually expressed in *pounds*. In most of the world, however, the measure of matter is commonly expressed in a mass unit, the kilogram. At the surface of Earth, a brick with a mass of 1 kilogram weighs 2.2 pounds. In metric units, the unit of force is the **newton,** which is equal to a little less than a quarter-pound (like the weight of a quarter-pound hamburger *after* it is cooked). A 1-kilogram brick weighs about 10 newtons

[2] Weight and mass are directly proportional; weight = mg, where g is the constant of proportionality and has the value 10 N/kg (or more precisely, 9.8 N/kg). Equivalently, g is the acceleration due to gravity, 10 m/s^2 (the units N/kg are equivalent to m/s^2). In Chapter 9 we'll extend the definition of weight as the force that an object exerts on a supporting surface.

(more precisely, 9.8 N).[3] Away from Earth's surface, where the influence of gravity is less, a 1-kilogram brick weighs less. It would also weigh less on the surface of planets with less gravity than Earth. On the Moon's surface, for example, where the gravitational force on things is only 1/6 as strong as on Earth, a 1-kilogram brick weighs about 1.6 newtons (or 0.36 pounds). On planets with stronger gravity, it would weigh more, but the mass of the brick is the same everywhere. The brick offers the same resistance to speeding up or slowing down regardless of whether it's on Earth, on the Moon, or on any other body attracting it. In a drifting spaceship, where a scale with a brick on it reads zero, the brick still has mass. Even though it doesn't press down on the scale, the brick has the same resistance to a change in motion as it has on Earth. Just as much force would have to be exerted by an astronaut in the spaceship to shake it back and forth as would be required to shake it back and forth while on Earth. You'd have to provide the same amount of push to accelerate a huge truck to a given speed on a level surface on the Moon as on Earth. The difficulty of *lifting* it against gravity (weight), however, is something else. Mass and weight are different from each other (Figure 4.7).

FIGURE 4.7
The astronaut in space finds that it is just as difficult to shake the "weightless" anvil as it would be on Earth. If the anvil were more massive than the astronaut, which would shake more—the anvil or the astronaut?

A nice demonstration that distinguishes mass and weight is the massive ball suspended on the string, shown by David Yee in the Chapter 2 opener photo, and in Figure 4.8. The top string breaks when the lower string is pulled with a gradual increase in force, but the bottom string breaks when the lower string is jerked. Which of these cases illustrates the weight of the ball, and which illustrates the mass of the ball? Note that only the top string bears the weight of the ball. So, when the lower string is gradually pulled, the tension supplied by the pull is transmitted to the top string. The total tension in the top string is caused by the pull plus the weight of the ball. The top string breaks when the breaking point is reached. But, when the bottom string is jerked, the mass of the ball—its tendency to remain at rest—is responsible for the bottom string breaking.

FIGURE 4.8
Why will a slow, continuous increase in downward force break the string above the massive ball, while a sudden increase will break the lower string?

It is also easy to confuse mass and volume. When we think of a massive object, we often think of a big object. An object's size (volume), however, is not necessarily a good way to judge its mass. Which is easier to get moving: a car battery or an empty cardboard box of the same size? So, we find that mass is neither weight nor volume.

CHECK POINT

1. Does a 2-kg iron brick have twice as much *inertia* as a 1-kg iron brick? Twice as much *mass*? Twice as much *volume*? Twice as much *weight*?
2. Would it be easier to lift a cement truck on Earth's surface or to lift it on the Moon's surface?

Check Your Answers

1. The answers to all parts are *yes*.
2. A cement truck would be easier to lift on the Moon because the gravitational force is less on the Moon. When you *lift* an object, you are contending with the force of gravity (its weight). Although its mass is the same anywhere, its weight is only 1/6 as much on the Moon, so only 1/6 as much effort is required to lift it there. To move it horizontally, however, you are not pushing against gravity. When mass is the only factor, equal forces will produce equal accelerations, whether the object is on Earth or the Moon.

[3]So 2.2 lb equal 9.8 N, or 1 N is approximately equal to 0.22 lb—about the weight of an apple. In the metric system it is customary to specify quantities of matter in units of mass (in grams or kilograms) and rarely in units of weight (in newtons). In the United States and countries that use the British system of units, however, quantities of matter are customarily specified in units of weight (in pounds). (The British unit of mass, the *slug*, is not well known.) See Appendix A for more about systems of measurement.

FIGURE 4.9
INTERACTIVE FIGURE
The greater the mass, the greater the force must be for a given acceleration.

Mass Resists Acceleration

Push your friend on a skateboard and your friend accelerates. Now push equally hard on an elephant on a skateboard and the acceleration is much less. You'll see that the amount of acceleration depends not only on the force but on the mass being pushed. The same force applied to twice the mass produces half the acceleration; for three times the mass, one-third the acceleration. We say that, for a given force, the acceleration produced is inversely proportional to the mass. That is,

$$\text{Acceleration} \sim \frac{1}{\text{mass}}$$

By inversely we mean that the two values change in opposite directions. As the denominator increases, the whole quantity decreases. For example, the quantity 1/100 is less than 1/10.

FIGURE 4.10
An enormous force is required to accelerate this three-story-high earth mover when it carries a typical 350-ton load.

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Tutorial
Newton's Second Law
Video
Newton's Second Law

Newton's Second Law of Motion

Newton was the first to discover the relationship among three basic physical concepts—acceleration, force, and mass. He proposed one of the most important rules of nature, his second law of motion. Newton's second law states

> **The acceleration of an object is directly proportional to the net force acting on the object, is in the direction of the net force, and is inversely proportional to the mass of the object.**

In summarized form, this is

$$\text{Acceleration} \sim \frac{\text{net force}}{\text{mass}}$$

We use the wiggly line ~ as a symbol meaning "is proportional to." We say that acceleration a is directly proportional to the overall net force F and inversely proportional to the mass m. By this we mean that, if F increases, a increases by the same factor (if F doubles, a doubles); but if m increases, a decreases by the same factor (if m doubles, a is cut in half).

By using consistent units, such as newtons (N) for force, kilograms (kg) for mass, and meters per second squared (m/s²) for acceleration, the proportionality may be

When two things are directly proportional to each other, as one increases, the other increases also. However, when two things are inversely proportional to each other, as one increases, the other decreases.

expressed as an exact equation:

$$\text{Acceleration} = \frac{\text{net force}}{\text{mass}}$$

In its briefest form, where a is acceleration, F_{net} is net force, and m is mass, it becomes

$$a = \frac{F_{net}}{m}$$

An object is accelerated in the direction of the force acting on it. Applied in the direction of the object's motion, a force will increase the object's speed. Applied in the opposite direction, it will decrease the speed of the object. Applied at right angles, it will deflect the object. Any other direction of application will result in a combination of speed change and deflection. *The acceleration of an object is always in the direction of the net force.*

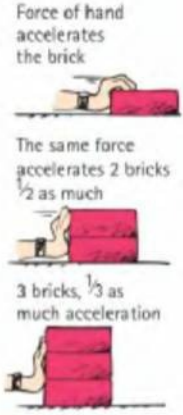

FIGURE 4.11
Acceleration is inversely proportional to mass.

CHECK POINT

1. In the previous chapter, acceleration was defined to be the time rate of change of velocity; that is, a = (change in v)/time. Are we in this chapter saying that acceleration is instead the ratio of force to mass; that is, $a = F/m$? Which is it?
2. A jumbo jet cruises at constant velocity of 1000 km/h when the thrusting force of its engines is a constant 100,000 N. What is the acceleration of the jet? What is the force of air resistance on the jet?

Check Your Answers

1. Acceleration is *defined* as the time rate of change of velocity and is *produced* by a force. How much force/mass (the cause) determines the rate change in v/time (the effect). So whereas we defined acceleration in Chapter 3, in this chapter we define the terms that produce acceleration.
2. The acceleration is zero because the velocity is constant. Since the acceleration is zero, it follows from Newton's second law that the net force is zero, which means that the force of air drag must just equal the thrusting force of 100,000 N and act in the opposite direction. So the air drag on the jet is 100,000 N. (Note that we don't need to know the velocity of the jet to answer this question. We need only to know that it is constant, our clue that acceleration and therefore net force is zero.)

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Free Fall Acceleration Explained

When Acceleration Is g—Free Fall

Although Galileo introduced both the concepts of inertia and acceleration, and although he was the first to measure the acceleration of falling objects, he could not explain *why* objects of various masses fall with equal accelerations. Newton's second law provides the explanation.

We know that a falling object accelerates toward Earth because of the gravitational force of attraction between the object and Earth. When the force of gravity is the only force—that is, when friction (such as air resistance) is negligible—we say that the object is in a state of free fall.

The greater the mass of an object, the greater is the gravitational force of attraction between it and Earth. The double brick in Figure 4.12, for example, has twice the gravitational attraction of the single brick. Why, then, as Aristotle supposed, doesn't the double brick fall twice as fast? The answer is that the acceleration of an object depends not only on the force—in this case, the weight—but also on the object's resistance to motion, its inertia. Whereas a force produces an acceleration,

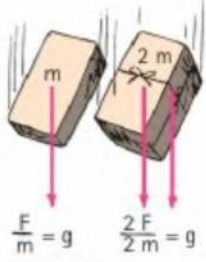

FIGURE 4.12
INTERACTIVE FIGURE
The ratio of weight (F) to mass (m) is the same for all objects in the same locality; hence, their accelerations are the same in the absence of air resistance.

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- We see in free fall that weight/mass = g. So we can say that weight = mg.

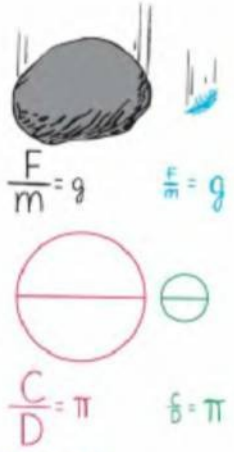

FIGURE 4.13

The ratio of weight (F) to mass (m) is the same for the large rock and the small feather; similarly, the ratio of circumference (C) to diameter (D) is the same for the large and the small circle.

inertia is a *resistance* to acceleration. So twice the force exerted on twice the inertia produces the same acceleration as half the force exerted on half the inertia. Both accelerate equally. The acceleration due to gravity is symbolized by g. We use the symbol g, rather than a, to denote that acceleration is due to gravity alone.

The ratio of weight to mass for freely falling objects equals a constant—g. This is similar to the constant ratio of circumference to diameter for circles, which equals the constant π (Figure 4.13).

We now understand that the acceleration of free fall is independent of an object's mass. A boulder 100 times more massive than a pebble falls with the same acceleration as the pebble because, although the force on the boulder (its weight) is 100 times greater than the force on the pebble, its resistance to a change in motion (its mass) is 100 times that of the pebble. The greater force offsets the equally greater mass.

CHECK POINT

In a vacuum, a coin and a feather fall at the same rate, side by side. Would it be correct to say that equal forces of gravity act on both the coin and the feather when in a vacuum?

Check Your Answer

No, no, no, a thousand times no! These objects accelerate equally not because the forces of gravity on them are equal, but because the *ratios* of their weights to their masses are equal. Although air resistance is not present in a vacuum, gravity is. (You'd know this if you stuck your hand into a vacuum chamber and the truck shown in Figure 4.10 rolled over it!) If you answered *yes* to this question, let this be a warning to be more careful when you think physics!

When Acceleration Is Less Than g—Nonfree Fall

Objects falling in a vacuum are one thing, but what of the practical cases of objects falling in air? Although a feather and a coin will fall equally fast in a vacuum, they fall quite differently in air. How do Newton's laws apply to objects falling in air? The answer is that Newton's laws apply for *all* objects, whether freely falling or falling in the presence of resistive forces. The accelerations, however, are quite different for the two cases. The important thing to keep in mind is the idea of *net force*. In a vacuum or in cases in which air resistance can be neglected, the net force is the weight because it is the only force. In the presence of air resistance, however, the net force is less than the weight—it is the weight minus air drag, the force arising from air resistance.[4]

When Galileo tried to explain why all objects fall with equal accelerations, wouldn't he have loved to know the rule $a = F/m$?

[4]In mathematical notation,

$$a = \frac{F_{net}}{m} = \frac{mg - R}{m}$$

where mg is the weight and R is the air resistance. Note that when $R = mg$, $a = 0$; then, with no acceleration, the object falls at constant velocity. With elementary algebra we can go another step and get

$$a = \frac{F_{net}}{m} = \frac{mg - R}{m} = g - \frac{R}{m}$$

We see that the acceleration a will always be less than g if air resistance R impedes falling. Only when $R = 0$ does $a = g$.

The force of air drag experienced by a falling object depends on two things. First, it depends on the frontal area of the falling object—that is, on the amount of air the object must plow through as it falls. Second, it depends on the speed of the falling object; the greater the speed, the greater the number of air molecules an object encounters per second and the greater the force of molecular impact. Air drag depends on the size and the speed of a falling object.

In some cases, air drag greatly affects falling; in other cases, it doesn't. Air drag is important for a falling feather. Because a feather has so much area for an object so light in weight, it doesn't have to fall very fast before the upward-acting air resistance cancels the downward-acting weight. The net force on the feather is then zero and acceleration terminates. When acceleration terminates, we say that the object has reached its **terminal speed.** If we are concerned with direction, down for falling objects, we say the object has reached its terminal velocity. The same idea applies to all objects falling in air. Consider skydiving. As a falling skydiver gains speed, air drag may finally build up until it equals the weight of the skydiver. If and when this happens, the *net force* becomes zero and the skydiver no longer accelerates; she has reached her terminal velocity. For a feather, terminal velocity is a few centimeters per second, whereas, for a skydiver, it is about 200 kilometers per hour. A skydiver may vary this speed by varying position. Head or feet first is a way of encountering less air and thus less air drag and attaining maximum terminal velocity. A smaller terminal velocity is attained by spreading oneself out like a flying squirrel.

Terminal velocities are very much less if the skydiver wears a wingsuit, as shown in the center opening photo at the beginning of this chapter. The wingsuit not only increases the frontal area of the diver, but provides a lift similar to that achieved by flying squirrels when they fashion their bodies into "wings." This new and exhilarating sport, *wingsuit flying*, goes beyond what flying squirrels can accomplish, for a wingsuit flyer can achieve horizontal speeds of more than 160 km/h (100 mph). Looking more like flying bullets than flying squirrels, high-performance wingsuits allow these "bird people" to glide with remarkable precision. To land safely, parachutes are deployed. Projects to land without a parachute, however, are underway.

The large frontal area provided by a parachute produces low terminal speeds for safe landings. To understand the physics of a parachute, consider a man and woman parachuting together from the same altitude (Figure 4.15). Suppose that the man is twice as heavy as the woman and that their same-sized parachutes are initially opened. Having parachutes of the same size means that, at equal speeds, the air resistance is the same on both of them. Who reaches the ground first—the heavy man or the lighter woman? The answer is that the person who falls faster gets to the ground first—that is, the person with the greatest terminal speed. At first we might think that, because the parachutes are the same, the terminal speeds for each would be the same and, therefore, that both would reach the ground at the same time. This doesn't happen, however, because air drag depends on speed. Greater speed means greater force of air impact. The woman will reach her terminal speed when the air drag against her parachute equals her weight. When this occurs, the air drag against the parachute of the man will not yet equal his weight. He must fall faster than she does for the air drag to match his greater weight.[5] Terminal velocity is greater for the heavier person, with the result that the heavier person reaches the ground first.

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Video
Falling and Air Resistance

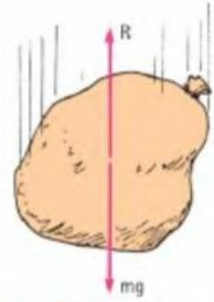

FIGURE 4.14
When weight mg is greater than air resistance R, the falling sack of mail accelerates. At higher speeds, R increases. When $R = mg$, acceleration reaches zero, and the sack reaches its terminal velocity.

FIGURE 4.15
The heavier parachutist must fall faster than the lighter parachutist for air resistance to cancel his greater weight.

[5]Terminal speed for the twice-as-heavy man will be about 41% greater than the woman's terminal speed, because the retarding force of air resistance is proportional to speed squared. ($v_{man}^2/v_{woman}^2 = 1.41^2 = 2$.)

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- Headfirst, with arms tucked in, skydivers can reach terminal speeds of about 180 km/h (110 mph). Terminal speeds are less with a wingsuit, and greatly reduced with a parachute.

CHECK POINT

Nellie Newton skydives from a high-flying helicopter. As she falls faster and faster through the air, does her acceleration increase, decrease, or remain the same?

Check Your Answer

Acceleration decreases because the net force on Nellie decreases. Net force is equal to her weight minus her air resistance, and since air resistance increases with increasing speed, net force and hence acceleration decrease. By Newton's second law,

$$a = \frac{f_{net}}{m} = \frac{mg - R}{m}$$

where mg is her weight and R is the air resistance she encounters. As R increases, a decreases. Note that if she falls fast enough so that $R = mg$, $a = 0$, then with no acceleration she falls at constant speed.

FIGURE 4.16

A stroboscopic study of a golf ball (left) and a Styrofoam ball (right) falling in air. The air resistance is negligible for the heavier golf ball, and its acceleration is nearly equal to g. Air resistance is not negligible for the lighter Styrofoam ball, which reaches its terminal velocity sooner.

Consider a pair of tennis balls, one a regular hollow ball and the other filled with iron pellets. Although they are the same size, the iron-filled ball is considerably heavier than the regular ball. If you hold them above your head and drop them simultaneously, you'll see that they strike the ground at about the same time. But if you drop them from a greater height—say, from the top of a building—you'll note the heavier ball strikes the ground first. Why? In the first case, the balls do not gain much speed in their short fall. The air drag they encounter is small compared with their weights, even for the regular ball. The tiny difference in their arrival time is not noticed. But, when they are dropped from a greater height, the greater speeds of fall are met with greater air resistance. At any given speed, each ball encounters the same air resistance because each has the same size. This same air resistance may be a lot compared with the weight of the lighter ball, but only a little compared with the weight of the heavier ball (like the parachutists in Figure 4.15). For example, 1 N of air drag acting on a 2-N object will reduce its acceleration by half, but 1 N of air drag on a 200-N object will only slightly diminish its acceleration. So, even with equal air resistances, the accelerations of each are different. There is a moral to be learned here. Whenever you consider the acceleration of something, use the equation of Newton's second law to guide your thinking: The acceleration is equal to the ratio of *net* force to the mass. For the falling tennis balls, the net force on the hollow ball is appreciably reduced as air drag builds up, while the net force on the iron-filled ball is only slightly reduced. Acceleration decreases as net force decreases, which, in turn, decreases as air drag increases. If and when the air drag builds up to equal the weight of the falling object, then the net force becomes zero and acceleration terminates.

SUMMARY OF TERMS

Force Any influence that can cause an object to be accelerated, measured in newtons (or in pounds, in the British system).

Friction The resistive force that opposes the motion or attempted motion of an object either past another object with which it is in contact or through a fluid.

Mass The quantity of matter in an object. More specifically, it is the measure of the inertia or sluggishness that an object exhibits in response to any effort made to start it, stop it, deflect it, or change in any way its state of motion.

Weight The force due to gravity on an object (mg).

Volume The quantity of space an object occupies.

Newton's second law The acceleration of an object is directly proportional to the net force acting on the object, is in the direction of the net force, and is inversely proportional to the mass of the object.

Newton The SI unit of force. One newton (symbol N) is the force that will give an object of mass 1 kg an acceleration of 1 m/s^2.

Kilogram The fundamental SI unit of mass. One kilogram (symbol kg) is the mass of 1 liter (1 L) of water at 4 C°.

Free fall Motion under the influence of gravitational pull only.

Terminal speed The speed at which the acceleration of a falling object terminates because air resistance balances its weight. When direction is specified, then we speak of **terminal velocity.**

SUMMARY OF EQUATIONS

Weight $= mg$

Acceleration: $a = \frac{F_{net}}{m}$

Force $= ma$

REVIEW QUESTIONS

Force Causes Acceleration

1. Is acceleration proportional to net force, or does acceleration equal net force?

Friction

2. How does friction affect the net force on an object?
3. How great is the force of friction compared with your push on a crate that doesn't move on a level floor?
4. As you increase your push, will friction on the crate increase also?
5. Once the crate is sliding, how hard do you push to keep it moving at constant velocity?
6. Which is normally greater, static friction or sliding friction on the same object?
7. How does the force of friction for a sliding object vary with speed?
8. Slide a block on its widest surface, then tip the block so it slides on its narrowest surface. In which case is friction greater?
9. Does fluid friction vary with speed? With area of contact?

Mass and Weight

10. What relationship does mass have with inertia?
11. What relationship does mass have with weight?
12. Which is more fundamental, *mass* or *weight*? Which varies with location?
13. Fill in the blanks: Shake something to and fro and you're measuring its _____. Lift it against gravity and you're measuring its _____.
14. Fill in the blanks: The Standard International unit for mass is the _____. The Standard International unit for force is the _____.
15. What is the approximate weight of a quarter-pound hamburger after it is cooked?
16. What is the weight of a 1-kilogram brick?
17. In the string-pull illustration in Figure 4.8, a gradual pull of the lower string results in the top string breaking. Does this illustrate the ball's weight or its mass?
18. In the string-pull illustration in Figure 4.8, a sharp jerk on the bottom string results in the bottom string breaking. Does this illustrate the ball's weight or its mass?
19. Clearly distinguish among *mass, weight*, and *volume*.
20. Is acceleration *directly* proportional to mass, or is it *inversely* proportional to mass? Give an example.

Newton's Second Law of Motion

21. State Newton's second law of motion.
22. If we say that one quantity is *directly proportional* to another quantity, does this mean they are *equal* to each other? Explain briefly, using mass and weight as an example.
23. If the net force acting on a sliding block is somehow tripled, by how much does the acceleration increase?
24. If the mass of a sliding block is tripled while a constant net force is applied, by how much does the acceleration decrease?
25. If the mass of a sliding block is somehow tripled at the same time the net force on it is tripled, how does the resulting acceleration compare with the original acceleration?
26. How does the direction of acceleration compare with the direction of the net force that produces it?

When Acceleration Is *g*—Free Fall

27. What is meant by *free fall*?
28. The ratio of circumference to diameter for all circles is π. What is the ratio of force to mass for freely falling bodies?
29. Why doesn't a heavy object accelerate more than a light object when both are freely falling?

When Acceleration Is Less Than *g*—Nonfree Fall

30. What is the net force that acts on a 10-N freely falling object?
31. What is the net force that acts on a 10-N falling object when it encounters 4 N of air resistance? 10 N of air resistance?

32. What two principal factors affect the force of air resistance on a falling object?
33. What is the acceleration of a falling object that has reached its terminal velocity?
34. Why does a heavy parachutist fall faster than a lighter parachutist who wears a parachute of the same size?
35. If two objects having the same size fall through air at different speeds, which encounters the greater air resistance?

PROJECT

1. Write a letter to Grandma, similar to the one of Project 1 in Chapter 3. Tell her that Galileo introduced the concepts of acceleration and inertia and was familiar with forces but didn't see the connection among these three concepts. Tell her how Isaac Newton did see the connection and how it explains why heavy and light objects in free fall gain the same speed in the same time. In this letter, it's okay to use an equation or two, as long as you make it clear to Grandma that an equation is a shorthand notation of ideas you've explained.
2. Drop a sheet of paper and a coin at the same time. Which reaches the ground first? Why? Now crumple the paper into a small, tight wad and again drop it with the coin. Explain the difference observed. Will they fall together if dropped from a second-, third-, or fourth-story window? Try it and explain your observations.
3. Drop a book and a sheet of paper, and note that the book has a greater acceleration—g. Place the paper beneath the book so that it is forced against the book as both fall, so both fall at g. How do the accelerations compare if you place the paper on top of the raised book and then drop both? You may be surprised, so try it and see. Then explain your observation.
4. Drop two balls of different weight from the same height, and, at small speeds, they practically fall together. Will they roll together down the same inclined plane? If each is suspended from an equal length of string, making a pair of pendulums, and displaced through the same angle, will they swing back and forth in unison? Try it and see; then explain using Newton's laws.
5. The net force acting on an object and the resulting acceleration are always in the same direction. You can demonstrate this with a spool. If the spool is gently pulled horizontally to the right, in which direction will it roll?

PLUG AND CHUG

Make these simple one-step calculations and familiarize yourself with the equations that link the concepts of force, mass, and acceleration.

Weight = mg

1. Calculate the weight in newtons of a person having a mass of 50 kg.
2. Calculate the weight in newtons of a 2000-kg elephant.
3. Calculate the weight in newtons of a 2.5-kg melon. What is its weight in pounds?
4. An apple weighs about 1 N. What is its mass in kilograms? What is its weight in pounds?
5. Susie Small finds that she weighs 300 N. Calculate her mass.

Acceleration: $a = \dfrac{F_{net}}{m}$

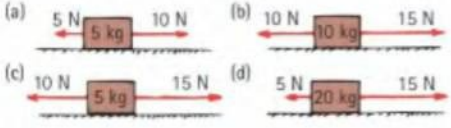
6. Calculate the acceleration of a 2000-kg, single-engine airplane just before takeoff when the thrust of its engine is 500 N.
7. Calculate the acceleration of a 300,000-kg jumbo jet just before takeoff when the thrust on the aircraft is 120,000 N.
8. (a) Calculate the acceleration of a 2-kg block on a horizontal friction-free air table when you exert a horizontal net force of 20 N. (b) What acceleration occurs if the friction force is 4 N?

Force = ma

9. Calculate the horizontal force that must be applied to a 1-kg puck to make it accelerate on a horizontal friction-free air table with the same acceleration it would have if it were dropped and fell freely.
10. Calculate the horizontal force that must be applied to produce an acceleration of 1.8 g for a 1.2-kg puck on a horizontal friction-free air table.

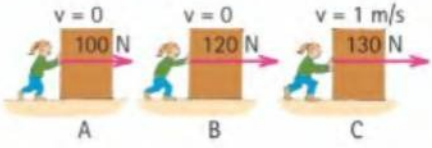
RANKING

1. Boxes of various masses are on a friction-free, level table. From greatest to least, rank the

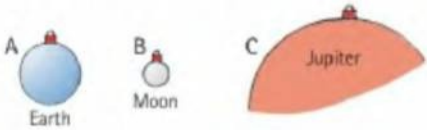


a. net forces on the boxes.
b. accelerations of the boxes.

2. In all three cases, A, B, and C, the crate is in equilibrium (no acceleration). From greatest to least, rank the amount of friction between the crate and the floor.



3. Consider a 100-kg box of tools in the locations A, B, and C. From greatest to least, rank the



a. masses of the 100-kg box of tools.
b. weights of the 100-kg box of tools.

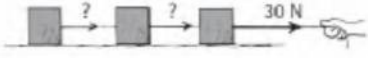
4. Three parachutists, A, B, and C, each have reached terminal velocity at the same distance above the ground below.

a. From fastest to slowest, rank the amount of their terminal velocities.
b. From longest to shortest times, rank their order in reaching the ground.

EXERCISES

1. Can the velocity of an object reverse direction while maintaining a constant acceleration? If so, give an example; if not, provide an explanation.
2. On a long alley, a bowling ball slows down as it rolls. Is any horizontal force acting on the ball? How do you know?
3. Is it possible to move in a curved path in the absence of a force? Defend your answer.
4. An astronaut tosses a rock on the Moon. What force(s) act(s) on the rock during its curved path?
5. Since an object weighs less on the surface of the Moon than on Earth's surface, does it have less inertia on the Moon's surface?
6. Which contains more apples, a 1-pound bag of apples on Earth or a 1-pound bag of apples on the Moon? Which contains more apples, a 1-kilogram bag of apples on Earth or a 1-kilogram bag of apples on the Moon?
7. A crate remains at rest on a factory floor while you push on it with a horizontal force F. How big is the friction force exerted on the crate by the floor? Explain.
8. A 400-kg bear grasping a vertical tree slides down at constant velocity. What is the friction force that acts on the bear?
9. In an orbiting space shuttle, you are handed two identical boxes, one filled with sand and the other filled with feathers. How can you determine which is which without opening the boxes?
10. Your empty hand is not hurt when it bangs lightly against a wall. Why does it hurt if you're carrying a heavy load? Which of Newton's laws is most applicable here?
11. Why is a massive cleaver more effective for chopping vegetables than an equally sharp knife?
12. Does the mass of an astronaut change when he or she is visiting the International Space Station? Defend your answer.
13. When a junked car is crushed into a compact cube, does its mass change? Its weight? Explain.
14. Gravity on the surface of the Moon is only 1/6 as strong as gravity on Earth. What is the weight of a 10-kg object on the Moon and on Earth? What is its mass on each?
15. Does a dieting person more accurately lose mass or lose weight?
16. What weight change occurs when your mass increases by 2 kg?
17. What is your own mass in kilograms? Your weight in newtons?
18. A grocery bag can withstand 300 N of force before it rips apart. How many kilograms of apples can it safely hold?
19. Consider a heavy crate resting on the bed of a flatbed truck. When the truck accelerates, the crate also accelerates and remains in place. Identify the force that accelerates the crate.
20. Explain how Newton's first law of motion can be considered to be a consequence of Newton's second law.
21. When a car is moving in reverse, backing from a driveway, the driver applies the brakes. In what direction is the car's acceleration?
22. The auto in the sketch moves forward as the brakes are applied. A bystander says that during the interval of braking, the auto's velocity and acceleration are in opposite directions. Do you agree or disagree?

23. Aristotle claimed that the speed of a falling object depends on its weight. We now know that objects in free fall, whatever their weights, undergo the same gain in speed. Why does weight not affect acceleration?
24. When blocking in football, a defending lineman often attempts to get his body under the body of his opponent and push upward. What effect does this have on the friction force between the opposing lineman's feet and the ground?
25. A race car travels along a raceway at a constant velocity of 200 km/h. What horizontal net force acts on the car?
26. Three identical blocks are pulled, as shown, on a horizontal frictionless surface. If tension in the rope held by the hand is 30 N, what is the tension in the other ropes?



27. To pull a wagon across a lawn with constant velocity, you have to exert a steady force. Reconcile this fact with Newton's first law, which says that motion with constant velocity requires no force.

28. Free fall is motion in which gravity is the only force acting. (a) Is a skydiver who has reached terminal speed in free fall? (b) Is a satellite above the atmosphere that circles Earth in free fall?

29. When a coin is tossed upward, what happens to its velocity while ascending? Its acceleration? (Neglect air resistance.)

30. How much force acts on a tossed coin when it is halfway to its maximum height? How much force acts on it when it reaches its peak? (Neglect air resistance.)

31. Sketch the path of a ball tossed vertically into the air. (Neglect air resistance.) Draw the ball halfway to the top, at the top, and halfway down to its starting point. Draw a force vector on the ball in all three positions. Is the vector the same or different in the three locations? Is the acceleration the same or different in the three locations?

32. As you leap upward in a standing jump, how does the force that you exert on the ground compare with your weight?

33. When you jump vertically off the ground, what is your acceleration when you reach your highest point?

34. What is the acceleration of a rock at the top of its trajectory when it has been thrown straight upward? (Is your answer consistent with Newton's second law?)

35. A common saying goes, "It's not the fall that hurts you; it's the sudden stop." Translate this into Newton's laws of motion.

36. A friend says that, as long as a car is at rest, no forces act on it. What do you say if you're in the mood to correct the statement of your friend?

37. When your car moves along the highway at constant velocity, the net force on it is zero. Why, then, do you have to keep running your engine?

38. What is the net force on a 1-N apple when you hold it at rest above your head? What is the net force on it after you release it?

39. A "shooting star" is usually a grain of sand from outer space that burns up and gives off light as it enters the atmosphere. What exactly causes this burning?

40. Does a stick of dynamite contain force?

41. A parachutist, after opening her parachute, finds herself gently floating downward, no longer gaining speed. She feels the upward pull of the harness, while gravity pulls her down. Which of these two forces is greater? Or are they equal in magnitude?

42. Does a falling object increase in speed if its acceleration of fall decreases?

43. What is the net force acting on a 1-kg ball in free fall?

44. What is the net force acting on a falling 1-kg ball if it encounters 2 N of air resistance?

45. A friend says that, before the falling ball in the previous exercise reaches terminal velocity, it *gains* speed while acceleration *decreases*. Do you agree or disagree with your friend? Defend your answer.

46. Why will a sheet of paper fall more slowly than one that is wadded into a ball?

47. Upon which will air resistance be greater—a sheet of falling paper or the same paper wadded into a ball that falls at a faster terminal speed? (Careful!)

48. Hold a Ping-Pong ball and a golf ball at arm's length and drop them simultaneously. You'll see them hit the floor at about the same time. But, if you drop them off the top of a high ladder, you'll see the golf ball hit first. What is your explanation?

49. How does the force of gravity on a raindrop compare with the air drag it encounters when it falls at constant velocity?

50. If you hold your book horizontally with a piece of paper beneath it, then drop both, they fall together. Repeat, but this time place the paper on *top* of the book. Describe the motion of the paper relative to the book. (Try it and see!)

51. When a parachutist opens her parachute after reaching terminal speed, in what direction does she accelerate?

52. How does the terminal speed of a parachutist before opening a parachute compare to terminal speed after? Why is there a difference?

53. How does the gravitational force on a falling body compare with the air resistance it encounters before it reaches terminal velocity? After reaching terminal velocity?

54. Why is it that a cat that accidentally falls from the top of a 50-story building hits a safety net below no faster than if it fell from the twentieth story?

55. Under what conditions would a metal sphere dropping through a viscous liquid be in equilibrium?

56. When and if Galileo dropped two balls from the top of the Leaning Tower of Pisa, air resistance was not really negligible. Assuming that both balls were of the same size, one made of wood and one of metal, which ball actually struck the ground first? Why?

57. If you drop a pair of tennis balls simultaneously from the top of a building, they will strike the ground at the same time. If you fill one of the balls with lead pellets and then drop them together, which one will hit the ground first? Which one will experience greater air resistance? Defend your answers.

58. In the absence of air resistance, if a ball is thrown vertically upward with a certain initial speed, on returning to its original level it will have the same speed. When air resistance is a factor, will the ball be moving faster, the same, or more slowly than its throwing speed when it gets back to the same level? Why? (Physicists often use a "principle of exaggeration" to help them analyze a problem. Consider the exaggerated case of a feather, not a ball, because the effect of air resistance on the feather is more pronounced and therefore easier to visualize.)

59. If a ball is thrown vertically into the air in the presence of air resistance, would you expect the time during which it rises to be longer or shorter than the time during which it falls? (Again use the "principle of exaggeration.")

60. Make up two multiple-choice questions that would check a classmate's understanding of the distinction between mass and weight.

PROBLEMS

1. One pound is the same as 4.45 newtons. What is the weight in pounds of 1 newton?

2. If your friend Katelyn weighs 500 N, what is her weight in pounds?

3. Consider a 40-kg block of cement that is pulled sideways with a net force of 200 N. Show that its acceleration is 5 m/s^2.

4. Consider a mass of 1 kg accelerated 1 m/s^2 by a force of 1 N. Show that the acceleration would be the same for a force of 2 N acting on 2 kg.

5. Consider a business jet of mass 30,000 kg in takeoff when the thrust for each of two engines is 30,000 N. Show that its acceleration is 2 m/s^2.

6. Leroy, who has a mass of 100 kg, is skateboarding at 9.0 m/s when he smacks into a brick wall and comes to a dead stop in 0.2 s.

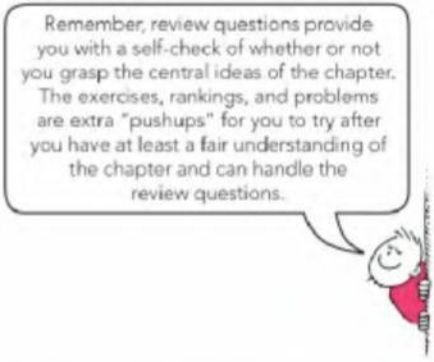
a. Show that his deceleration is 45 m/s^2.

b. Show that the force of impact is 4500 N. (ouch!)

• **7.** A rock band's tour bus, mass M, is accelerating away from a STOP sign at rate a when a piece of heavy metal, mass $M/6$, falls onto the top of the bus and remains there.

a. Show that the bus's acceleration is now $\frac{6}{7}a$.

b. If the initial acceleration of the bus is 1.2 m/s^2, show that when the bus carries the heavy metal with it, the acceleration will be 1.0 m/s^2.



CHAPTER 4 ONLINE RESOURCES

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Interactive Figures

- 4.9, 4.12

Tutorial

- Newton's Second Law

Videos

- Force Causes Acceleration
- Friction
- Newton's Second Law
- Free-Fall Acceleration Explained
- Falling and Air Resistance

Quizzes

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Links

5 Newton's Third Law of Motion

1 Darlene Librero pulls with one finger; Paul Doherty pulls with both hands. Who exerts more force on the scale? 2 Does the racquet hit the ball or does the ball hit the racquet? Answer: The racquet cannot hit the ball *unless* the ball simultaneously hits the racquet—that's the law! 3 Wife Lil and I demonstrate Newton's third law— that you cannot touch without being touched.

When Isaac Newton was 26 years old he was appointed the Lucasian Professor of Mathematics at Trinity College in Cambridge. He had personal conflicts with the religious positions of the College, namely questioning the idea of the Trinity as a foundational tenet of Christianity at that time. At the age of 46, his energies turned somewhat from science when he was elected to a 1-year term as a member of Parliament. (At 57, he was elected to a second term.) In his two years in Parliament, he never gave a speech. One day he rose and the House fell silent to hear the great man. Newton's "speech" was very brief; he simply requested that a window be closed because of a draft.

A further turn from his work in science was his appointment as warden, and then as master, of the mint. Newton resigned his professorship and directed his efforts toward greatly improving the workings of the mint, to the dismay of counterfeiters who were then flourishing. He maintained his membership in the Royal Society and at age 60 was elected president, then was reelected each year for the rest of his life.

Although Newton's hair turned gray at age 30, it remained full, long, and wavy all his life, and, unlike others in his time, he did not wear a wig. He was a modest man, overly sensitive to criticism, and he never married. He remained healthy in body and mind into old age. At 80, he still had all his teeth, his eyesight and hearing were sharp, and his mind was alert. In his lifetime he was regarded by his countrymen as the greatest scientist who ever lived. In 1705, he was knighted by Queen Anne. Newton died at the age of 84 and was buried in Westminster Abbey along with England's monarchs and heroes. His laws of motion were all that was needed 242 years later to put humans on the Moon. This chapter presents the third of his three laws of motion.

Forces and Interactions

So far we've treated force in its simplest sense—as a push or pull. Yet no push or pull ever occurs alone. Every force is part of an *interaction* between one thing and another. When you push on a wall with your fingers, more is happening than your push on the wall. You're interacting with the wall, which also pushes back on you. This is evident in your bent fingers, as illustrated in Figure 5.1. There is a pair of forces involved: your push on the wall and the wall pushes back on you. These forces are equal in magnitude (have the same strength) and opposite in direction, and they constitute a single interaction. In fact, you can't push on the wall *unless* the wall pushes back.[1]

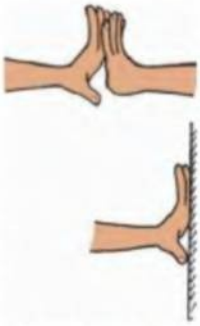

FIGURE 5.1
INTERACTIVE FIGURE
You can feel your fingers being pushed by your friend's fingers. You also feel the same amount of force when you push on a wall and it pushes back on you. As a point of fact, you can't push on the wall *unless* it pushes back on you!

Consider a boxer's fist hitting a massive punching bag. The fist hits the bag (and dents it) while the bag hits back on the fist (and stops its motion). A pair of forces is involved in hitting the bag. The force pair can be quite large. But what of hitting a piece of tissue paper, as discussed earlier? The boxer's fist can only exert as much force on the tissue paper as the tissue paper can exert on the fist. Furthermore, the fist can't exert any force at all unless what is being hit exerts the same amount of force back. An interaction requires a *pair* of forces acting on *two* separate objects.

FIGURE 5.2
When you lean against a wall, you exert a force on the wall. The wall simultaneously exerts an equal and opposite force on you. Hence you don't topple over.

FIGURE 5.3
He can hit the massive bag with considerable force. But with the same punch he can exert only a tiny force on the tissue paper in midair.

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Video
Forces and Interaction

Other examples: You pull on a rope attached to a cart, acceleration occurs. When doing so, the cart pulls back on you, as evidenced perhaps by the tightening of the rope wrapped around your hand. A hammer hits a stake and drives it into the ground. In doing so, the stake exerts an equal amount of force on the hammer, which brings the hammer to an abrupt halt. One thing interacts with another—you with the cart, or the hammer with the stake.

Which exerts the force and which receives the force? Isaac Newton's response was that neither force has to be identified as "exerter" or "receiver"; he concluded that both objects must be treated equally. For example, when you pull the cart, the cart pulls on you. This pair of forces, your pull on the cart and the cart's pull on you, makes up the single interaction between you and the cart. In the interaction between the hammer and the stake, the hammer exerts a force against the stake but is itself brought to a halt in the process. Such observations led Newton to his third law of motion.

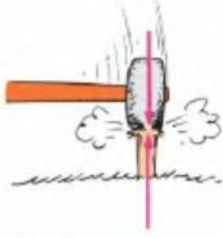

FIGURE 5.4
In the interaction between the hammer and the stake, each exerts the same amount of force on the other.

[1]We tend to think that only living things are capable of pushing and pulling. But inanimate things can do the same. So please don't be troubled about the idea of the inanimate wall pushing on you. It does, just as another person leaning against you would.

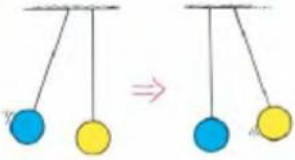

FIGURE 5.5
The impact forces between the blue ball and the yellow ball move the yellow ball and stop the blue ball.

Newton's Third Law of Motion

Newton's third law states:

Whenever one object exerts a force on a second object, the second object exerts an equal and opposite force on the first.

We can call one force the *action force* and the other the *reaction force*. Then we can express Newton's third law in the form:

To every action there is always an opposed equal reaction.

FIGURE 5.6
In the interaction between the car and the truck, is the force of impact the same on each? Is the damage the same?

It doesn't matter which force we call *action* and which we call *reaction*. The important thing is that they are co-parts of a single interaction and that neither force exists without the other.

When you walk, you interact with the floor. You push against the floor, and the floor pushes against you. The pair of forces occurs at the same time (they are *simultaneous*). Likewise, the tires of a car push against the road while the road pushes back on the tires—the tires and road simultaneously push against each other. In swimming, you interact with the water, pushing the water backward, while the water simultaneously pushes you forward—you and the water push against each other. The reaction forces are what account for our motion in these examples. These forces depend on friction; a person or car on ice, for example, may be unable to exert the action force to produce the needed reaction force. Forces occur in *force pairs*. Neither force exists without the other.

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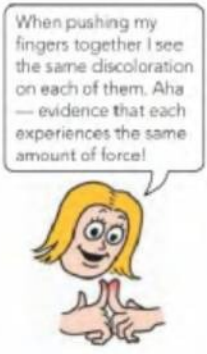
Tutorial
Newton's Third Law



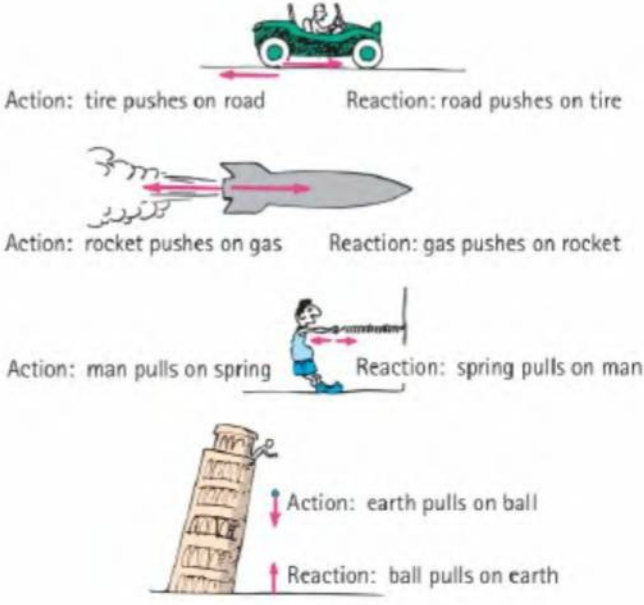


FIGURE 5.7
Action and reaction forces. Note that when action is "*A* exerts force on *B*," the reaction is then simply "*B* exerts force on *A*."

CHECK POINT

Does a speeding missile possess force?

Check Your Answer

No, a force is not something an object *has*, like mass, but is part of an interaction between one object and another. A speeding missile may possess the capability of exerting a force on another object when interaction occurs, but it does not possess force as a thing in itself. As we will see in the following chapters, a speeding missile possesses momentum and kinetic energy.

DEFINING YOUR SYSTEM

An interesting question often arises: Since action and reaction forces are equal and opposite, why don't they cancel to zero? To answer this question, we must consider the *system* involved. Consider, for example, a system consisting of a single orange, Figure 5.8. The dashed line surrounding the orange encloses and defines the system. The vector that pokes outside the dashed line represents an external force on the system. The system accelerates in accord with Newton's second law. In Figure 5.9, we see that this force is provided by an apple, which doesn't change our analysis. The apple is outside the system. The fact that the orange simultaneously exerts a force on the apple, which is external to the system, may affect the apple (another system), but not the orange. You can't cancel a force on the orange with a force on the apple. So, in this case, the action and reaction forces don't cancel.

FIGURE 5.8
INTERACTIVE FIGURE
A force acts on the orange, and the orange accelerates to the right.

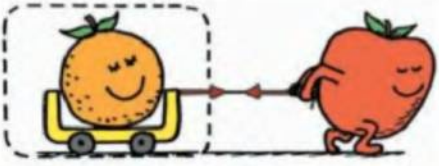


FIGURE 5.9
INTERACTIVE FIGURE
The force on the orange, provided by the apple, is not cancelled by the reaction force on the apple. The orange still accelerates.

A system may be as tiny as an atom or as large as the universe.

Now let's consider a larger system, enclosing *both* the orange and the apple. We see the system bounded by the dashed line in Figure 5.10. Notice that the force pair is *internal* to the orange–apple system. Then these forces *do* cancel each other. They play no role in accelerating the system. A force external to the system is needed for acceleration. That's where friction with the floor plays a role (Figure 5.11). When

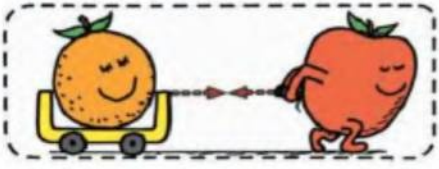


FIGURE 5.10
INTERACTIVE FIGURE
In the larger system of orange + apple, action and reaction forces are internal and cancel. If these are the only horizontal forces, with no external force, no acceleration of the system occurs.

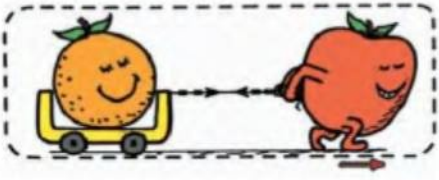


FIGURE 5.11
INTERACTIVE FIGURE
An external horizontal force occurs when the floor pushes on the apple (reaction to the apple's push on the floor). The orange–apple system accelerates.

FIGURE 5.12
A acts on B, and B accelerates.

FIGURE 5.13
Both A and C act on B. They can cancel each other, so B does not accelerate.

the apple pushes against the floor, the floor simultaneously pushes on the apple—an external force on the system. The system accelerates to the right.

Inside a football are trillions and trillions of interatomic forces at play. They hold the ball together, but they play no role in accelerating the ball. Although every one of the interatomic forces is part of an action–reaction pair within the ball, they combine to zero, no matter how many of them there are. A force external to the football, like a kick, is needed to accelerate it. In Figure 5.12, we note a single interaction between the foot and the football.

The football in Figure 5.13, however, does not accelerate. In this case, there are two interactions occurring—two forces acting on the football. If they are simultaneous, equal, and opposite, then the net force is zero. Do the two opposing kicks make up an action–reaction pair? No, for they act on the same object, not on different objects. They may be equal and opposite, but, unless they act on different objects, they are not an action–reaction pair. Get it?

If this is confusing, it may be well to note that Newton had difficulties with the third law himself. (See insightful examples of Newton's third law on pages 21 and 22 in the *Concept Development Practice Book*.)

CHECK POINT

1. On a cold, rainy day, you find yourself in a car with a dead battery. You must push the car to move it and get it started. Why can't you move the car by remaining comfortably inside and pushing against the dashboard?
2. Why does a book sitting on a table never accelerate "spontaneously" in response to the trillions of interatomic forces acting within it?
3. We know that Earth pulls on the Moon. Does it follow that the Moon also pulls on Earth?
4. Can you identify the action and reaction forces in the case of an object falling in a vacuum?

Check Your Answers

1. In this case, the system to be accelerated is the car. If you remain inside and push on the dashboard, the force pair you produce acts and reacts within the system. These forces cancel out as far as any motion of the car is concerned. To accelerate the car, there must be an interaction between the car and something external—for example, you on the outside pushing against the road and on the car.
2. Every one of these interatomic forces is part of an action–reaction pair within the book. These forces add up to zero, no matter how many of them there are. This is what makes Newton's *first* law apply to the book. The book has zero acceleration unless an *external* force acts on it.
3. Yes, both pulls make up an action–reaction pair of forces associated with the gravitational interaction between Earth and Moon. We can say that (1) Earth pulls on Moon and (2) Moon likewise pulls on Earth; but it is more insightful to think of this as a single interaction—both Earth and Moon simultaneously pulling on each other, each with the *same* amount of force. You can't push or pull on something unless that something simultaneously pushes or pulls on you. That's the law!
4. To identify a pair of action–reaction forces in any situation, first identify the pair of interacting objects involved—Body A and Body B. Body A, the falling object, is interacting (gravitationally) with Body B, the whole Earth. So Earth pulls downward on the object (call it action), while the object pulls upward on Earth (reaction).

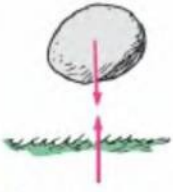


FIGURE 5.14
Earth is pulled up by the boulder with just as much force as the boulder is pulled downward by Earth.

ACTION AND REACTION ON DIFFERENT MASSES

As strange as it may first seem, a falling object pulls upward on Earth with as much force as Earth pulls downward on it. The resulting acceleration of the falling object is evident, while the upward acceleration of Earth is too small to

detect. So strictly speaking, when you step off a curb, the street rises ever so slightly to meet you.

We can see that Earth accelerates slightly in response to a falling object by considering the exaggerated examples of two planetary bodies, parts (a) through (e) in Figure 5.15. The forces between bodies A and B are equal in magnitude and oppositely directed in *each* case. If acceleration of planet A is unnoticeable in (a), then it is more noticeable in (b), where the difference between the masses is less extreme. In (c), where both bodies have equal mass, acceleration of object A is as evident as it is for B. Continuing, we see that the acceleration of A becomes even more evident in (d) and even more so in (e).

The role of different masses is evident in a fired cannon. When a cannon is fired, there is an interaction between the cannon and the cannonball (Figure 5.16). A pair of forces acts on both cannon and cannonball. The force exerted on the cannonball is as great as the reaction force exerted on the cannon; hence, the cannon recoils. Since the forces are equal in magnitude, why doesn't the cannon recoil with the same speed as the cannonball? In analyzing changes in motion, Newton's second law reminds us that we must also consider the masses involved. Suppose we let F represent both the action and reaction force, m the mass of the cannonball, and $\mathcal{M}$ the mass of the much more massive cannon. The accelerations of the cannonball and the cannon are then found by comparing the ratio of force to mass. The accelerations are:

$$\text{Cannonball: } \frac{F}{m} = a$$

$$\text{Cannon: } \frac{F}{\mathcal{M}} = a$$

This shows why the change in velocity of the cannonball is so large compared with the change in velocity of the cannon. A given force exerted on a small mass produces a large acceleration, while the same force exerted on a large mass produces a small acceleration.

Going back to the example of the falling object, if we used similarly exaggerated symbols to represent the acceleration of Earth reacting to a falling object, the symbol m for the Earth's mass would be astronomical in size. The force F, the weight of the falling object, divided by this large mass would result in a microscopic a to represent the acceleration of Earth toward the falling object.

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Videos

Action and Reaction on Different Masses
Action and Reaction on Rifle and Bullet

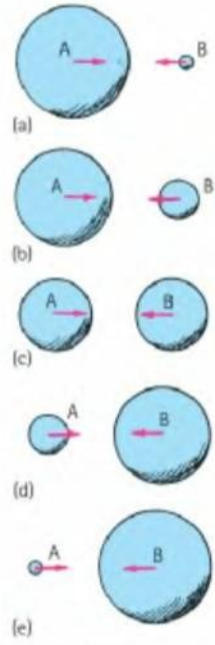


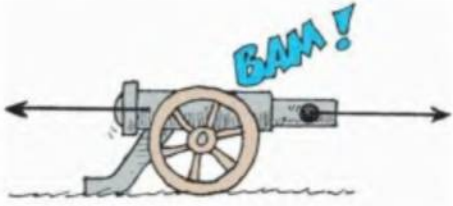
FIGURE 5.15

Which falls toward the other, A or B? Although the forces between each pair are the same, do accelerations differ?

FIGURE 5.16

INTERACTIVE FIGURE

The force exerted against the recoiling cannon is just as great as the force that drives the cannonball inside the barrel. Why, then, does the cannonball accelerate more than the cannon?



We can extend the idea of a cannon recoiling from the ball it fires to understanding rocket propulsion. Consider an inflated balloon recoiling when air is expelled (Figure 5.17). If the air is expelled downward, the balloon accelerates upward. The same principle applies to a rocket, which continually "recoils" from the ejected exhaust gas. Each molecule of exhaust gas is like a tiny cannonball shot from the rocket (Figure 5.18).

A common misconception is that a rocket is propelled by the impact of exhaust gases against the atmosphere. In fact, before the advent of rockets, it was generally thought that sending a rocket to the Moon was impossible. Why? Because there is no air above Earth's atmosphere for the rocket to push against. But this is like saying

FIGURE 5.17

The balloon recoils from the escaping air, and it moves upward.

FIGURE 5.18

The rocket recoils from the "molecular cannonballs" it fires, and it moves upward.

a cannon wouldn't recoil unless the cannonball had air to push against. Not true! Both the rocket and recoiling cannon accelerate because of the reaction forces exerted by the material they fire—not because of any pushes on the air. In fact, a rocket operates better above the atmosphere where there is no air resistance.

Using Newton's third law, we can understand how a helicopter gets its lifting force. The whirling blades are shaped to force air particles down (action), and the air forces the blades up (reaction). This upward reaction force is called *lift*. When lift equals the weight of the aircraft, the helicopter hovers in midair. When lift is greater, the helicopter climbs upward.

This is true for birds and airplanes. Birds fly by pushing air downward. The air in turn pushes the bird upward. When the bird is soaring, the wings must be shaped so that moving air particles are deflected downward. Slightly tilted wings that deflect oncoming air downward produce lift on an airplane. Air that is pushed downward continuously maintains lift. This supply of air is obtained by the forward motion of the aircraft, which results from propellers or jets that push air backward. The air, in turn, pushes the propellers or jets forward. We will learn in Chapter 14 that the curved surface of a wing is an airfoil, which enhances the lifting force.

We see Newton's third law at work everywhere. A fish pushes the water backward with its fins, and the water pushes the fish forward. When the wind pushes against the branches of a tree and the branches push back on the wind, we have whistling sounds. Forces are interactions between different things. Every contact requires at least a twoness; there is no way that an object can exert a force on nothing. Forces, whether large shoves or slight nudges, always occur in pairs, each of which is opposite to the other. Thus, we cannot touch without being touched.

FIGURE 5.19

Geese fly in a V formation because air pushed downward at the tips of their wings swirls upward, creating an updraft that is strongest off to the side of the bird. A trailing bird gets added lift by positioning itself in this updraft, pushes air downward, and creates another updraft for the next bird, and so on. The result is a flock flying in a V formation.

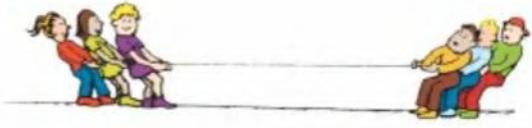
FIGURE 5.20

You cannot touch without being touched—Newton's third law.

Practicing Physics

Tug of War

Perform a tug-of-war between guys and gals. Do it on a polished floor that's somewhat slippery, with guys wearing socks and gals wearing rubber-soled shoes. Who will surely win, and why? [*Hint:* Who wins a tug-of-war, those who pull harder on the rope or those who push harder against the floor?]



CHECK POINT

1. A car accelerates along a road. Identify the force that moves the car.
2. A high-speed bus and an innocent bug have a head-on collision. The force of impact splatters the poor bug over the windshield. Is the corresponding force that the bug exerts against the windshield greater, less, or the same? Is the resulting deceleration of the bus greater than, less than, or the same as that of the bug?

Jellyfish have been using rocket or jet propulsion for eons.

Check Your Answers

1. It is the road that pushes the car along. Really! Only the road provides the horizontal force to move the car forward. How does it do this? The rotating tires of the car push back on the road (action). The road simultaneously pushes forward on the tires (reaction). How about that!
2. The magnitudes of both forces are the same, for they constitute an action–reaction force pair that makes up the interaction between the bus and the bug. The accelerations, however, are very different because the masses are different. The bug undergoes an enormous and lethal deceleration, while the bus undergoes a very tiny deceleration—so tiny that the very slight slowing of the bus is unnoticed by its passengers. But if the bug were more massive—as massive as another bus, for example—the slowing down would unfortunately be very apparent. (Can you see the wonder of physics here? Although so much is *different* for the bug and the bus, the amount of force each encounters is the *same*. Amazing!)

Summary of Newton's Three Laws

Newton's first law, the law of inertia: An object at rest tends to remain at rest; an object in motion tends to remain in motion at constant speed along a straight-line path. This property of objects to resist change in motion is called *inertia*. Mass is a measure of inertia. Objects will undergo changes in motion only in the presence of a net force.

Newton's second law, the law of acceleration: When a net force acts on an object, the object will accelerate. The acceleration is directly proportional to the net force and inversely proportional to the mass. Symbolically, $a = F/m$. Acceleration is always in the direction of the net force. When objects fall in a vacuum, the net force is simply the weight—the pull of gravity—and the acceleration is g (the symbol g denotes that acceleration is due to gravity alone). When objects fall in air, the net force is equal to the weight minus the force of air resistance, and the acceleration is less than g. If and when the force of air resistance equals the weight of a falling object, acceleration terminates, and the object falls at constant speed (called *terminal speed*).

Newton's third law, the law of action–reaction: Whenever one object exerts a force on a second object, the second object exerts an equal and opposite force on the first. Forces occur in pairs, one action and the other reaction, which together constitute the interaction between one object and the other. Action and reaction always occur simultaneously and act on different objects. Neither force exists without the other.

Isaac Newton's three laws of motion are rules of nature that enable us to see how beautifully so many things connect with one another. We see these rules in operation in our everyday environment.

FIGURE 5.21

This vector, scaled so that 1 cm equals 20 N, represents a force of 60 N to the right.

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Tutorial
Vectors

The valentine vector says, "I was only a scalar until you came along and gave me direction."

Vectors

We have learned that any quantity that requires both magnitude and direction for a complete description is a **vector quantity.** Examples of vector quantities include force, velocity, and acceleration. By contrast, a quantity that can be described by magnitude only, not involving direction, is called a **scalar quantity.** Mass, volume, and speed are scalar quantities.

A vector quantity is nicely represented by an arrow. When the length of the arrow is scaled to represent the quantity's magnitude, and the direction of the arrow shows the direction of the quantity, we refer to the arrow as a **vector.**

Adding vectors that act along parallel directions is simple enough: If they act in the same direction, they add; if they act in opposite directions, they subtract. The sum of two or more vectors is called their **resultant.** To find the resultant of two vectors that don't act in exactly the same or opposite direction, we use the *parallelogram rule.*[2] Construct a parallelogram wherein the two vectors are adjacent sides—the diagonal of the parallelogram shows the resultant. In Figure 5.22, the parallelograms are rectangles.

FIGURE 5.22

INTERACTIVE FIGURE

The pair of vectors at right angles to each other make two sides of a rectangle, the diagonal of which is their resultant.

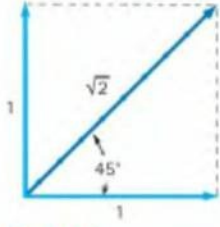

FIGURE 5.23

When a pair of equal-length vectors at right angles to each other are added, they form a square. The diagonal of the square is the resultant, $\sqrt{2}$ times the length of either side.

In the special case of two vectors that are equal in magnitude and perpendicular to each other, the parallelogram is a square (Figure 5.23). Since for any square the length of a diagonal is $\sqrt{2}$, or 1.41, times one of the sides, the resultant is $\sqrt{2}$ times one of the vectors. For example, the resultant of two equal vectors of magnitude 100 acting at a right angle to each other is 141.

FORCE VECTORS

Figure 5.24 shows a pair of forces acting on a box. One is 30 newtons and the other is 40 newtons. Simple measurement shows the resultant of this pair of forces is 50 newtons.

Figure 5.25 shows Nellie Newton hanging at rest from a clothesline. Note that the clothesline acts like a pair of ropes that make different angles with the vertical. Which side has the greater tension? Investigation will show there are three forces acting on Nellie: her weight, a tension in the left-hand side of the rope, and a tension in the right-hand side of the rope. Because of the different angles, different rope tensions will occur in each side. Figure 5.25 shows a step-by-step solution. Because Nellie hangs in equilibrium, her weight must be supported by two rope

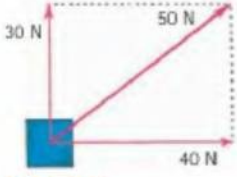

FIGURE 5.24

The resultant of the 30-N and 40-N forces is 50 N.

[2]A parallelogram is a four-sided figure with opposite sides parallel to each other. Usually, you determine the length of the diagonal by measurement; but, in the special case in which the two vectors **X** and **Y** are perpendicular (a square or a rectangle), you can apply the Pythagorean Theorem, $\mathbf{R}^2 = \mathbf{X}^2 + \mathbf{Y}^2$, to find the resultant: $\mathbf{R} = \sqrt{\mathbf{X}^2 + \mathbf{Y}^2}$.

tensions, which must add vectorially to be equal and opposite to her weight. The parallelogram rule shows that the tension in the right-hand rope is greater than the tension in the left-hand rope. If you measure the vectors, you'll see that tension in the right rope is about twice the tension in the left rope. Both rope tensions combine to support her weight.

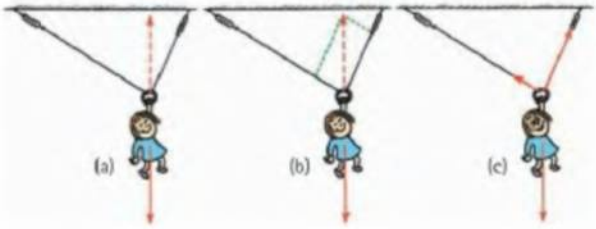

FIGURE 5.25

INTERACTIVE FIGURE

(a) Nellie's weight is shown by the downward vertical vector. An equal and opposite vector is needed for equilibrium, shown by the dashed vector. (b) This dashed vector is the diagonal of a parallelogram defined by the green lines. (c) Both rope tensions are shown by the constructed vectors. Tension is greater in the right rope, the one more likely to break.

More about force vectors can be found in Appendix D at the end of this book and in the *Practicing Physics* book.

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Videos

Vector Representations: How to Add and Subtract Vectors

Geometric Addition of Vectors

VELOCITY VECTORS

Recall, from Chapter 3, the difference between speed and velocity—speed is a measure of "how fast"; velocity is a measure of both how fast and "in which direction." If the speedometer in a car reads 100 kilometers per hour (km/h), you know your speed. If there is also a compass on the dashboard, indicating that the car is moving due north, for example, you know your velocity—100 km/h north. To know your velocity is to know your speed and your direction.

FIGURE 5.26

Diana Lininger Markham illustrates the vector arrangement of Figure 5.25.

Consider an airplane flying due north at 80 km/h relative to the surrounding air. Suppose that the plane is caught in a 60-km/h crosswind (wind blowing at right angles to the direction of the airplane) that blows it off its intended course. This example is represented with vectors in Figure 5.27 with velocity vectors scaled so that 1 centimeter (cm) represents 20 km/h. Thus, the 80-km/h velocity of the airplane is shown by the 4-cm vector, and the 60-km/h crosswind is shown by the 3-cm vector. The diagonal of the constructed parallelogram (a rectangle, in this case) measures 5 cm, which represents 100 km/h. So the airplane moves at 100 km/h relative to the ground, in a direction between north and northeast.

The pair of 6-unit and 8-unit vectors at right angles to each other say, "We may be a six and an eight, but together we're a perfect ten."

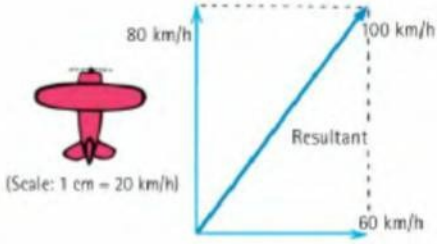


FIGURE 5.27
The 60-km/h crosswind blows the 80-km/h aircraft off course at 100 km/h.

CHECK POINT

Consider a motorboat that normally travels 10 km/h in still water. If the boat heads directly across the river, which also flows at a rate of 10 km/h, what will be its velocity relative to the shore?

Check Your Answer

When the boat heads cross-stream (at right angles to the river flow), its velocity is 14.1 km/h, 45 degrees downstream (in accord with the diagram in Figure 5.23).

COMPONENTS OF VECTORS

Just as two vectors at right angles can be combined into one resultant vector, any vector can be resolved into two *component* vectors perpendicular to each other. These two vectors are known as the **components** of the given vector they replace (Figure 5.28). The process of determining the components of a vector is called *resolution*. Any vector drawn on a piece of paper can be resolved into a vertical and a horizontal component.

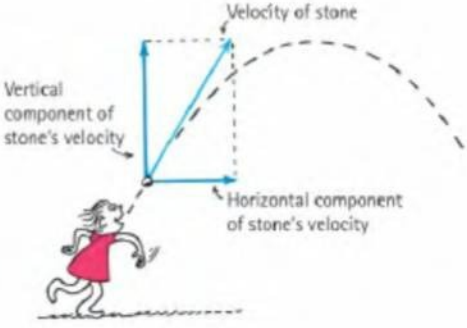


FIGURE 5.28
The horizontal and vertical components of a stone's velocity.

Vector resolution is illustrated in Figure 5.29. A vector **V** is drawn in the proper direction to represent a vector quantity. Then vertical and horizontal lines *(axes)* are

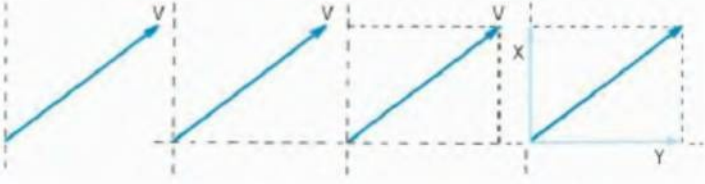


FIGURE 5.29
Construction of the vertical and horizontal components of a vector.

drawn at the tail of the vector. Next, a rectangle is drawn that has **V** as its diagonal. The sides of this rectangle are the desired components, vectors **X** and **Y.** In reverse, note that the vector sum of vectors **X** and **Y** is **V.**

We'll return to vector components when we treat projectile motion in Chapter 10.

CHECK POINT

With a ruler, draw the horizontal and vertical components of the two vectors shown. Measure the components and compare your findings with the answers given at the bottom of the page.

Answers

Left vector: The horizontal component is 2 cm; the vertical component is 2.6 cm.
Right vector: The horizontal component is 3.8 cm; the vertical component is 2.6 cm.

SUMMARY OF TERMS

Newton's third law Whenever one object exerts a force on a second object, the second object exerts an equal and opposite force on the first.

Vector quantity A quantity that has both magnitude and direction. Examples are force, velocity, and acceleration.

Scalar quantity A quantity that has magnitude but not direction. Examples are mass, volume, and speed.

Vector An arrow drawn to scale used to represent a vector quantity.

Resultant The net result of a combination of two or more vectors.

Components Mutually perpendicular vectors, usually horizontal and vertical, whose vector sum is a given vector.

REVIEW QUESTIONS

Forces and Interactions

1. When you push against a wall with your fingers, they bend because they experience a force. Identify this force.
2. A boxer can hit a heavy bag with great force. Why can't he hit a piece of tissue paper in midair with the same amount of force?
3. How many forces are required for an interaction?

Newton's Third Law of Motion

4. State Newton's third law of motion.
5. Consider hitting a baseball with a bat. If we call the force on the bat against the ball the *action* force, identify the *reaction* force.
6. Consider the apple and the orange (Figure 5.9). If the system is considered to be only the orange, is there a net force on the system when the apple pulls?
7. If the system is considered to be the apple and the orange together (Figure 5.10), is there a net force on the system when the apple pulls (ignoring friction with the floor)?
8. To produce a net force on a system, must there be an externally applied net force?
9. Consider the system of a single football. If you kick it, is there a net force to accelerate the system? If a friend kicks it at the same time with an equal and opposite force, is there a net force to accelerate the system?

Action and Reaction on Different Masses

10. Earth pulls down on you with a gravitational force that you call your weight. Do you pull up on Earth with the same amount of force?
11. If the forces that act on a cannonball and the recoiling cannon from which it is fired are equal in magnitude,

why do the cannonball and cannon have very different accelerations?

12. Identify the force that propels a rocket.
13. How does a helicopter get its lifting force?
14. Can you physically touch a person without that person touching you with the same amount of force?

Summary of Newton's Three Laws

15. Fill in the blanks: Newton's first law is often called the law of _____; Newton's second law is the law of _____; and Newton's third law is the law of _____ and _____.
16. Which of the three laws deals with interactions?

Vectors

17. Cite three examples of a vector quantity and three examples of a scalar quantity.
18. Why is speed considered a scalar and velocity a vector?
19. According to the parallelogram rule, what quantity is represented by the diagonal of a constructed parallelogram?
20. Consider Nellie hanging at rest in Figure 5.25. If the ropes were vertical, with no angle involved, what would be the tension in each rope?
21. When Nellie's ropes make an angle, what quantity must be equal and opposite to her weight?
22. When a pair of vectors are at right angles, is the resultant always greater in magnitude than either of the vectors separately?

PROJECT

Hold your hand like a flat wing outside the window of a moving automobile. Then slightly tilt the front edge upward and notice the lifting effect. Can you see Newton's laws at work here?

PLUG AND CHUG

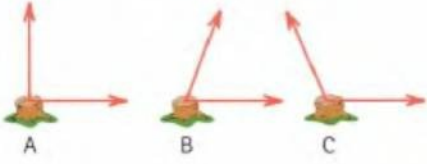
1. Calculate the resultant of the pair of velocities 100 km/h north and 75 km/h south. Calculate the resultant if both of the velocities are directed north.

Resultant of two vectors at right angles to each other:
$R = \sqrt{X^2 + Y^2}$

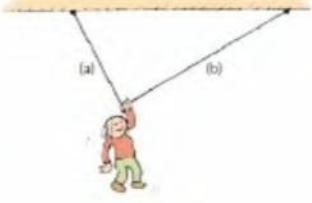
2. Calculate the magnitude of the resultant of a pair of 100-km/h velocity vectors that are at right angles to each other.
3. Calculate the resultant of a horizontal vector with a magnitude of 4 units and a vertical vector with a magnitude of 3 units.
4. Calculate the resultant velocity of an airplane that normally flies at 200 km/h if it encounters a 50-km/h wind from the side (at a right angle to the airplane).

RANKING

1. As seen from above, a stubborn stump is pulled by a pair of ropes, each with a force of 200 N, but at different angles as shown. From greatest to least, rank the net force on the stump.

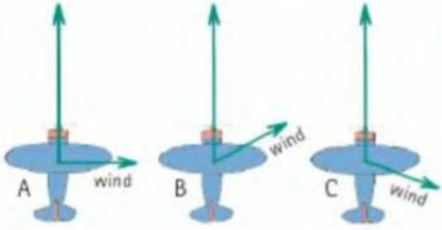


2. Nellie Newton hangs motionless by one hand from a clothesline. Which side of the line, a or b, has the greater

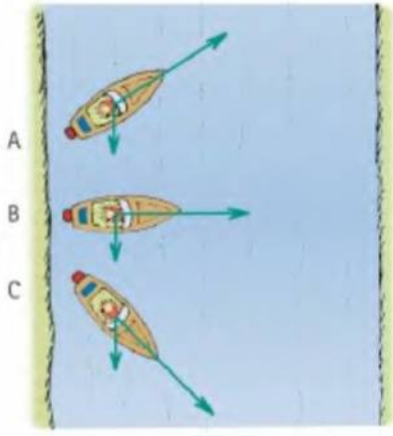


a. horizontal component of tension?
b. vertical component of tension?
c. tension?

3. Here we see a top view of an airplane being blown off course by wind in three different directions. Use a pencil and the parallelogram rule and sketch the vectors that show the resulting velocities for each case. Rank the speeds of the airplane across the ground from fastest to slowest.



4. Here we see top views of three motorboats crossing a river. All have the same speed relative to the water, and all experience the same river flow. Construct resultant vectors showing the speed and direction of the boats. Rank them from most to least for
a. the time for the boats to reach the opposite shore.
b. the fastest ride.



EXERCISES

1. A rocket becomes progressively easier to accelerate as it travels through space. Why is this so? (*Hint:* About 90% of the mass of a newly launched rocket is fuel.)

2. The photo shows Steve Hewitt and daughter Gretchen. Is Gretchen touching her dad, or is dad touching her? Explain.

3. When you rub your hands together, can you push harder on one hand than the other?

4. For each of the following interactions, identify action and reaction forces. (a) A hammer hits a nail. (b) Earth gravity pulls down on a book. (c) A helicopter blade pushes air downward.

5. You hold an apple over your head. (a) Identify all the forces acting on the apple and their reaction forces. (b) When you drop the apple, identify all the forces acting on it as it falls and the corresponding reaction forces. Neglect air drag.

6. Identify the action–reaction pairs of forces for the following situations: (a) You step off a curb. (b) You pat your tutor on the back. (c) A wave hits a rocky shore.

7. Consider a baseball player batting a ball. (a) Identify the action–reaction pairs when the ball is being hit and (b) while the ball is in flight.

8. What physics is involved for a passenger feeling pushed backward into the seat of an airplane when it accelerates along the runway during takeoff?

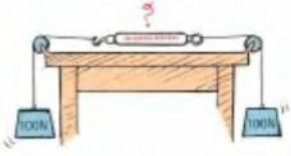
9. If you drop a rubber ball on the floor, it bounces back up. What force acts on the ball to provide the bounce?

10. When you kick a football, what action and reaction forces are involved? Which force, if any, is greater?

11. Is it true that when you drop from a branch to the ground below, you pull upward on Earth? If so, then why is the acceleration of Earth not noticed?

12. Within a book on a table, there are billions of forces pushing and pulling on all the molecules. Why is it that these forces never by chance add up to a net force in one direction, causing the book to accelerate "spontaneously" across the table?

13. Two 100-N weights are attached to a spring scale as shown. Does the scale read 0, 100, or 200 N, or does it give some other reading? (*Hint:* Would it read any differently if one of the ropes were tied to the wall instead of to the hanging 100-N weight?)



14. If you exert a horizontal force of 200 N to slide a crate across a factory floor at constant velocity, how much friction is exerted by the floor on the crate? Is the force of friction equal and oppositely directed to your 200-N

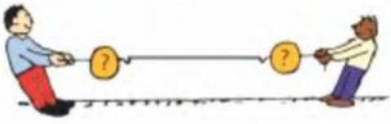
push? If the force of friction isn't the reaction force to your push, what is?

15. When the athlete holds the barbell overhead, the reaction force is the weight of the barbell on his hand. How does this force vary for the case in which the barbell is accelerated upward? Downward?

16. Consider the two forces acting on the person who stands still—namely, the downward pull of gravity and the upward support of the floor. Are these forces equal and opposite? Do they form an action–reaction pair? Why or why not?
17. Why can you exert greater force on the pedals of a bicycle if you pull up on the handlebars?
18. Does a baseball bat slow down when it hits a ball? Defend your answer.
19. Why does a rope climber pull downward on the rope to move upward?
20. A farmer urges his horse to pull a wagon. The horse refuses, saying that to try would be futile, for it would flout Newton's third law. The horse concludes that she can't exert a greater force on the wagon than the wagon exerts on her and, therefore, that she won't be able to accelerate the wagon. What is your explanation to convince the horse to pull?
21. You push a heavy car by hand. The car, in turn, pushes back with an opposite but equal force on you. Doesn't this mean that the forces cancel one another, making acceleration impossible? Why or why not?
22. The strong man will push the two initially stationary freight cars of equal mass apart before he himself drops straight to the ground. Is it possible for him to give either of the cars a greater speed than the other? Why or why not?

23. Suppose that two carts, one twice as massive as the other, fly apart when the compressed spring that joins them is released. What is the acceleration of the heavier cart relative to that of the lighter cart as they start to move apart?

24. If a Mack truck and Honda Civic have a head-on collision, upon which vehicle is the impact force greater? Which vehicle experiences the greater deceleration? Explain your answers.
25. Ken and Joanne are astronauts floating some distance apart in space. They are joined by a safety cord whose ends are tied around their waists. If Ken starts pulling on the cord, will he pull Joanne toward him, or will he pull himself toward Joanne, or will both astronauts move? Explain.
26. Which team wins in a tug-of-war—the team that pulls harder on the rope, or the team that pushes harder against the ground? Explain.
27. In a tug-of-war between Sam and Maddy, each pulls on the rope with a force of 250 N. What is the tension in the rope? If both remain motionless, what horizontal force does each exert against the ground?
28. Your instructor challenges you and your friend to each pull on a pair of scales attached to the ends of a horizontal rope, in tug-of-war fashion, so that the readings on the scales will differ. Can this be done? Explain.



29. Two people of equal mass attempt a tug-of-war with a 12-m rope while standing on frictionless ice. When they pull on the rope, each of them slides toward the other. How do their accelerations compare, and how far does each person slide before they meet?
30. What aspect of physics was not known by the writer of this newspaper editorial that ridiculed early experiments by Robert H. Goddard on rocket propulsion above Earth's atmosphere? "Professor Goddard . . . does not know the relation of action to reaction, and of the need to have something better than a vacuum against which to react . . . he seems to lack the knowledge ladled out daily in high schools."
31. Which of the following are scalar quantities, which are vector quantities, and which are neither? (a) velocity; (b) age; (c) speed; (d) acceleration; (e) temperature.
32. What can you correctly say about two vectors that add together to equal zero?
33. Can a pair of vectors with unequal magnitudes ever add to zero? Can three unequal vectors add to zero? Defend your answers.
34. When can a nonzero vector have a zero horizontal component?
35. When, if ever, can a vector quantity be added to a scalar quantity?
36. Which is more likely to break—a hammock stretched tightly between a pair of trees or one that sags more when you sit on it?
37. A heavy bird sits on a clothesline. Will the tension in the clothesline be greater if the line sags a lot or if it sags a little?
38. The rope supports a lantern that weighs 50 N. Is the tension in the rope less than, equal to, or more than 50 N? Use the parallelogram rule to defend your answer.

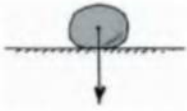
39. The rope is repositioned as shown and still supports the 50-N lantern. Is the tension in the rope less than, equal to, or more than 50 N? Use the parallelogram rule to defend your answer.

40. Why does vertically falling rain make slanted streaks on the side windows of a moving automobile? If the streaks make an angle of 45°, what does this tell you about the relative speed of the car and the falling rain?

41. A balloon floats motionless in the air. A balloonist begins climbing the supporting cable. In which direction does the balloon move as the balloonist climbs? Defend your answer.

42. Consider a stone at rest on the ground. There are two interactions that involve the stone. One is between the stone and Earth as a whole: Earth pulls down on the stone (its weight) and the stone pulls up on Earth. What is the other interaction?

43. A stone is shown at rest on the ground. (a) The vector shows the weight of the stone. Complete the vector diagram showing another vector that results in zero net force on the stone. (b) What is the conventional name of the vector you have drawn?



44. Here a stone is suspended at rest by a string. (a) Draw force vectors for all the forces that act on the stone. (b) Should your vectors have a zero resultant? (c) Why or why not?

45. Here the same stone is being accelerated vertically upward. (a) Draw force vectors to some suitable scale showing relative forces acting on the stone. (b) Which is the longer vector, and why?

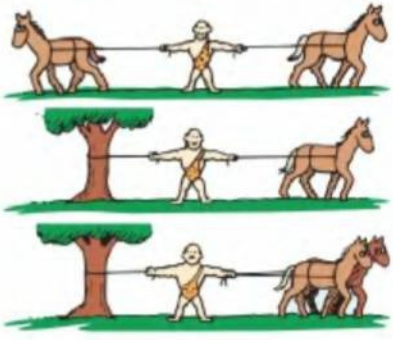
46. Suppose the string in the preceding exercise breaks and the stone slows in its upward motion. Draw a force vector diagram of the stone when it reaches the top of its path.

47. What is the acceleration of the stone of Exercise 46 at the top of its path?

48. Here the stone is sliding down a friction-free incline. (a) Identify the forces that act on it, and draw appropriate force vectors. (b) By the parallelogram rule, construct the resultant force on the stone (carefully showing that it has a direction parallel to the incline—the same direction as the stone's acceleration).

49. Here the stone is at rest, interacting with both the surface of the incline and the block. (a) Identify all the forces that act on the stone, and draw appropriate force vectors. (b) Show that the net force on the stone is zero. (*Hint 1:* There are two normal forces on the stone. *Hint 2:* Be sure the vectors you draw are for forces that act *on* the stone, not *by* the stone on the surfaces.)

50. The strong man can withstand the tension force exerted by the two horses pulling in opposite directions. How would the tension compare if only one horse pulled and the left rope were tied to a tree? How would the tension compare if the two horses pulled in the same direction, with the left rope tied to the tree?



PROBLEMS

1. A boxer punches a sheet of paper in midair and brings it from rest up to a speed of 25 m/s in 0.05 s. (a) What acceleration is imparted to the paper? (b) If the mass of the paper is 0.003 kg, what force does the boxer exert on it? (c) How much force does the paper exert on the boxer?

2. If you stand next to a wall on a frictionless skateboard and push the wall with a force of 40 N, how hard does the wall push on you? If your mass is 80 kg, show that your acceleration is 0.5 m/s^2.

3. If raindrops fall vertically at a speed of 3 m/s and you are running at 4 m/s, how fast do they hit your face?

4. Forces of 3.0 N and 4.0 N act at right angles on a block of mass 2.0 kg. Show that the acceleration of the block is 2.5 m/s^2.

5. Consider an airplane that normally has an airspeed of 100 km/h in a 100-km/h crosswind blowing from west to east. Calculate its ground velocity when its nose is pointed north in the crosswind.

6. You are paddling a canoe at a speed of 4 km/h directly across a river that flows at 3 km/h, as shown in the figure. (a) What is your resultant speed relative to the shore? (b) In approximately what direction should you paddle the canoe so that it reaches a destination directly across the river?

• 7. When two identical air pucks with repelling magnets are held together on an air table and released, they end up moving in opposite directions at the same speed, v. Assume the mass of one of the pucks is doubled and the procedure is repeated.

a. From Newton's third law, derive an equation that shows how the final speed of the double-mass puck compares with the speed of the single puck.

b. Calculate the speed of the double-mass puck if the single puck moves away at 0.4 m/s.

CHAPTER 5 ONLINE RESOURCES

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- 5.1, 5.8, 5.9, 5.10, 5.11, 5.16, 5.22, 5.25

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- Action and Reaction on Rifle and Bullet
- Vector Representation: How to Add and Subtract Vectors
- Geometrical Addition of Vectors

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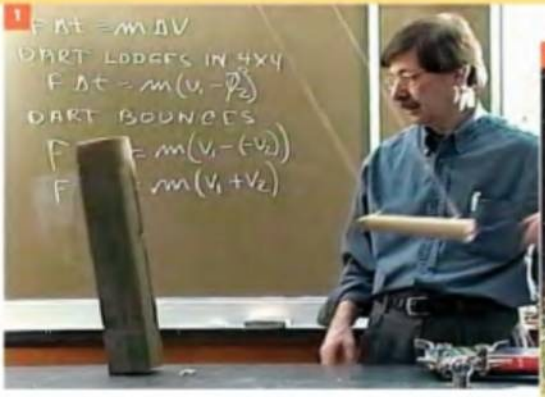
6 Momentum



1 Howie Brand demonstrates the different results when a dart bounces from a wooden block, rather than sticking to it. A bouncing dart produces more impulse, which tips the block. 2 Likewise for the Pelton wheel, where water bouncing from the curved paddles produces more impulse, which imparts more momentum to the wheel. 3 Momentum is mass times speed, as Alex Hewitt shows with his skateboard.

The gold rush that started in 1849 in California brought wealth to many who arrived with picks, shovels, and equipment for gold mining. But mining wasn't the only way to make money in the gold rush. Lester A. Pelton showed up without pick, shovel, or mining equipment and made his fortune by applying some physics (common sense) to the waterwheels used in mining operations at the time. He saw that the low efficiency of waterwheels was due to their flat paddles. Pelton designed a curved paddle with a ridge in the middle that caused the water to make a pair of U-turns upon impact. This produced more force on the paddles, just as more force is required to catch a ball and toss it back than to merely stop the ball. Water made to bounce exerts a greater impulse on the wheel. Pelton patented his idea and ushered in the impulse water turbine, more simply called the Pelton wheel (above). Pelton's story illustrates the fact that physics can indeed enrich your life in more ways than one.

We begin this chapter by examining the concept of momentum and the impulse that causes it to change.

Lester A. Pelton (1829–1908)

FIGURE 6.1
The boulder, unfortunately, has more momentum than the runner.

PhysicsPlace.com™
Tutorial
Newton's Third Law and Momentum
Video
Definition of Momentum

Momentum

We all know that a heavy truck is harder to stop than a small car moving at the same speed. We state this fact by saying that the truck has more momentum than the car. By **momentum** we mean inertia in motion. More specifically, momentum is defined as the product of the mass of an object and its velocity; that is,

$$\text{Momentum} = \text{mass} \times \text{velocity}$$

Or, in shorthand notation,

$$\text{Momentum} = mv$$

When direction is not an important factor, we can say:

$$\text{Momentum} = \text{mass} \times \text{speed}$$

which we still abbreviate mv.

We can see from the definition that a moving object can have a large momentum if either its mass or its velocity is large or if both its mass and its velocity are large. The truck has more momentum than the car moving at the same speed because it has a greater mass. We can see that a huge ship moving at a small speed can have a large momentum, as can a small bullet moving at a high speed. And, of course, a huge object moving at a high speed, such as a massive truck rolling down a steep hill with no brakes, has a huge momentum, whereas the same truck at rest has no momentum at all—because the v term in mv is zero.

FIGURE 6.2
Why are the engines of a supertanker normally cut off 25 km from port? Timing is especially important when changing momentum.

Impulse

If the momentum of an object changes, then either the mass or the velocity or both change. If the mass remains unchanged, as is most often the case, then the velocity changes and acceleration occurs. What produces acceleration? We know the answer is *force*. The greater the force acting on an object, the greater its change in velocity and, hence, the greater its change in momentum.

But something else is important in changing momentum: time—how long a time the force acts. If you apply a brief force to a stalled automobile, you produce a

change in its momentum. Apply the same force over an extended period of time, and you produce a greater change in the automobile's momentum. A force sustained for a long time produces more change in momentum than does the same force applied briefly. So, both force and time interval are important in changing momentum.

The quantity *force* × *time interval* is called **impulse.** In shorthand notation

$$\text{Impulse} = Ft$$

FIGURE 6.3
When you push with the same force for twice the time, you impart twice the impulse and produce twice the change in momentum.

CHECK POINT

1. Which has more momentum, a 1-ton car moving at 100 km/h or a 2-ton truck moving at 50 km/h?
2. Does a moving object have impulse?
3. Does a moving object have momentum?
4. For the same force, which cannon imparts a greater impulse to a cannonball—a long cannon or a short one?

Check Your Answers

1. Both have the same momentum (1 ton × 100 km/h = 2 ton × 50 km/h).
2. No, impulse is not something an object *has*, like momentum. Impulse is what an object can *provide* or what it can *experience* when it interacts with some other object. An object cannot possess impulse just as it cannot possess force.
3. Yes, but, like velocity, in a relative sense—that is, with respect to a frame of reference, usually Earth's surface. The momentum possessed by a moving object with respect to a stationary point on Earth may be quite different from the momentum it possesses with respect to another moving object.
4. The long cannon will impart a greater impulse because the force acts over a longer time. (A greater impulse produces a greater change in momentum, so a long cannon will impart more speed to a cannonball than a short cannon.)

Timing is important especially when you're changing your momentum.

Impulse Changes Momentum

The greater the impulse exerted on something, the greater will be the change in momentum. The exact relationship is

$$\text{Impulse} = \text{change in momentum}$$

We can express all terms in this relationship in shorthand notation and introduce the delta symbol Δ (a letter in the Greek alphabet used to denote "change in" or "difference in"):[1]

$$Ft = \Delta(mv)$$

The symbol p is often used to represent momentum.

The impulse–momentum relationship helps us to analyze many examples in which forces act and motion changes. Sometimes the impulse can be considered to be the cause of a change of momentum. Sometimes a change of momentum can be considered to be the cause of an impulse. It doesn't matter which way you think about it. The important thing is that impulse and change of momentum are always linked. Here we will consider some ordinary examples in which impulse is related to

[1]This relationship is derived by rearranging Newton's second law to make the time factor more evident. If we equate the formula for acceleration, $a = F/m$, with what acceleration actually is, $a = \Delta v/\Delta t$, we get $F/m = \Delta v/\Delta t$. From this we derive $F\Delta t = \Delta(mv)$ Calling Δt simply t, the time interval, $Ft = \Delta(mv)$.

FIGURE 6.4

The force of impact on a golf ball varies throughout the duration of impact.

(1) increasing momentum, (2) decreasing momentum over a long time, and (3) decreasing momentum over a short time.

CASE 1: INCREASING MOMENTUM

To increase the momentum of an object, it makes sense to apply the greatest force possible for as long as possible. A golfer teeing off and a baseball player trying for a home run do both of these things when they swing as hard as possible and follow through with their swings. Following through extends the time of contact.

The forces involved in impulses usually vary from instant to instant. For example, a golf club that strikes a ball exerts zero force on the ball until it comes in contact; then the force increases rapidly as the ball is distorted (Figure 6.4). The force then diminishes as the ball comes up to speed and returns to its original shape. So, when we speak of such forces in this chapter, we mean the *average* force.

CASE 2: DECREASING MOMENTUM

If you were in a car that was out of control and you had to choose between hitting a concrete wall or a haystack, you wouldn't have to call on your knowledge of physics to make up your mind. Common sense tells you to choose the haystack. But, knowing the physics helps you to understand *why* hitting a soft object is entirely different than hitting a hard one. In the case of hitting either the wall or the haystack and coming to a stop, it takes the *same* impulse to decrease your momentum to zero. The same impulse does not mean the same amount of force or the same amount of time; rather it means the same *product* of force and time. By hitting the haystack instead of the wall, you extend the *time during which your momentum is brought to zero.* A longer time interval reduces the force and decreases the resulting deceleration. For example, if the time interval is extended 100 times, the force is reduced to a hundredth. Whenever we wish the force to be small, we extend the time of contact. Hence, the padded dashboards and airbags in motor vehicles.

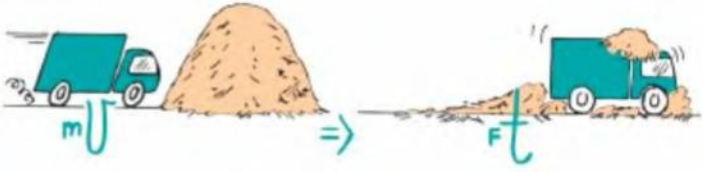


FIGURE 6.5

If the change in momentum occurs over a long time, the hitting force is small.

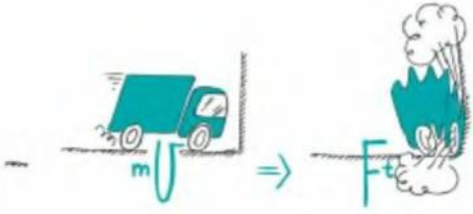


FIGURE 6.6

If the change in momentum occurs over a short time, the hitting force is large.

PhysicsPlace.com™
Video
Changing Momentum—Follow-Through

When jumping from an elevated position down to the ground, what happens if you keep your legs straight and stiff? Ouch! Instead, you bend your knees when your feet make contact with the ground. By doing so you extend the time during which your momentum decreases by 10 to 20 times that of a stiff-legged, abrupt landing. The resulting force on your bones is reduced by 10 to 20 times. A wrestler

thrown to the floor tries to extend his time of impact with the mat by relaxing his muscles and spreading the impact into a series of smaller ones as his foot, knee, hip, ribs, and shoulder successively hit the mat. Of course, falling on a mat is preferable to falling on a solid floor because the mat also increases the time during which the force acts.

The safety net used by circus acrobats is a good example of how to achieve the impulse needed for a safe landing. The safety net reduces the force experienced by a fallen acrobat by substantially increasing the time interval during which the force acts. If you're about to catch a fast baseball with your bare hand, you extend your hand forward so you'll have plenty of room to let your hand move backward after you make contact with the ball. You extend the time of impact and thereby reduce the force of impact. Similarly, a boxer rides or rolls with the punch to reduce the force of impact (Figure 6.8).

FIGURE 6.7
A large change in momentum over a long time requires a safely small average force.

CASE 3: DECREASING MOMENTUM OVER A SHORT TIME

When boxing, if you move into a punch instead of away, you're in trouble. Likewise, if you catch a high-speed baseball while your hand moves toward the ball instead of away upon contact. Or, when your car is out of control, if you drive it into a concrete wall instead of a haystack, you're really in trouble. In these cases of short impact times, the impact forces are large. Remember that, for an object brought to rest, the impulse is the same, no matter how it is stopped. But, if the time is short, the force will be large.

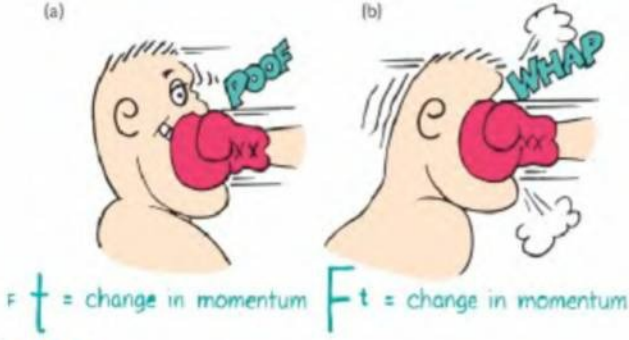


FIGURE 6.8
In both cases, the impulse provided by the boxer's jaw reduces the momentum of the punch. (a) When the boxer moves away (rides with the punch), he extends the time and diminishes the force. (b) If the boxer moves into the glove, the time is reduced and he must withstand a greater force.

PhysicsPlace.com™
Video
Decreasing Momentum Over a Short Time

The idea of short time of contact explains how a karate expert can split a stack of bricks with the blow of her bare hand (Figure 6.9). She brings her arm and hand swiftly against the bricks with considerable momentum. This momentum is quickly reduced when she delivers an impulse to the bricks. The impulse is the force of her hand against the bricks multiplied by the time during which her hand makes contact with the bricks. By swift execution, she makes the time of contact very brief and correspondingly makes the force of impact huge. If her hand is made to bounce upon impact, the force is even greater.

FIGURE 6.9
Cassy imparts a large impulse to the bricks in a short time and produces a considerable force.

Different forces exerted over different time intervals can produce the same impulse.

Ft or rt

CHECK POINT

1. If the boxer in Figure 6.8 is able to increase the duration of impact 3 times as long by riding with the punch, by how much will the force of impact be reduced?
2. If the boxer instead moves *into* the punch so as to decrease the duration of impact by half, by how much will the force of impact be increased?
3. A boxer being hit with a punch contrives to extend time for best results, whereas a karate expert delivers a force in a short time for best results. Isn't there a contradiction here?
4. When does impulse equal momentum?

Check Your Answers

1. The force of impact will be only a third of what it would have been if he hadn't pulled back.
2. The force of impact will be 2 times greater than it would have been if he had held his head still. Impacts of this kind account for many knockouts.
3. There is no contradiction because the best results for each are quite different. The best result for the boxer is reduced force, accomplished by maximizing time, and the best result for the karate expert is increased force delivered in minimum time.
4. Generally, impulse equals a *change* in momentum. If the initial momentum of an object is zero when the impulse is applied, then impulse = final momentum. And, if an object is brought to rest, impulse = initial momentum.

Bouncing

A flowerpot dropped onto your head bounces quickly. Ouch! If bouncing took a longer time, as with a safety net, then the force of the bounce would be much smaller.

If a flowerpot falls from a shelf onto your head, you may be in trouble. If it bounces from your head, you may be in more serious trouble. Why? Because impulses are greater when an object bounces. The impulse required to bring an object to a stop and then to "throw it back again" is greater than the impulse required merely to bring the object to a stop. Suppose, for example, that you catch the falling pot with your hands. You provide an impulse to reduce its momentum to zero. If you throw the pot upward again, you have to provide additional impulse. This increased amount of impulse is the same that your head supplies if the flowerpot bounces from it.

The left opening photo at the beginning of this chapter shows physics instructor Howie Brand swinging a dart against a wooden block. When the dart has a nail at its nose, the dart comes to a halt as it sticks to the block. The block remains upright.

FIGURE 6.10
Another view of a Pelton wheel. The curved blades cause water to bounce and make a U-turn, which produces a greater impulse to turn the wheel.

When the nail is removed and the nose of the dart is half of a solid rubber ball, the dart bounces upon contact with the block. The block topples over. The force against the block is greater when bouncing occurs.

The fact that impulses are greater when bouncing occurs was used with great success during the California Gold Rush, as discussed at the beginning of the chapter. Pelton designed a curved paddle that caused the incoming water to bounce upon impact, increasing the impulse on the wheel.

CHECK POINT

1. In reference to Figure 6.9, how does the force that Cassy exerts on the bricks compare with the force exerted on her hand?
2. How will the impulse resulting from the impact differ if her hand bounces back upon striking the bricks?

Check Your Answers

1. In accord with Newton's third law, the forces will be equal. Only the resilience of the human hand and the training she has undergone to toughen her hand allow this feat to be performed without broken bones.
2. The impulse will be greater if her hand bounces from the bricks upon impact. If the time of impact is not correspondingly increased, a greater force is then exerted on the bricks (and her hand!).

Conservation of Momentum

From Newton's second law, you know that to accelerate an object, a net force must be applied to it. This chapter states much the same thing, but in different language. If you wish to change the momentum of an object, exert an impulse on it.

Only an impulse external to a system can change the momentum of the system. Internal forces and impulses won't work. For example, the molecular forces within a baseball have no effect on the momentum of the baseball, just as a push against the dashboard of a car you're sitting in does not affect the momentum of the car. Molecular forces within the baseball and a push on the dashboard are internal forces. They come in balanced pairs that cancel to zero within the object. To change the momentum of the ball or the car, an external push or pull is required. If no external force is present, then no external impulse is present, and no change in momentum is possible.

Momentum is conserved for all collisions, elastic and inelastic (whenever external forces don't interfere).

As another example, consider the cannon being fired in Figure 6.11. The force on the cannonball inside the cannon barrel is equal and opposite to the force causing the cannon to recoil. Since these forces act for the same time, the impulses are also equal and opposite. Recall Newton's third law about action and reaction forces. It applies to impulses, too. These impulses are internal to the system comprising the cannon and the cannonball, so they don't change the momentum of the

fyi

- In Figure 6.11, most of the cannonball's momentum is in speed; most of the recoiling cannon's momentum is in mass. So $mV = MV$.

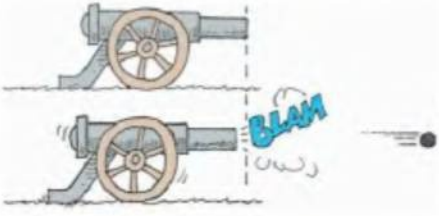


FIGURE 6.11
INTERACTIVE FIGURE

The momentum before firing is zero. After firing, the net momentum is still zero, because the momentum of the cannon is equal and opposite to the momentum of the cannonball.

cannon–cannonball system. Before the firing, the system is at rest and the momentum is zero. After the firing, the net momentum, or total momentum, is *still* zero. Net momentum is neither gained nor lost.

Momentum, like the quantities velocity and force, has both direction and magnitude. It is a *vector quantity.* Like velocity and force, momentum can be cancelled. So, although the cannonball in the preceding example gains momentum when fired and the recoiling cannon gains momentum in the opposite direction, there is no gain in the cannon–cannonball *system.* The momenta (plural form of momentum) of the cannonball and the cannon are equal in magnitude and opposite in direction.[2] Therefore, these momenta cancel to zero for the system as a whole. Since no net external force acts on the system, there is no net impulse on the system and no net change in momentum. You can see that, *if no net force or net impulse acts on a system, the momentum of that system cannot change.*

FIGURE 6.12

A cue ball hits an 8 ball head-on. Consider this event in three systems: (a) An external force acts on the 8-ball system, and its momentum increases. (b) An external force acts on the cue-ball system, and its momentum decreases. (c) No external force acts on the cue-ball + 8-ball system, and momentum is conserved (simply transferred from one part of the system to the other).

When momentum, or any quantity in physics, does not change, we say it is *conserved.* The idea that momentum is conserved when no external force acts is elevated to a central law of mechanics, called the **law of conservation of momentum,** which states:

In the absence of an external force, the momentum of a system remains unchanged.

Can you see how Newton's laws relate to momentum conservation?

In any system wherein all forces are internal—as, for example, cars colliding, atomic nuclei undergoing radioactive decay, or stars exploding—the net momentum of the system before and after the event is the same.

CHECK POINT

1. Newton's second law states that, if no net force is exerted on a system, no acceleration occurs. Does it follow that no change in momentum occurs?
2. Newton's third law states that the force a cannon exerts on a cannonball is equal and opposite to the force the cannonball exerts on the cannon. Does it follow that the *impulse* the cannon exerts on the cannonball is equal and opposite to the *impulse* the cannonball exerts on the cannon?

Check Your Answers

1. Yes, because no acceleration means that no change occurs in velocity or in momentum (mass × velocity). Another line of reasoning is simply that no net force means there is no net impulse and thus no change in momentum.
2. Yes, because the interaction between both occurs during the same *time* interval. Since time is equal and the forces are equal and opposite, the impulses, Ft, are also equal and opposite. Impulse is a vector quantity and can be cancelled.

[2]Here we neglect the momentum of ejected gases from the exploding gunpowder, which can be considerable. Firing a gun with blanks at close range is a definite no-no because of the considerable momentum of ejecting gases. More than one person has been killed by close-range firing of blanks. In 1998, a minister in Jacksonville, Florida, dramatizing his sermon before several hundred parishioners, including his family, shot himself in the head with a blank round from a .357-caliber Magnum. Although no slug emerged from the gun, exhaust gases did—enough to be lethal. So, strictly speaking, the momentum of the bullet + the momentum of the exhaust gases is equal to the opposite momentum of the recoiling gun.

Conservation Laws

A conservation law specifies that certain quantities in a system remain precisely constant, regardless of what changes may occur within the system. It is a law of constancy during change. In this chapter, we see that momentum is unchanged during collisions. We say that momentum is conserved. In the next chapter, we'll learn that energy is conserved as it transforms—the amount of energy in light, for example, transforms completely to thermal energy when the light is absorbed. We'll see, in Chapter 8, that angular momentum is conserved—whatever the rotational motion of a planetary system, its angular momentum remains unchanged so long as it is free of outside influences. In Chapter 22, we'll learn that electric charge is conserved, which means that it can neither be created nor destroyed. When we study nuclear physics, we'll see that these and other conservation laws rule in the submicroscopic world. Conservation laws are a source of deep insights into the simple regularity of nature and are often considered the most fundamental of physical laws. Can you think of things in your own life that remain constant as other things change?

Collisions

Momentum is conserved in collisions—that is, the net momentum of a system of colliding objects is unchanged before, during, and after the collision. This is because the forces that act during the collision are internal forces—forces acting and reacting within the system itself. There is only a redistribution or sharing of whatever momentum exists before the collision. In any collision, we can say

Net momentum before collision = net momentum after collision.

This is true no matter how the objects might be moving before they collide.

When a moving billiard ball makes a head-on collision with another billiard ball at rest, the moving ball comes to rest and the other ball moves with the speed of the colliding ball. We call this an **elastic collision;** ideally, the colliding objects rebound without lasting deformation or the generation of heat (Figure 6.13). But momentum is conserved even when the colliding objects become entangled during the collision. This is an **inelastic collision,** characterized by deformation, or the generation of heat, or both. In a perfectly inelastic collision, both objects stick together. Consider, for example, the case of a freight car moving along a track and colliding with another freight car at rest (Figure 6.14). If the freight cars are of equal mass and are coupled by the collision, can we predict the velocity of the coupled cars after impact?

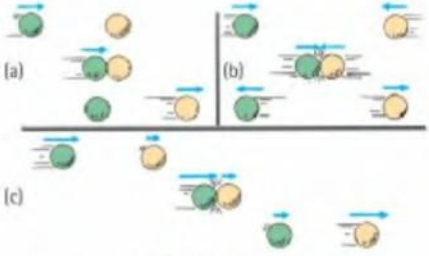


FIGURE 6.13
INTERACTIVE FIGURE

Elastic collisions of equally massive balls. (a) A green ball strikes a yellow ball at rest. (b) A head-on collision. (c) A collision of balls moving in the same direction. In each case, momentum is transferred from one ball to the other.

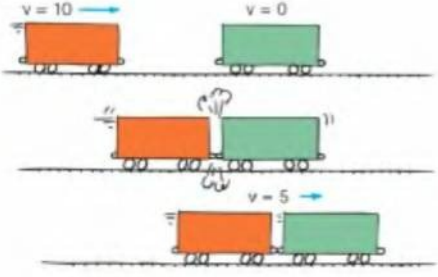


FIGURE 6.14
INTERACTIVE FIGURE

Inelastic collision. The momentum of the freight car on the left is shared with the same-mass freight car on the right after collision.

Suppose the single car is moving at 10 meters per second (m/s), and we consider the mass of each car to be m. Then, from the conservation of momentum,

$$(\text{net } mv)_{\text{before}} = (\text{net } mv)_{\text{after}}$$

$$(m \times 10)_{\text{before}} = (2m \times V)_{\text{after}}$$

By simple algebra, $V = 5$ m/s. This makes sense because, since twice as much mass is moving after the collision, the velocity must be half as much as the velocity before collision. Both sides of the equation are then equal.

Note the inelastic collisions shown in Figure 6.15. If A and B are moving with equal momenta in opposite directions (A and B colliding head-on), then one of these is considered to be negative, and the momenta add algebraically to zero. After collision, the coupled wreck remains at the point of impact, with zero momentum.

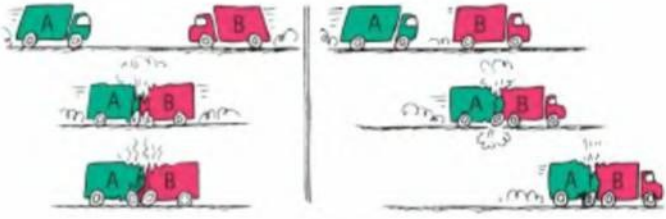


FIGURE 6.15

INTERACTIVE FIGURE

Inelastic collisions. The net momentum of the trucks before and after collision is the same.

If, on the other hand, A and B are moving in the same direction (A catching up with B), the net momentum is simply the addition of their individual momenta.

If A, however, moves east with, say, 10 more units of momentum than B moving west (not shown in the figure), after collision, the coupled wreck moves east with 10 units of momentum. The wreck will finally come to a rest, of course, because of the external force of friction by the ground. The time of impact is short, however, and the impact force of the collision is so much greater than the external friction force that momentum immediately before and after the collision is, for practical purposes, conserved. The net momentum just before the trucks collide (10 units) is equal to the combined momentum of the crumpled trucks just after impact (10 units). The same principle applies to gently docking spacecraft, where friction is entirely absent. Their net momentum just before docking is preserved as their net momentum just after docking.

Galileo worked hard to produce smooth surfaces to minimize friction. How he would have loved to experiment with today's air tracks!

FIGURE 6.16

Will Maynez demonstrates his air track. Blasts of air from tiny holes provide a friction-free surface for the carts to glide upon.

CHECK POINT

Consider the air track in Figure 6.16. Suppose a gliding cart with a mass of 0.5 kg bumps into, and sticks to, a stationary cart that has a mass of 1.5 kg. If the speed of the gliding cart before impact is v_{before}, how fast will the coupled carts glide after collision?

Check Your Answer

According to momentum conservation, the momentum of the 0.5-kg cart before the collision = momentum of both carts stuck together afterwards.

$$0.5v_{before} = (0.5 + 1.5)\,v_{after}$$

$$v_{after} = \frac{0.5\,v_{before}}{(0.5 + 1.5)} = \frac{0.5\,v_{before}}{2} = \frac{v_{before}}{4}$$

This makes sense, because four times as much mass will be moving after the collision, so the coupled carts will glide more slowly. The same momentum means four times the mass glides 1/4 as fast.

For a numerical example of momentum conservation, consider a fish that swims toward and swallows a smaller fish at rest (Figure 6.17). If the larger fish has a mass of 5 kg and swims 1 m/s toward a 1-kg fish, what is the velocity of the larger fish immediately after lunch? Neglect the effects of water resistance.

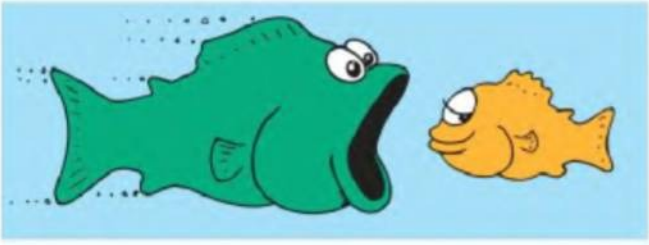


FIGURE 6.17
Two fish make up a system, which has the same momentum just before lunch and just after lunch.

$$\text{Net momentum before lunch} = \text{net momentum after lunch}$$

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

$$5\text{ kg}\cdot\text{m/s} = (6\text{ kg})\,v$$

$$v = 5/6\text{ m/s}$$

Here we see that the small fish has no momentum before lunch because its velocity is zero. After lunch, the combined mass of both fishes moves at velocity v, which, by simple algebra, is seen to be 5/6 m/s. This velocity is in the same direction as that of the larger fish.

Suppose the small fish in this example is not at rest, but swims toward the left at a velocity of 4 m/s. It swims in a direction opposite that of the larger fish—a negative direction, if the direction of the larger fish is considered positive. In this case,

$$\text{Net momentum before lunch} = \text{net momentum after lunch}$$

$$(5\text{ kg})(1\text{ m/s}) + (1\text{ kg})(-4\text{ m/s}) = (5\text{ kg} + 1\text{ kg})\,v$$

$$(5\text{ kg}\cdot\text{m/s}) - (4\text{ kg}\cdot\text{m/s}) = (6\text{ kg})\,v$$

$$1\text{ kg}\cdot\text{m/s} = 6\text{ kg}\,v$$

$$v = 1/6\text{ m/s}$$

Note that the negative momentum of the smaller fish before lunch effectively slows the larger fish after lunch. If the smaller fish were swimming twice as fast, then

$$\text{Net momentum before lunch} = \text{net momentum after lunch}$$

$$(5\text{ kg})(1\text{ m/s}) + (1\text{ kg})(-8\text{ m/s}) = (5\text{ kg} + 1\text{ kg})\,v$$

$$(5\text{ kg}\cdot\text{m/s}) - (8\text{ kg}\cdot\text{m/s}) = (6\text{ kg})\,v$$

$$-3\text{ kg}\cdot\text{m/s} = 6\text{ kg}\,v$$

$$v = -1/2\text{ m/s}$$

Here we see the final velocity is $-1/2$ m/s. What is the significance of the minus sign? It means that the final velocity is *opposite* to the initial velocity of the larger fish. After lunch, the two-fish system moves toward the left. We leave as a chapter-end problem finding the initial velocity of the smaller fish to halt the larger fish in its tracks.

More Complicated Collisions

Unlike billiard balls after a collision, nuclear particles experience no air drag or other friction and fly on in straight lines without losing speed until hitting another particle or undergoing radioactive decay.

The net momentum remains unchanged in any collision, regardless of the angle between the paths of the colliding objects. Expressing the net momentum when different directions are involved can be achieved with the parallelogram rule of vector addition. We will not treat such complicated cases in great detail here, but will show some simple examples to convey the concept.

In Figure 6.18, we see a collision between two cars traveling at right angles to each other. Car A has a momentum directed due east, and car B's momentum is directed due north. If their individual momenta are equal in magnitude, then their combined momentum is in a northeasterly direction. This is the direction the coupled cars will travel after collision. We see that, just as the diagonal of a square is not equal to the sum of two of the sides, the magnitude of the resulting momentum will not simply equal the arithmetic sum of the two momenta before collision. Recall the relationship between the diagonal of a square and the length of one of its sides, Figure 5.23 in Chapter 5—the diagonal is $\sqrt{2}$ times the length of the side of a square. So, in this example, the magnitude of the resultant momentum will be equal to $\sqrt{2}$ times the momentum of either vehicle.

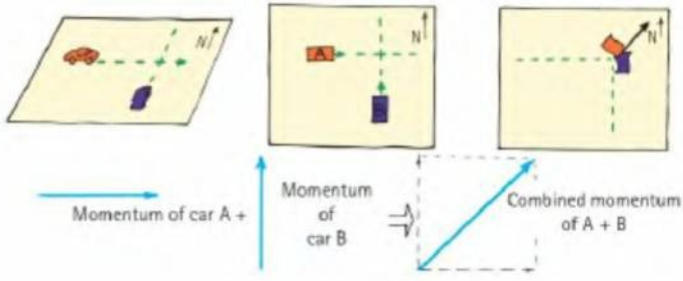


FIGURE 6.18
INTERACTIVE FIGURE
Momentum is a vector quantity.

Figure 6.20 shows a falling Fourth-of-July firecracker exploding into two pieces. The momenta of the fragments combine by vector addition to equal the original momentum of the falling firecracker. Figure 6.19b extends this idea to the microscopic realm, where the tracks of subatomic particles are revealed in a liquid hydrogen bubble chamber.

Whatever the nature of a collision or however complicated it is, the total momentum before, during, and after remains unchanged. This extremely useful law enables us to learn much from collisions without knowing any details about the forces that act in the collision. We will see, in the next chapter, that energy, perhaps in multiple forms, is also conserved. By applying momentum and energy conservation to the collisions of subatomic particles as observed in various detection chambers, we can compute the masses of these tiny particles. We obtain this information by measuring momenta and energy before and after collisions. Remarkably, this achievement is possible without any exact knowledge of the forces that act.

Conservation of momentum and conservation of energy (which we will cover in the next chapter) are the two most powerful tools of mechanics. Applying them yields detailed information that ranges from facts about the interactions of subatomic particles to the structure and motion of entire galaxies.

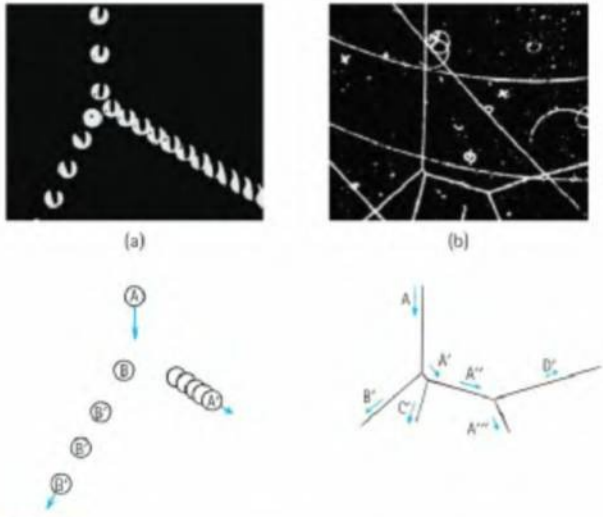


FIGURE 6.19

Momentum is conserved for colliding billiard balls and for colliding nuclear particles in a liquid hydrogen bubble chamber. In (a), billiard ball A strikes billiard ball B, which was initially at rest. In (b), proton A collides successively with protons B, C, and D. The moving protons leave tracks of tiny bubbles.

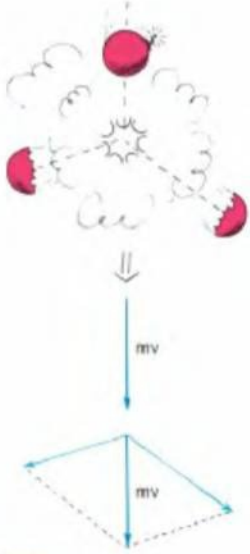


FIGURE 6.20

After the firecracker bursts, the momenta of its fragments add up (by vector addition) to the original momentum.

SUMMARY OF TERMS

Momentum The product of the mass of an object and its velocity.

Impulse The product of the force acting on an object and the time during which it acts.

Relationship of impulse and momentum Impulse is equal to the change in the momentum of the object that the impulse acts upon. In symbol notation,

$$Ft = \Delta mv$$

Law of conservation of momentum In the absence of an external force, the momentum of a system remains unchanged. Hence, the momentum before an event involving only internal forces is equal to the momentum after the event:

$$mv_{(\text{before event})} = mv_{(\text{after event})}$$

Elastic collision A collision in which colliding objects rebound without lasting deformation or the generation of heat.

Inelastic collision A collision in which the colliding objects become distorted, generate heat, and possibly stick together.

REVIEW QUESTIONS

Momentum

1. Which has a greater momentum, a heavy truck at rest or a moving skateboard?

Impulse

2. How does impulse differ from force?
3. What are the two ways to increase impulse?
4. For the same force, why does a long cannon impart more speed to a cannonball than a small cannon?

Impulse Changes Momentum

5. Is the impulse–momentum relationship related to Newton's second law?
6. To impart the greatest momentum to an object, should you exert the largest force possible, extend that force for as long a time as possible, or both? Explain.
7. When you are in the way of a moving object and an impact force is your fate, are you better off decreasing its momentum over a short time or over a long time? Explain.
8. Why is it a good idea to have your hand extended forward when you are getting ready to catch a fast-moving baseball with your bare hand?
9. Why would it be a poor idea to have the back of your hand up against the outfield wall when you catch a long fly ball?
10. In karate, why is a force that is applied for a short time more advantageous?
11. In boxing, why is it advantageous to roll with the punch?

Bouncing

12. Which undergoes the greatest change in momentum: (1) a baseball that is caught, (2) a baseball that is thrown, or (3) a baseball that is caught and then thrown back, if all of the baseballs have the same speed just before being caught and just after being thrown?
13. In the preceding question, in which case is the greatest impulse required?

Conservation of Momentum

14. Can you produce a net impulse on an automobile by sitting inside and pushing on the dashboard? Can the internal forces within a soccer ball produce an impulse on the soccer ball that will change its momentum?
15. Is it correct to say that, if no net impulse is exerted on a system, then no change in the momentum of the system will occur?
16. What does it mean to say that momentum (or any quantity) is *conserved?*
17. When a cannonball is fired, momentum is conserved for the *system* of cannon plus cannonball. Would momentum be conserved for the system if momentum were not a vector quantity? Explain.

Collisions

18. Distinguish between an *elastic collision* and an *inelastic collision*. For which type of collision is momentum conserved?
19. Railroad car A rolls at a certain speed and makes a perfectly elastic collision with car B of the same mass. After the collision, car A is observed to be at rest. How does the speed of car B compare with the initial speed of car A?
20. If the equally massive cars of the previous question stick together after colliding inelastically, how does their speed after the collision compare with the initial speed of car A?

More Complicated Collisions

21. Suppose a ball of putty moving horizontally with 1 kg·m/s of momentum collides and sticks to an identical ball of putty moving vertically with 1 kg·m/s of momentum. Why is their combined momentum not simply the arithmetic sum, 2 kg·m/s?
22. In the preceding question, what is the total momentum of the balls of putty before and after the collision?

PLUG AND CHUG

Momentum = mv

1. What is the momentum of an 8-kg bowling ball rolling at 2 m/s?
2. What is the momentum of a 50-kg carton that slides at 4 m/s across an icy surface?

Impulse = Ft

3. What impulse occurs when an average force of 10 N is exerted on a cart for 2.5 s?
4. What impulse occurs when the same force of 10 N acts on the cart for twice the time?

Impulse = change in momentum: $Ft = \Delta mv$

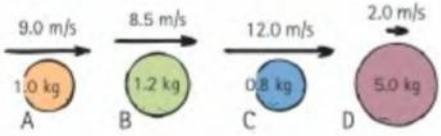
5. What is the impulse on an 8-kg ball rolling at 2 m/s when it bumps into a pillow and stops?
6. How much impulse stops a 50-kg carton sliding at 4 m/s when it meets a rough surface?

Conservation of momentum: $mv_{before} = mv_{after}$

7. A 2-kg blob of putty moving at 3 m/s slams into a 2-kg blob of putty at rest. Calculate the speed of the two stuck-together blobs of putty immediately after colliding.
8. Calculate the speed of the two blobs if the one at rest is 4 g.

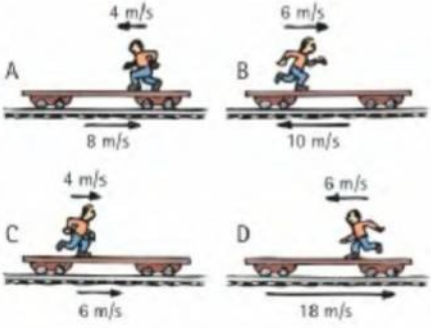
RANKING

1. The balls have different masses and speeds. Rank the following from greatest to least.



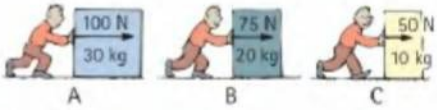
a. Momentum
b. The impulses needed to stop the balls

2. Jogging Jake runs along a train flatcar that moves at the velocities shown. In each case, Jake's velocity is given relative to the car. Call direction to the right positive. Rank the following from greatest to least.



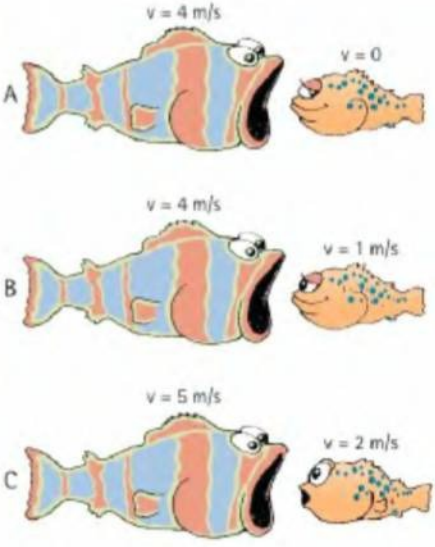
a. The magnitude of Jake's momentum relative to the flatcar
b. Jake's momentum relative to an observer at rest on the ground

3. Marshall pushes crates starting from rest across the floor of his classroom for 3 s with a net force as shown. For each crate, rank the following from greatest to least.



a. Impulse delivered
b. Change in momentum
c. Final speed
d. Momentum in 3 s

4. A hungry fish is about to have lunch at the speeds shown. Assume the hungry fish has a mass 5 times that of the small fish. Immediately after lunch, for each case, rank from greatest to least the speed of the formerly hungry fish.



PROJECT

When you get a bit ahead in your studies, cut classes some afternoon and visit your local pool or billiards parlor and bone up on momentum conservation. Note that no matter how complicated the collision of balls, the momentum along the line of action of the cue ball before impact is the same as the combined momentum of all the balls along this direction after impact and that the components of momenta perpendicular to this line of action cancel to zero after impact, the same value as before impact in this direction. You'll see both the vector nature of momentum and its conservation more clearly when rotational skidding—"English"—is not imparted to the cue ball. When English is imparted by striking the cue ball off center, rotational momentum, which is also conserved, somewhat complicates analysis. But, regardless of how the cue ball is struck, in the absence of external forces, both linear and rotational momenta are always conserved. Both pool and billiards offer a first-rate exhibition of momentum conservation in action.

EXERCISES

1. When a supertanker is brought to a stop, its engines are typically cut off about 25 km from port. Why is it so difficult to stop or turn a supertanker?
2. In terms of impulse and momentum, why do padded dashboards make automobiles safer?
3. In terms of impulse and momentum, why do air bags in cars reduce the chances of injury in accidents?
4. Why do gymnasts use floor mats that are very thick?
5. In terms of impulse and momentum, why are nylon ropes, which stretch considerably under tension, favored by mountain climbers?
6. Why is it a serious folly for a bungee jumper to use a steel cable rather than an elastic cord?
7. When jumping from a significant height, why is it advantageous to land with your knees bent?
8. A person can survive a feet-first impact at a speed of about 12 m/s (27 mi/h) on concrete; 15 m/s (34 mi/h) on soil; and 34 m/s (76 mi/h) on water. Why the different values for different surfaces?
9. When catching a foul ball at a baseball game, why is it important to extend your bare hands upward so they can move downward as the ball is being caught?
10. Automobiles in past times were manufactured to be as rigid as possible, whereas modern autos are designed to crumple upon impact. Why?
11. In terms of impulse and momentum, why is it important that helicopter blades deflect air downward?
12. It is generally much more difficult to stop a heavy truck than a skateboard when they move at the same speed. State a case in which the moving skateboard could require more stopping force. (Consider relative times.)
13. A lunar vehicle is tested on Earth at a speed of 10 km/h. When it travels as fast on the Moon, is its momentum more, less, or the same?
14. If you throw a raw egg against a wall, you'll break it. But when Peter Hopkinson throws an egg at the same speed into a sagging sheet, it doesn't break. Explain, using concepts from this chapter.

15. Why is it difficult for a firefighter to hold a hose that ejects large amounts of water at a high speed?
16. Would you care to fire a gun that has a bullet 10 times as massive as the gun? Explain.
17. Why are the impulses that colliding objects exert on each other equal and opposite?
18. If a ball is projected upward from the ground with 10 kg·m/s of momentum, what is Earth's momentum of recoil? Why do we not feel this?
19. When an apple falls from a tree and strikes the ground without bouncing, what becomes of its momentum?
20. Why does a baseball catcher's mitt have more padding than a conventional glove?
21. Why do 8-ounce boxing gloves hit harder than 16-ounce gloves?
22. A boxer can punch a heavy bag for more than an hour without tiring but will tire quickly when boxing with an opponent for a few minutes. Why? (*Hint:* When the boxer's fist is aimed at the bag, what supplies the impulse to stop the punches? When the boxer's fist is aimed at the opponent, what or who supplies the impulse to stop the punches that don't connect?)
23. Railroad cars are loosely coupled so that there is a noticeable time delay from the time the first car is moved until the last cars are moved from rest by the locomotive. Discuss the advisability of this loose coupling and slack between cars from the point of view of impulse and momentum.

24. If only an external force can change the velocity of a body, how can the internal force of the brakes bring a moving car to rest?
25. You are at the front of a floating canoe near a dock. You jump, expecting to land on the dock easily. Instead you land in the water. Explain.
26. Explain how a swarm of flying insects can have a net momentum of zero.
27. A fully dressed person is at rest in the middle of a pond on perfectly frictionless ice and must get to shore. How can this be accomplished?
28. If you throw a ball horizontally while standing on roller skates, you roll backward with a momentum that matches that of the ball. Will you roll backward if you go through the motions of throwing the ball, but instead hold on to it? Explain.
29. The examples of the two previous exercises can be explained in terms of momentum conservation and in terms of Newton's third law. Assuming you've answered them in terms of momentum conservation, answer them also in terms of Newton's third law (or vice versa, if you answered already in terms of Newton's third law).
30. In Chapter 5, rocket propulsion was explained in terms of Newton's third law. That is, the force that propels a rocket is from the exhaust gases pushing against the rocket, the reaction to the force the rocket exerts on the exhaust gases. Explain rocket propulsion in terms of momentum conservation.
31. Explain how the conservation of momentum is a consequence of Newton's third law.
32. Go back to Exercise 23 in Chapter 5 and answer it in terms of momentum conservation.

33. If you place a box on an inclined plane, it gains momentum as it slides down. What is responsible for this change in momentum?

34. Your friend says that the law of momentum conservation is violated when a ball rolls down a hill and gains momentum. What do you say?

35. What is meant by a system, and how is it related to the conservation of momentum?

36. If you toss a ball upward, is the momentum of the moving ball conserved? Is the momentum of the system consisting of ball + Earth conserved? Explain your answers.

37. The momentum of an apple falling to the ground is not conserved because the external force of gravity acts on it. But momentum is conserved in a larger system. Explain.

38. Drop a stone from the top of a high cliff. Identify the system wherein the net momentum is zero as the stone falls.

39. A car hurtles off a cliff and crashes on the canyon floor below. Identify the system wherein the net momentum is zero during the crash.

40. Bronco dives from a hovering helicopter and finds his momentum increasing. Does this violate the conservation of momentum? Explain.

41. Which exerts the greater impulse on a steel plate—machine gun bullets that bounce from the plate, or the same bullets squashing and sticking to the plate?

42. An ice sailcraft is stalled on a frozen lake on a windless day. The skipper sets up a fan as shown. If all the wind bounces backward from the sail, will the craft be set in motion? If so, in what direction?

43. Will your answer to the preceding exercise be different if the air is brought to a halt by the sail without bouncing?

44. Discuss the advisability of simply removing the sail in the preceding exercises.

45. As you toss a ball upward, is there a change in the normal force on your feet? Is there a change when you catch the ball? (Think of doing this while standing on a bathroom scale.)

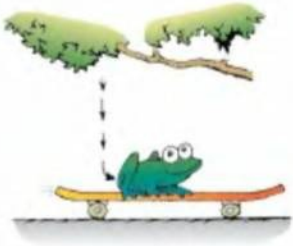
46. When you are traveling in your car at highway speed, the momentum of a bug is suddenly changed as it splatters onto your windshield. Compared with the change in momentum of the bug, by how much does the momentum of your car change?

47. If a tennis ball and a bowling ball collide in midair, does each undergo the same amount of momentum change? Defend your answer.

48. If a Mack truck and a MiniCooper have a head-on collision, which vehicle will experience the greater force of impact? The greater impulse? The greater change in momentum? The greater deceleration?

49. Would a head-on collision between two cars be more damaging to the occupants if the cars stuck together or if the cars rebounded upon impact?

50. Freddy Frog drops vertically from a tree onto a horizontally moving skateboard. The skateboard slows. Give two reasons for this, one in terms of a horizontal friction force between Freddy's feet and the skateboard, and one in terms of momentum conservation.

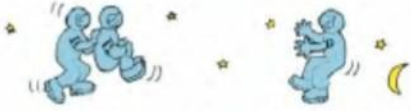


51. A 0.5-kg cart on an air track moves 1.0 m/s to the right, heading toward a 0.8-kg cart moving to the left at 1.2 m/s. What is the direction of the two-cart system's momentum?

52. In a movie, the hero jumps straight down from a bridge onto a small boat that continues to move with no change in velocity. What physics is being violated here?

53. To throw a ball, do you exert an impulse on it? Do you exert an impulse to catch it at the same speed? About how much impulse do you exert, in comparison, if you catch it and immediately throw it back again? (Imagine yourself on a skateboard.)

54. Suppose that there are three astronauts outside a spaceship and that they decide to play catch. All the astronauts weigh the same on Earth and are equally strong. The first astronaut throws the second one toward the third one and the game begins. Describe the motion of the astronauts as the game proceeds. How long will the game last?



55. In reference to Figure 6.9, how will the impulse at impact differ if Cassy's hand bounces back upon striking the bricks? In any case, how does the force exerted on the bricks compare to the force exerted on her hand?

56. Light possesses momentum. This can be demonstrated with a radiometer, shown in the sketch. Metal vanes painted black on one side and white on the other are free to rotate around the point of a needle mounted in a vacuum. When light is incident on the black surface, it is absorbed; when light is incident upon the white surface, it is reflected. Upon which surface is the impulse of incident light greater, and which way will the vanes rotate? (They rotate in the opposite direction in the more common radiometers in which air is present in the glass chamber; your instructor may tell you why.)

57. A deuteron is a nuclear particle of unique mass made up of one proton and one neutron. Suppose that a deuteron is accelerated up to a certain very high speed in a

cyclotron and directed into an observation chamber, where it collides with and sticks to a target particle that is initially at rest and then is observed to move at exactly half the speed of the incident deuteron. Why do the observers state that the target particle is itself a deuteron?

58. A billiard ball will stop short when it collides head-on with a ball at rest. The ball cannot stop short, however, if the collision is not exactly head-on—that is, if the second ball moves at an angle to the path of the first. Do you know why? (*Hint:* Consider momentum before and after the collision along the initial direction of the first ball and also in a direction perpendicular to this initial direction.)

59. When a stationary uranium nucleus undergoes fission, it breaks into two unequal chunks that fly apart. What can you conclude about the momenta of the chunks? What can you conclude about the relative speeds of the chunks?

60. You have a friend who says that after a golf ball collides with a bowling ball at rest, although the speed gained by the bowling ball is very small, its momentum exceeds the initial momentum of the golf ball. Your friend further asserts this is related to the "negative" momentum of the golf ball after collision. Another friend says this is hogwash—that momentum conservation would be violated. Which friend do you agree with?

PROBLEMS

1. When bowling, your physics buddy asks how much impulse is needed to stop a 10-kg bowling ball moving at 6 m/s. What is your answer?

2. Joanne drives her car with a mass of 1000 kg at a speed of 20 m/s. Show that to bring her car to a halt in 10 s road friction must exert a force of 2000 N on the car.

3. A car carrying a 75-kg test dummy crashes into a wall at 25 m/s and is brought to rest in 0.1 s. Show that the average force exerted by the seat belt on the dummy is 18,750 N.

4. Judy (mass 40 kg), standing on slippery ice, catches her leaping dog (mass 15 kg) moving horizontally at 3.0 m/s. Show that the speed of Judy and her dog after the catch is 0.8 m/s.

5. A 2-kg ball of putty moving to the right has a head-on inelastic collision with a 1-kg putty ball moving to the left. If the combined blob doesn't move just after the collision, what can you conclude about the relative speeds of the balls before they collided?

6. A railroad diesel engine weighs four times as much as a freight car. If the diesel engine coasts at 5 km/h into a freight car that is initially at rest, show that the speed of the coupled cars is 4 km/h.

7. A 5-kg fish swimming 1 m/s swallows an absentminded 1-kg fish swimming toward it at a speed that brings both fish to a halt immediately after lunch. Show that the speed of the approaching smaller fish before lunch must have been 5 m/s.

8. Comic-strip hero Superman meets an asteroid in outer space and hurls it at 800 m/s, as fast as a bullet. The asteroid is a thousand times more massive than Superman. In the strip, Superman is seen at rest after the throw. Taking physics into account, what would be his recoil velocity?

9. Two automobiles, each of mass 1000 kg, are moving at the same speed, 20 m/s, when they collide and stick together. In what direction and at what speed does the wreckage move (a) if one car was driving north and one south; (b) if one car was driving north and one east (as shown in Figure 6.18)?

•10. An ostrich egg of mass m is tossed at a speed v into a sagging bed sheet and is brought to rest in a time t.

a. Show that the force acting on the egg when it hits the sheet is mv/t.

b. If the mass of the egg is 1 kg, its initial speed is 2 m/s, and the time to stop is 0.2 s, show that the average force on the egg is 10 N.

CHAPTER 6 ONLINE RESOURCES

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Interactive Figures

- 6.11, 6.13, 6.14, 6.15, 6.18

Tutorial

- Newton's Third Law and Momentum

Videos

- Definition of Momentum
- Changing Momentum: Follow-through
- Decreasing Momentum Over a Short Time

Quizzes

Flashcards

Links

7 Energy

1 Electrical energy is created by wind turbines; we call them windmills when they are used to mill grain or pump water. 2 Roy Unruh converts light energy to electrical energy with small photovoltaic cells mounted on model solar-powered vehicles. 3 On a grander scale, this photovoltaic farm at Nellis Air Force Base in Nevada leads America's way in harvesting clean solar energy.

One of France's greatest scientists was Emilie du Chatelet, who lived during the 1700s when all of Europe was celebrating the achievements of Isaac Newton. She was accomplished not only in science but also in philosophy and even Biblical studies. She was the first to translate Newton's *Principia* into French, and she annotated her translation with new results in mechanics.

Of du Chatelet's several lovers, Voltaire was the most intense. For 15 years they lived together, collecting a library of more than 20,000 volumes, each encouraging and critiquing the work of the other. Theirs was one of the most exciting and passionate European love stories.

At the time there was a great debate in physics about the nature of the "oomph" possessed by moving objects. Scientists in England claimed oomph (what we would now call kinetic energy) was mass × velocity, whereas scientists such as Leibniz in Germany claimed it was mass × velocity squared. The debate was finally settled by observations and a paper published by du Chatelet that cited another scientist's simple experiment to distinguish between the two hypotheses. When a small solid brass sphere is dropped into clay, it makes a dent. If the ball hits with twice the speed, and if its oomph is mass × velocity, the dent in the clay should be twice as deep. But experiment showed it was 4 times as deep (2 squared). Dropping the ball higher so it hit with 3 times the speed produced a dent that was not 3 times as deep, but 9 times as deep (3 squared). Since Emilie du Chatelet was so highly respected by the scientific community, she ended the controversy by supporting the argument that the oomph of moving things is proportional to mass × velocity squared.

Emilie became pregnant at the age of 42, which was dangerous at the time. Doctors then had no awareness that they should wash their hands or instruments. There were no antibiotics to control infections, which were common. She died a week after the birth. Voltaire was beside himself: "I have lost the half of myself—a soul for which mine was made." Although Voltaire's collected publications had exceeded 10,000 printed pages, after her death he published no other scientific commentaries, even into a ripe old age.

As we learned in the previous chapter, mass × velocity is what we call *momentum*. In this chapter, we see that mass × velocity squared (together with a factor of 1/2) is what we call *kinetic energy*. We will now learn about forms of energy, including kinetic energy.

We begin by considering a related concept: *work*.

Work

In the previous chapter, we saw that changes in an object's motion depend both on force and on how long the force acts. "How long" meant time. We called the quantity "force × time" *impulse*. But "how long" does not always mean time. It can mean distance also. When we consider the concept of force × *distance*, we are talking about an entirely different concept—**work.** Work is the effort exerted on something that will change its energy.

When we lift a load of gravel against Earth's gravity, work is done. The heavier the load or the higher we lift the load, the more work is done. Two things enter the picture whenever work is done: (1) application of a force and (2) the movement of something by that force. For the simplest case, where the force is constant and the motion is in a straight line in the direction of the force,[1] we define the work done on an object by an applied force as the product of the force and the distance through which the object is moved. In shorter form:

$$\text{Work} = \text{force} \times \text{distance}$$

$$W = Fd$$

The word *work*, in common usage, means physical or mental exertion. Don't confuse the physics definition of work with the everyday notion of work. Work is a transfer of energy.

If we lift two loads of gravel one story up, we do twice as much work as in lifting one load the same distance, because the *force* needed to lift twice the weight is twice as much. Similarly, if we lift a load two stories instead of one story, we do twice as much work because the *distance* is twice as great.

PhysicsPlace.com™
Tutorial
Energy

FIGURE 7.1
Compared with the work done in lifting a load of gravel one story high, twice as much work is done in lifting the same load two stories high. Twice the work is done because the distance is twice as much.

FIGURE 7.2
When twice the load of gravel is lifted to the same height, twice as much work is done because the force needed to lift it is twice as much.

We see that the definition of work involves both a force and a distance. A weightlifter who holds a barbell weighing 1000 newtons overhead does no work on the barbell. He may get really tired holding the barbell, but, if it is not moved by

[1]More generally, work is the product of only the component of force that acts in the direction of motion and the distance moved. For example, if a force acts at an angle to the motion, the component of force parallel to motion is multiplied by the distance moved. When a force acts at right angles to the direction of motion, with no force component in the direction of motion, no work is done. A common example is a satellite in a circular orbit; the force of gravity is at right angles to its circular path and no work is done on the satellite. Hence, it orbits with no change in speed.

the force he exerts, he does no work *on the barbell*. Work may be done on the muscles by stretching and contracting, which is force times distance on a biological scale, but this work is not done on the barbell. Lifting the barbell, however, is a different story. When the weightlifter raises the barbell from the floor, he does work on it.

Work generally falls into two categories. One of these is the work done against another force. When an archer stretches her bowstring, she is doing work against the elastic forces of the bow. Similarly, when the ram of a pile driver is raised, work is required to raise the ram against the force of gravity. When you do push-ups, you do work against your own weight. You do work on something when you force it to move against the influence of an opposing force—often friction.

The other category of work is work done to change the speed of an object. This kind of work is done in bringing an automobile up to speed or in slowing it down. Another example of this kind of work occurs when a club hits a stationary golf ball and gets it moving. In both categories (working against a force or changing speed), work involves a transfer of energy.

The unit of measurement for work combines a unit of force (N) with a unit of distance (m): the unit of work is the newton-meter (N·m), also called the *joule* (J), which rhymes with *cool*. One joule of work is done when a force of 1 newton is exerted over a distance of 1 meter, as in lifting an apple over your head. For larger values, we speak of kilojoules (kJ, thousands of joules), or megajoules (MJ, millions of joules). The weightlifter in Figure 7.3 does work in kilojoules. To stop a loaded truck going at 100 km/h takes megajoules of work.

FIGURE 7.3
Work is done in lifting the barbell.

FIGURE 7.4
He may expend energy when he pushes on the wall, but, if the wall doesn't move, no work is done on the wall.

CHECK POINT

1. How much work is needed to lift a bag of groceries that weighs 200 N to a height of 3 m?
2. How much work is needed to lift it twice as high?

Check Your Answers

1. $W = F \times d = 200\ \text{N} \times 3\ \text{m} = 600\ \text{J}$.
2. Lifting the bag twice as high requires twice the work ($200\ \text{N} \times 6\ \text{m} = 1200\ \text{J}$).

Power

The definition of work says nothing about how long it takes to do the work. The same amount of work is done when carrying a load of groceries up a flight of stairs, whether we walk up or run up. So why are we more tired after running upstairs in a few seconds than after walking upstairs in a few minutes? To understand this difference, we need to talk about a measure of how fast the work is done—*power*. **Power** is equal to the amount of work done per time it takes to do it:

$$\text{Power} = \frac{\text{work done}}{\text{time interval}}$$

A high-power engine does work rapidly. An automobile engine that delivers twice the power of another automobile engine does not necessarily produce twice as much work or make a car go twice as fast as the less powerful engine. Twice the power means the engine can do twice the work in the same time or do the same amount of work in half the time. A more powerful engine can get an automobile up to a given speed in less time than a less powerful engine can.

fyi

- Your heart uses slightly more than 1 W of power in pumping blood through your body.

FIGURE 7.5

The three main engines of a space shuttle can develop 33,000 MW of power when fuel is burned at the enormous rate of 3400 kg/s. This is like emptying an average-size swimming pool in 20 s.

Here's another way to look at power: A liter (L) of fuel can do a certain amount of work, but the power produced when we burn it can be any amount, depending on how *fast* it is burned. It can operate a lawnmower for a half hour or a jet engine for a half second.

The unit of power is the joule per second (J/s), also known as the watt (in honor of James Watt, the 18th-century developer of the steam engine). One watt (W) of power is expended when 1 joule of work is done in 1 second. One kilowatt (kW) equals 1000 watts. One megawatt (MW) equals 1 million watts. In the United States, we customarily rate engines in units of horsepower and electricity in kilowatts, but either may be used. In the metric system of units, automobiles are rated in kilowatts. (One horsepower is the same as three-fourths of a kilowatt, so an engine rated at 134 horsepower is a 100-kW engine.)

CHECK POINT

If a forklift is replaced with a new forklift that has twice the power, how much more dirt can it lift in the same amount of time? If it lifts the same dirt, how much faster can it operate?

Check Your Answer

The forklift that delivers twice the power will lift twice the load of dirt in the same time or the same load in half the time. Either way, the owner of the new forklift is happy.

Mechanical Energy

When work is done by an archer in drawing a bowstring, the bent bow acquires the ability to do work on the arrow. When work is done to raise the heavy ram of a pile driver, the ram acquires the ability to do work on the object it hits when it falls. When work is done to wind a spring mechanism, the spring acquires the ability to do work on various gears to run a clock, ring a bell, or sound an alarm.

In each case, something has been acquired that enables the object to do work. It may be in the form of a compression of atoms in the material of an object, a physical separation of attracting bodies, or a rearrangement of electric charges in the molecules of a substance. This "something" that enables an object to do work is **energy.**[2] Like work, energy is measured in joules. It appears in many forms that will be discussed in the following chapters. For now, we will focus on the two most common forms of **mechanical energy**—the energy due to the position of something or the movement of something. Mechanical energy can be in the form of potential energy, kinetic energy, or the sum of the two.

fyi

- The concept of energy was unknown to Isaac Newton, and its existence was still being debated in the 1850s. Although familiar, energy is difficult to define because it is both a "thing" and a process—similar to both a noun and a verb. We observe the energy in things only when it is being transferred or being transformed.

POTENTIAL ENERGY

An object may store energy by virtue of its position. The energy that is stored and held in readiness is called **potential energy** (PE) because in the stored state it has the potential for doing work. A stretched or compressed spring, for example, has the potential for doing work. When a bow is drawn, energy is stored in the bow. The bow can do work on the arrow. A stretched rubber band has potential energy because of the relative position of its parts. If the rubber band is part of a slingshot, it is capable of doing work.

The chemical energy in fuels is also potential energy. It is actually energy of position at the submicroscopic level. This energy is available when the positions of

[2]Strictly speaking, that which enables an object to do work is its *available energy*, for not all the energy in an object can be transformed to work.

electric charges within and between molecules are altered—that is, when a chemical change occurs. Any substance that can do work through chemical action possesses potential energy. Potential energy is found in fossil fuels, electric batteries, and the foods we consume.

Work is required to elevate objects against Earth's gravity. The potential energy due to elevated positions is called *gravitational potential energy*. Water in an elevated reservoir and the raised ram of a pile driver both have gravitational potential energy. Whenever work is done, energy is exchanged.

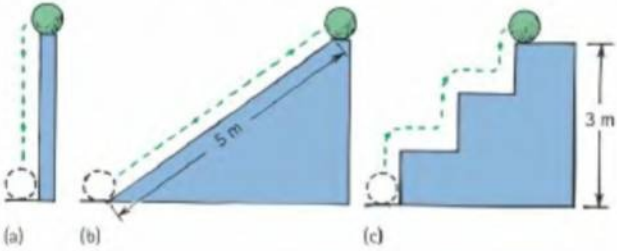

FIGURE 7.6
The potential energy of the 10-N ball is the same (30 J) in all three cases because the work done in elevating it 3 m is the same whether it is (a) lifted with 10 N of force, (b) pushed with 6 N of force up the 5-m incline, or (c) lifted with 10 N up each 1-m stair. No work is done in moving it horizontally (neglecting friction).

The amount of gravitational potential energy possessed by an elevated object is equal to the work done against gravity in lifting it. The work done equals the force required to move it upward times the vertical distance it is moved (remember $W = Fd$). The upward force required while moving at constant velocity is equal to the weight, mg, of the object, so the work done in lifting it through a height h is the product mgh.

$$\text{Gravitational potential energy} = \text{weight} \times \text{height}$$

$$\text{PE} = mgh$$

Note that the height is the distance above some chosen reference level, such as the ground or the floor of a building. The gravitational potential energy, mgh, is relative to that level and depends only on mg and h. We can see, in Figure 7.6, that the potential energy of the elevated ball does not depend on the path taken to get it there.

Potential energy, gravitational or otherwise, has significance only when it *changes*—when it does work or transforms to energy of some other form. For example, if the ball in Figure 7.6 falls from its elevated position and does 20 joules of work when it lands, then it has lost 20 joules of potential energy. The potential energy of the ball or any object is relative to some reference level. Only *changes* in potential energy are meaningful. One of the kinds of energy into which potential energy can change is energy of motion, or *kinetic energy*.

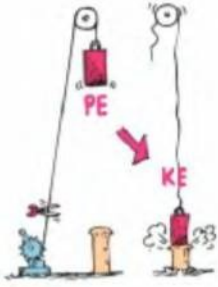

FIGURE 7.7
The potential energy of the elevated ram of the pile driver is converted to kinetic energy when it is released.

CHECK POINT

1. How much work is done in lifting the 100-N block of ice a vertical distance of 2 m, as shown in Figure 7.8?
2. How much work is done in pushing the same block of ice up the 4-m-long ramp? (The force needed is only 50 N, which is the reason ramps are used).
3. What is the increase in the block's gravitational potential energy in each case?

Check your Answers

1. $W = Fd = 100\text{ N} \times 2\text{ m} = 200\text{ J}$.
2. $W = Fd = 50\text{ N} \times 4\text{ m} = 200\text{ J}$.
3. Either way increases the block's potential energy by 200 J. The ramp simply makes this work easier to perform.

FIGURE 7.8
Both do the same work in elevating the block.

FIGURE 7.9

The potential energy of Tenny's drawn bow equals the work (average force × distance) that she did in drawing the arrow into position. When the arrow is released, most of the potential energy of the drawn bow will become the kinetic energy of the arrow.

KINETIC ENERGY

If you push on an object, you can set it in motion. If an object is moving, then it is capable of doing work. It has energy of motion. We say it has *kinetic energy* (KE). The **kinetic energy** of an object depends on the mass of the object as well as its speed. It is equal to the mass multiplied by the square of the speed, multiplied by the constant $\frac{1}{2}$.

$$\text{Kinetic energy} = \frac{1}{2}\,\text{mass} \times \text{speed}^2$$

$$\text{KE} = \frac{1}{2}mv^2$$

When you throw a ball, you do work on it to give it speed as it leaves your hand. The moving ball can then hit something and push it, doing work on what it hits. The kinetic energy of a moving object is equal to the work required to bring it from rest to that speed, or the work the object can do while being brought to rest:

$$\text{Net force} \times \text{distance} = \text{kinetic energy}$$

or, in equation notation,

$$Fd = \frac{1}{2}mv^2$$

Note that the speed is squared, so if the speed of an object is doubled, its kinetic energy is quadrupled ($2^2 = 4$). Consequently, it takes 4 times the work to double the speed. Whenever work is done, energy changes.

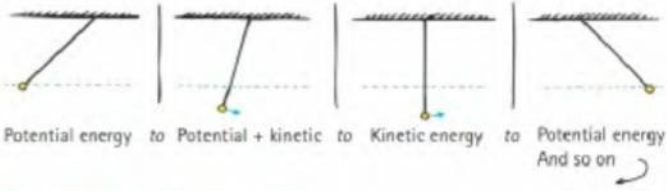

FIGURE 7.10

Energy transitions in a pendulum. PE is relative to the lowest point of the pendulum, when it is vertical.

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Video

Bowling Ball and Conservation of Energy

FIGURE 7.11

INTERACTIVE FIGURE

The pendulum bob will swing to its original height whether or not the peg is present.

FIGURE 7.12

The downhill "fall" of the roller coaster results in its roaring speed in the dip, and this kinetic energy sends it up the steep track to the next summit.

WORK-ENERGY THEOREM

When a car speeds up, its gain in kinetic energy comes from the work done on it. Or, when a moving car slows, work is done to reduce its kinetic energy. We can say[3]

$$\text{Work} = \Delta\text{KE}$$

Work equals *change* in kinetic energy. This is the **work-energy theorem.** The work in this equation is the *net* work—that is, the work based on the net force. If, for instance, you push on an object and friction also acts on the object, the change of kinetic energy is equal to the work done by the net force, which is your push minus friction. In this case, only part of the total work that you do changes the object's kinetic energy. The rest is soaked up by friction, which goes into heat. If the force of friction is equal and opposite to your push, the net force on the object is zero and no net work is done. Then there is zero change in the object's kinetic energy. The work-energy theorem applies to decreasing speed as well. When you slam on the brakes of an old car, causing it to skid, the road does work on the car. This work is the friction force multiplied by the distance over which the friction force acts.

Interestingly, the maximum friction that the road can supply to a skidding tire is nearly the same whether the car moves slowly or quickly. A car moving at twice the speed of another takes 4 times ($2^2 = 4$) as much work to stop. Since the frictional force is nearly the same for both cars, the faster one skids 4 times as far before it stops. So, as accident investigators are well aware, an automobile going 100 km/h, with 4 times the kinetic energy that it would have at 50 km/h, skids 4 times as far with its wheels locked as it would from a speed of 50 km/h. Kinetic energy depends on speed *squared*. The same reasoning applies for antilock brakes (which keep wheels from skidding). For the not-quite-skidding tire, the maximum road friction is also nearly independent of speed, so even with antilock brakes, it takes 4 times as far to stop at twice the speed.

When an automobile is braked, the drums and tires convert kinetic energy to heat. Some drivers are familiar with another way to slow a vehicle—shift to low gear and allow the engine to do the braking. Today's hybrid cars do something similar: they use an electric generator to convert the kinetic energy of the slowing car to electric energy that can be stored in batteries, where it is used to complement the energy produced by gasoline combustion. (Chapter 25 treats how they do this.) Hooray for hybrid cars!

The work-energy theorem applies to more than changes in kinetic energy. Work can change the potential energy of a mechanical device, the heat energy in a thermal system, or the electrical energy in an electrical device. Work is not a form of energy, but a way of transferring energy from one place to another or one form to another.

Kinetic energy and potential energy are two among many forms of energy, and they underlie other forms of energy, such as chemical energy, nuclear energy, and the energy carried by sound and light. Kinetic energy of random molecular motion is related to temperature; potential energies of electric charges account for voltage; and kinetic and potential energies of vibrating air define sound intensity. Even light energy originates from the motion of electrons within atoms. Every form of energy can be transformed into every other form.

Energy is nature's way of keeping score. Scams that sell energy-making machines rely on funding from deep pockets and shallow brains!

[3]This can be derived as follows: If we multiply both sides of $F = ma$ (Newton's second law) by d, we get $Fd = mad$. Recall from Chapter 3 that for constant acceleration from rest, $d = \frac{1}{2}at^2$, so we can say $Fd = ma(\frac{1}{2}at^2) = (\frac{1}{2})mat^2 = \frac{1}{2}m(at)^2$; and substituting $v = at$, we get $Fd = \frac{1}{2}mv^2$. That is, Work = KE gained.

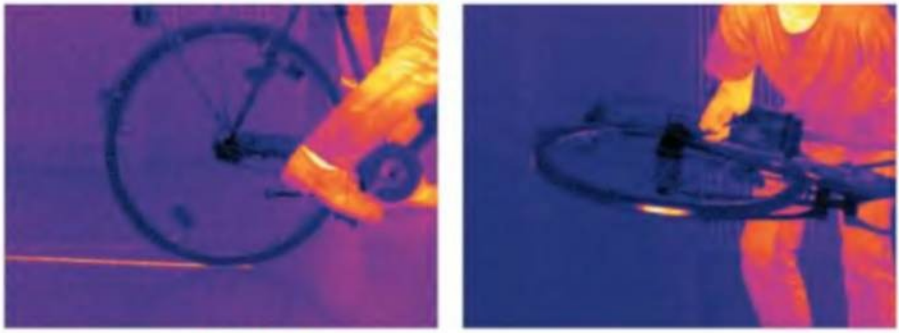

FIGURE 7.13

Due to friction, energy is transferred both into the floor and into the tire when the bicycle skids to a stop. An infrared camera reveals the heated tire track (the red streak on the floor, left) and the warmth of the tire (right). (Courtesy of Michael Vollmer.)

CHECK POINT

1. When you are driving at 90 km/h, how much more distance do you need to stop compared with driving at 30 km/h?
2. Can an object have energy?
3. Can an object have work?

Check Your Answers

1. Nine times farther. The car has 9 times as much kinetic energy when it travels 3 times as fast: $\frac{1}{2}m(3v)^2 = \frac{1}{2}mgv^2 = 9(\frac{1}{2}mv^2)$. The friction force will ordinarily be the same in either case; therefore, 9 times as much work requires 9 times as much distance.
2. Yes, but in a relative sense. For example, an elevated object may possess PE relative to the ground below, but none relative to a point at the same elevation. Similarly, the KE that an object has is relative to a frame of reference, usually Earth's surface. (We will see that material objects have *energy of being*, $E = mc^2$, the congealed energy that makes up their mass. Read on!)
3. No, unlike momentum or energy, work is not something that an object *has*. Work is something that an object *does* to some other object. An object does work when it exchanges energy.

Conservation of Energy

More important than knowing *what energy is* is understanding how it behaves—*how it transforms*. We can better understand the processes and changes that occur in nature if we analyze them in terms of energy *changes*—transformations from one form into another, or of transfers from one location to another. Energy is nature's way of keeping score.

Inventors take heed: When introducing a new idea, first be sure it is in context with what is presently known. For example, it should be consistent with the conservation of energy.

Consider the changes in energy in the operation of the pile driver back in Figure 7.7. Work done to raise the ram, giving it potential energy, becomes kinetic energy when the ram is released. This energy transfers to the piling below. The distance the piling penetrates into the ground multiplied by the average force of impact is almost equal to the initial potential energy of the ram. We say *almost* because some energy goes into heating the ground and ram during penetration. Taking heat energy into account, we find energy transforms without net loss or net gain. Quite remarkable!

The study of various forms of energy and their transformations from one form into another has led to one of the greatest generalizations in physics—the law of **conservation of energy:**

Energy cannot be created or destroyed; it may be transformed from one form into another, but the total amount of energy never changes.

When we consider any system in its entirety, whether it be as simple as a swinging pendulum or as complex as an exploding supernova, there is one quantity that isn't created or destroyed: energy. It may change form or it may simply be transferred from one place to another, but, as scientists have learned, the total energy score stays the same. This energy score takes into account the fact that the atoms that make up matter are themselves concentrated bundles of energy. When the nuclei (cores) of atoms rearrange themselves, enormous amounts of energy can be released. The Sun shines because some of this nuclear energy is transformed into radiant energy.

Enormous compression due to gravity and extremely high temperatures in the deep interior of the Sun fuse the nuclei of hydrogen atoms together to form helium nuclei. This is *thermonuclear fusion*, a process that releases radiant energy, a small part of which reaches Earth. Part of the energy reaching Earth falls on plants (and on other photosynthetic organisms), and part of this, in turn, is later stored in the form of coal. Another part supports life in the food chain that begins with plants (and other photosynthesizers), and part of this energy later is stored in oil. Part of the energy from the Sun goes into the evaporation of water from the ocean, and part of this returns to Earth in rain that may be trapped behind a dam. By virtue of its elevated position, the water behind a dam has energy that may be used to power a generating plant below, where it will be transformed to electric energy. The energy travels through wires to homes, where it is used for lighting, heating, cooking, and operating electrical gadgets. How wonderful that energy transforms from one form to another!

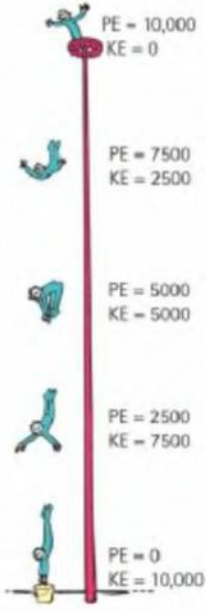

FIGURE 7.14
INTERACTIVE FIGURE

A circus diver at the top of a pole has a PE of 10,000 J. As he dives, his PE converts to KE. Note that, at successive positions one-fourth, one-half, three-fourths, and all the way down, the total energy is constant.

Energy and Technology

Try to imagine life before energy was something that humans controlled. Imagine home life without electric lights, refrigerators, heating and cooling systems, the telephone, and radio and TV—not to mention the family automobile. We may romanticize a better life without these, but only if we overlook the hours of daily toil devoted to doing laundry, cooking, and heating our homes. We'd also have to overlook how difficult it was getting a doctor in times of emergency before the advent of the telephone—when a doctor had little more in his bag than laxatives, aspirins, and sugar pills—and when infant death rates were staggering.

We have become so accustomed to the benefits of technology that we are only faintly aware of our dependence on dams, power plants, mass transportation, electrification, modern medicine, and modern agricultural science for our very existence. When we dig into a good meal, we give little thought to the technology that went into growing, harvesting, and delivering the food on our table. When we turn on a light, we give little thought to the centrally controlled power grid that links the widely separated power stations by long-distance transmission lines. These lines serve as the productive arteries of industry, transportation, and the electrification of our society. Anyone who thinks of science and technology as "inhuman" fails to grasp the ways in which they make our lives more human.

CHECK POINT

1. Does an automobile consume more fuel when its air conditioner is turned on? When its lights are on? When its radio is on while it is sitting in the parking lot?
2. Rows of wind-powered generators are used in various windy locations to generate electric power. Does the power that is generated affect the speed of the wind? That is, would locations behind the wind generators be windier if the generators weren't there?

Check Your Answers

1. The answer to all three questions is yes, for energy consumed ultimately comes from the fuel. Even the energy taken from the battery must be given back to the battery by the alternator, which is turned by the engine, which runs from the energy of the fuel. There's no free lunch!
2. Wind-powered generators take KE from the wind, so the wind is slowed by interaction with the blades. So, yes, it would be windier behind the wind generators if they weren't there.

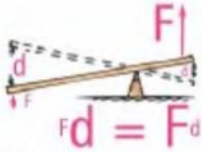

FIGURE 7.15
The lever.

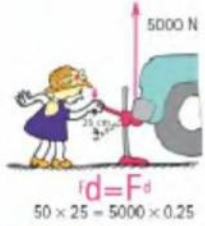

FIGURE 7.16
Applied force × applied distance = output force × output distance.

Machines

A **machine** is a device for multiplying force or simply changing the direction of force. The principle underlying every machine is the **conservation of energy** concept. Consider one of the simplest machines, the **lever** (Figure 7.15). At the same time that we do work on one end of the lever, the other end does work on the load. We see that the direction of force is changed: If we push down, the load is lifted up. If the work done by friction forces is small enough to neglect, the work input will be equal to the work output.

$$\text{Work input} = \text{work output}$$

Since work equals force times distance, input force × input distance = output force × output distance:

$$(\text{Force} \times \text{distance})_{\text{input}} = (\text{force} \times \text{distance})_{\text{output}}$$

The point of support on which a lever rotates is called a *fulcrum*. When the fulcrum of a lever is relatively close to the load, then a small input force will produce a large output force. This is because the input force is exerted through a large distance

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Video
Machines: Pulleys

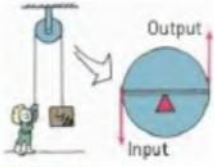

FIGURE 7.17
INTERACTIVE FIGURE
This pulley acts like a lever with equal lever arms. It changes only the direction of the input force.

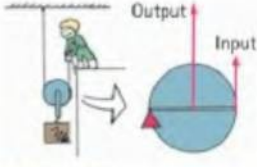

FIGURE 7.18
INTERACTIVE FIGURE
In this arrangement, a load can be lifted with half the input force. Note the "fulcrum" is at the left end rather than at the center.

and the load is moved through a correspondingly short distance. So a lever can be a force multiplier. But no machine can multiply work or multiply energy. That's a conservation-of-energy no-no!

The principle of the lever was understood by Archimedes, a famous Greek scientist in the third century BC. He said, "Give me a place to stand, and I will move the world."

Today, a child can use the principle of the lever to jack up the front end of an automobile. By exerting a small force through a large distance, she can provide a large force that acts through a small distance. Consider the ideal example illustrated in Figure 7.16. Every time she pushes the jack handle down 25 centimeters, the car rises only a hundredth as far but with 100 times the force.

Another simple machine is a pulley. Can you see that it is a lever "in disguise"? When used as in Figure 7.17, it changes only the direction of the force; but, when used as in Figure 7.18, the output force is doubled. Force is increased and distance moved is decreased. As with any machine, forces can change while work input and work output are unchanged.

A block and tackle is a system of pulleys that multiplies force more than a single pulley can do. With the ideal pulley system shown in Figure 7.19, the man pulls 7 m of rope with a force of 50 N and lifts a load of 500 N through a vertical distance of 0.7 m. The energy the man expends in pulling the rope is numerically equal to the increased potential energy of the 500-N block. Energy is transferred from the man to the load.

Any machine that multiplies force does so at the expense of distance. Likewise, any machine that multiplies distance, such as your forearm and elbow, does so at the expense of force. No machine or device can put out more energy than is put into it. No machine can create energy; it can only transfer energy or transform it from one form to another.

FIGURE 7.19
INTERACTIVE FIGURE

Applied force × applied distance = output force × output distance.

Efficiency

The three previous examples were of *ideal machines;* 100% of the work input appeared as work output. An ideal machine would operate at 100% efficiency. In practice, this doesn't happen, and we can never expect it to happen. In any transformation, some energy is dissipated to molecular kinetic energy—thermal energy. This makes the machine and its surroundings warmer.

Even a lever rocks about its fulcrum and converts a small fraction of the input energy into thermal energy. We may do 100 J of work and get out 98 J of work. The lever is then 98% efficient, and we degrade only 2 J of work input into thermal energy. If the girl back in Figure 7.16 puts in 100 J of work and increases the potential energy of the car by 60 J, the jack is 60% efficient; 40 J of her input work has been applied against friction, making its appearance as thermal energy.

In a pulley system, a considerable fraction of input energy typically goes into thermal energy. If we do 100 J of work, the forces of friction acting through the distances through which the pulleys turn and rub about their axles may dissipate 60 J of energy as thermal energy. In that case, the work output is only 40 J and the pulley system has an efficiency of 40%. The lower the efficiency of a machine, the greater the percentage of energy that is degraded to thermal energy.

Inefficiency exists whenever energy in the world around us is transformed from one form to another. **Efficiency** can be expressed by the ratio

$$\text{Efficiency} = \frac{\text{useful energy output}}{\text{total energy input}}$$

An automobile engine is a machine that transforms chemical energy stored in fuel into mechanical energy. The bonds between the molecules in the petroleum fuel break

A machine can multiply force, but never *energy*—no way!

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- A perpetual-motion machine (a device that can do work without energy input) is a no-no. But perpetual motion itself is a yes-yes. Atoms and their electrons, and stars and their planets, for example, are in a state of perpetual motion. Perpetual motion is the natural order of things.

fyi

- Comparing transportation efficiencies, the most efficient is the human on a bicycle—far more efficient than train and car travel, and even that of fish and animals. Hooray for bicycles and those who use them!

when the fuel burns. Carbon atoms in the fuel combine with oxygen in the air to form carbon dioxide, hydrogen atoms in the fuel combine with oxygen to form water, and energy is released. How nice if all this energy could be converted into useful mechanical energy—that is to say, how nice it would be if we could have an engine that is 100% efficient. This is impossible, however, because much of the energy is transformed into thermal energy, a little of which may be used to warm passengers in the winter but most of which is wasted. Some goes out in the hot exhaust gases, and some is dissipated to the air through the cooling system or directly from hot engine parts.[5]

Look at the inefficiency that accompanies transformations of energy in this way: In any transformation, there is a dilution of available *useful energy*. The amount of usable energy decreases with each transformation until there is nothing left but thermal energy at ordinary temperature. When we study thermodynamics, we'll see that thermal energy is useless for doing work unless it can be transformed to a lower temperature. Once it reaches the lowest practical temperature, that of our environment, it cannot be used. The environment around us is the graveyard of useful energy.

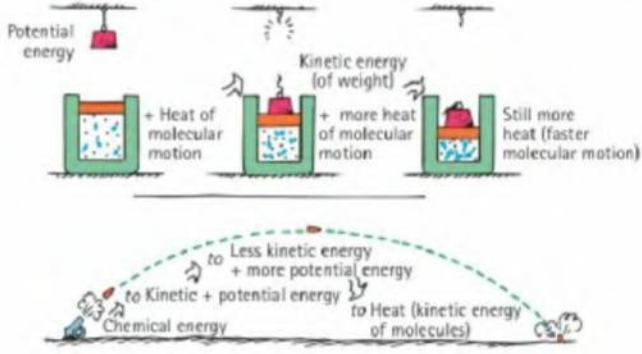

FIGURE 7.20
Energy transitions. The graveyard of mechanical energy is thermal energy.

Recycled Energy

Recycled energy is the reemployment of energy that otherwise would be wasted. A typical fossil-fuel-fired power plant discards about two-thirds of the energy present in fuel as wasted thermal energy. Only about one-third of the energy input is converted to useful electricity. What other business throws away two-thirds of its input? This was not always so. Thomas Edison's early power plants in the late 1880s, for example, converted much more input energy to useful purposes than today's electric-only power plants. Edison used the castoff heat from his generators to warm nearby homes and factories. The company he founded still delivers heat to thousands of Manhattan buildings via the largest commercial steam system in the world. New York is not alone: Most homes in the region around Copenhagen, Denmark, are warmed by heat from power plants. More than 50% of energy used in Denmark is recycled energy. In contrast, recycled energy in the United States amounts to less than 10% of all energy used. A principal reason is that power plants are now typically built far from buildings that would benefit from recycled energy. Nevertheless, we can't continue to throw heat energy to the sky in one place and then burn more fossil fuel to supply heat somewhere else. Watch for more energy recycling.

Watch for the production of biofuels made from edible corn, soybeans, and sugar cane to take a back seat to cellulose biofuels—liquid fuels made from inedible fast-growing grasses and agricultural leftovers such as cornstalks and wood waste.

[5]When you study thermodynamics in Chapter 18, you'll learn that an internal combustion engine *must* transform some of its fuel energy into thermal energy. A fuel cell that powers vehicles, on the other hand, doesn't have this limitation.

CHECK POINT

Consider an imaginary miracle car that has a 100% efficient engine and burns fuel that has an energy content of 40 MJ per liter. If the air drag and overall frictional forces on the car traveling at highway speed is 500 N, how far could the car travel per liter of fuel at this speed?

Check Your Answer

From the definition work = force × distance, simple rearrangement gives distance = work/force. If all 40 million J of energy in 1 L were used to do the work of overcoming the air drag and frictional forces, the distance would be

$$\text{Distance} = \frac{\text{work}}{\text{force}} = \frac{40{,}000{,}000\ \text{J/L}}{500\ \text{N}} = 80{,}000\ \text{m/L} = 80\ \text{km/L}$$

(This is about 190 mpg.) The important point here is that, even with a hypothetically perfect engine, there is an upper limit of fuel economy dictated by the conservation of energy.

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Video

Conservation of Energy: Numerical Example

Energy for Life

Your body is a machine—an extraordinarily wonderful machine. It is made up of smaller machines—living cells. Like any machine, a living cell needs a source of energy. In animals—including you—cells feed on various hydrocarbon compounds that release energy when they react with oxygen. Like gasoline burned in an automobile engine, there is more potential energy in the food molecules than there is in the reaction products after food metabolism. The energy difference is what sustains life.

We see inefficiency at work in the food chain. Larger creatures feed on smaller creatures, which, in turn, eat smaller creatures, and so on down the line to land plants and ocean plankton that are nourished by the Sun. Advancing each step up the food chain involves inefficiency. In the African bush, 10 kg of grass may produce 1 kg of gazelle. However, it will require 10 kg of gazelle to sustain 1 kg of lion. We see that each energy transformation along the food chain contributes to overall inefficiency. Interestingly enough, some of the largest creatures on the planet, the elephant and the blue whale, consume lower down on the food chain. Humans also are considering such tiny organisms as krill and yeast as efficient sources of nourishment.

Sources of Energy

Sunlight evaporates water, which later falls as rain; rainwater flows into rivers and into reservoirs behind dams where it is directed to generator turbines. Then it returns to the sea, where the cycle continues. The Sun is the source of practically all our energy (except that from nuclear power). Even the energy we obtain from petroleum, coal, natural gas, and wood originally came from the Sun. That's because these fuels are created by photosynthesis—the process by which plants trap solar energy and store it as plant tissue. A square mile of sunlight at midday can provide a gigawatt of electric power, the same output as a large coal or nuclear plant. Solar power is a growing green industry.

Photovoltaic solar cells transform sunlight to electricity, as is impressively shown on the cover of this book. They are more familiar in solar-powered calculators and iPods. Photovoltaic cells are already established as building materials, roofing, tiles, and soon windows. Photovoltaic cells have normally been crystal wafers produced the same way

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- Imagine you're in a completely dark room with no windows. Suppose you cut a 1-ft^2 round hole in the roof. When the Sun is high in the sky, about 100 W of solar power enters the hole. On the floor where the light hits, place a beachball covered with aluminum foil, the shiny side out. Guess what? Your room is illuminated with just as much light as a 100-W lamp produces!

FIGURE 7.21

In Bermuda, where fresh water is scarce, rooftops are designed to catch water, which is stored in containers for household use.

FIGURE 7.22

Photovoltaic solar cells on more and more rooftops (and sides of homes such as these in Holland) catch sunlight and convert it to electrical energy.

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- Watch for the downscaling of today's large-scale power grids as local solar power becomes more widespread for buildings and vehicles. Smaller local grids in dense urban areas will remain. Big power plants of all kinds may become unnecessary, with the exception of those located near virgin steel mills—for a while. Most steel mills are already powered electrically.

that semiconductors are made for computers, or as thin coatings on glass or metal backing. Newer technology is replacing panels composed of these cells. Light and flexible photovoltaic "power sheets" are now produced by machines similar to printing presses that roll out photovoltaic ink onto sheets about the thickness of aluminum foil. Power sheets can be mounted almost everywhere and don't need the sturdy surfaces that solar panels require.

The production of solar power is not confined to photovoltaics. Sunlight can be reflected by mirrors to water-filled boilers perched on towers. Concentration of sunlight by thousands of mirrors can heat water to more than four times its normal boiling point, which becomes superhot steam to drive turbines that generate electricity. Although parabolic mirrors are sometimes used at solar thermal power plants, others use inexpensive easy-to-install small flat ones, each about the size of a big-screen television. Computerized tracking keeps each mirror focused at the optimal angle throughout the day. When the Sun isn't shining, some facilities run the turbines with natural gas. Also, solar power can be combined with traditional fossil fuel power plants to increase their efficiencies. This is *solar hybridization*. Watch for more hybridization of solar power.

Even the wind, caused by unequal warming of Earth's surface, is a form of solar power. The energy of wind can be used to turn generator turbines within specially equipped windmills. Wind power is much about location—placing turbines where wind blows steady and strong, and where it overcomes the objections of residents who don't want their views compromised. That can be out at sea, away from shores. Where water isn't too deep, turbine towers can be anchored to the ocean bottom. In deeper water the towers can be mounted on floating platforms. Like solar power, wind produces power with no carbon footprint.

Interestingly, wind power can be useful when the wind isn't blowing, when it has been used to compress air in tanks or caverns underground. The compressed air can then be used to run a generator. Wind energy can also be used to produce hydrogen, which can be transported and stored for various uses.

Hydrogen is the least polluting of all fuels. Most hydrogen in America is produced from natural gas, where high temperatures and pressures separate hydrogen from hydrocarbon molecules. A downside to hydrogen separation from hydrocarbon compounds is the unavoidable production of carbon dioxide, a greenhouse gas. A simpler and cleaner method that doesn't produce greenhouse gases is *electrolysis*—

FIGURE 7.23

When electric current passes through conducting water, bubbles of hydrogen form at one wire and bubbles of oxygen form at the other. This is *electrolysis*. A fuel cell does the opposite—hydrogen and oxygen enter the fuel cell and are combined to produce electricity and water.

electrically splitting water into its constituent parts. Figure 7.23 shows how you can perform this in a lab or at home. Place two platinum wires that are connected to the terminals of an ordinary battery into a glass of water (with an electrolyte such as salt dissolved in the water for conductivity). Be sure the wires don't touch each other. Bubbles of hydrogen form on one wire, and bubbles of oxygen form on the other. A fuel cell is similar, but runs backwards. Hydrogen and oxygen gas are compressed at electrodes and electric current is produced, along with water. The space shuttle uses fuel cells to meet its electrical needs while producing drinking water for the astronauts. Here on Earth, fuel-cell researchers are developing fuel cells for buses, automobiles, and trains.

A hydrogen economy may likely start with railroad trains powered with fuel cells. Hydrogen can be obtained via solar cells, many along train tracks and on the rail ties themselves (Figure 7.24). Solar energy can extract hydrogen from water. It is important to know that hydrogen is not a *source* of energy. It takes energy to make hydrogen (to extract it from water and hydrocarbon compounds). Like electricity, it needs an energy source and is a way of storing and transporting that energy. Again, for emphasis, hydrogen is *not* an energy source.

FIGURE 7.24
The power harvested by photovoltaic cells can be used to separate hydrogen for fuel-cell transportation. Plans for trains that run on solar power collected on railroad-track ties are presently at the drawing board stage (www.SuntrainUSA.com).

The energy of ocean waves is being tapped off the coast of Portugal, where bobbing pontoons at the surface turn generators on the ocean floor. Of greater interest is the energy of ocean tides, another clean source of energy currently being tapped in various locations. Positioned across an estuary or inlet, the surging of rising and falling ocean tides turns turbines to produce electrical power, much as the flow of water from dams turns turbines in hydroelectric plants. The River Rance in France has been churning out electric power for more than 40 years, as have others in Canada and Russia. Interestingly, this form of energy is neither nuclear nor from the Sun. It comes from the rotational energy of our planet. Watch for larger-scale tidal power plants.

The most concentrated source of usable energy is that stored in nuclear fuels—uranium and plutonium. For the same weight of fuel, nuclear reactions release about 1 million times more energy than do chemical or food reactions. Watch for renewed interest in this form of power that doesn't pollute the atmosphere. Interestingly, Earth's interior is kept hot because of nuclear power, which has been with us since time zero.

A by-product of nuclear power in Earth's interior is geothermal energy. Geothermal energy is held in underground reservoirs of hot rock and hot water. Geothermal energy relatively close to the surface is predominantly limited to areas of volcanic activity, such as Iceland, New Zealand, Japan, and Hawaii. In these locations, heated water is tapped to provide steam for driving electric generators.

In other locations, another method holds promise for producing electricity. That's dry-rock geothermal power (Figure 7.25). With this method, water is pumped into hot fractured rock far below the surface. When the water turns to steam, it is piped to a turbine at the surface. After turning the turbine, it is pumped back into the ground for reuse. In this way, electricity is produced cleanly.

As the world population increases, so does our need for energy, especially since per capita demand is also growing. With the rules of physics to guide them, technologists are presently researching newer and cleaner ways to develop energy sources. But they race to keep ahead of a growing world population and greater demand in the developing world. Unfortunately, so long as controlling population is politically and religiously incorrect, human misery becomes the check to unrestrained population growth. H. G. Wells once wrote (in *The Outline of History*), "Human history becomes more and more a race between education and catastrophe."

Sooner or later, all the sunlight that falls on Earth will be radiated back into space. Energy in any ecosystem is always in transit—you can rent it, but you can't own it.

Fuel cells are electrochemical devices that combine stored hydrogen with atmospheric oxygen to generate electricity and water vapor. Vehicles operating on fuel cells produce no CO_2 emissions directly. (They do indirectly only if the source of energy to produce hydrogen is via fossil-fuel plants.)

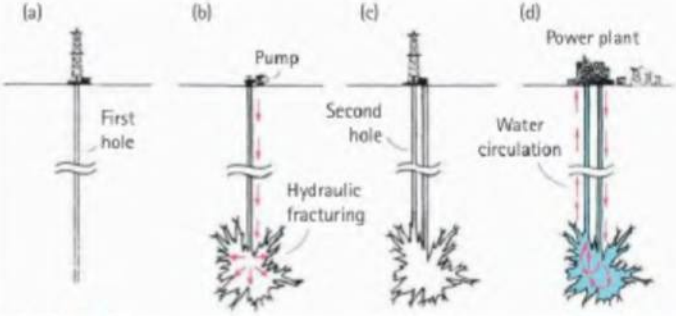


FIGURE 7.25

Dry-rock geothermal power. (a) A hole is sunk several kilometers into dry granite. (b) Water is pumped into the hole at high pressure and fractures surrounding rock to form cavities with increased surface area. (c) A second hole is sunk nearby. (d) Water is circulated down one hole and through the fractured rock, where it is superheated, before rising through the second hole. After driving a turbine, it is recirculated into the hot rock again, making a closed cycle.

Junk Science

Scientists have to be open to new ideas. That's how science grows. But there is a body of established knowledge that can't be easily overthrown. That includes energy conservation, which is woven into every branch of science and supported by countless experiments from the atomic to the cosmic scale. Yet no concept has inspired more "junk science" than energy. Wouldn't it be wonderful if we could get energy for nothing, to possess a machine that gives out more energy than is put into it? That's what many practitioners of junk science offer. Gullible investors put their money into some of these schemes. But none of the schemes passes the test of being real science. Perhaps some day a flaw in the law of energy conservation will be discovered. If it ever is, scientists will rejoice at the breakthrough. But so far, energy conservation is as solid as any knowledge we have. Don't bet against it.

SUMMARY OF TERMS

Work The product of the force and the distance moved by the force:

$$W = Fd$$

(More generally, work is the component of force in the direction of motion times the distance moved.)

Power The time rate of work:

$$\text{Power} = \frac{\text{work done}}{\text{time interval}}$$

(More generally, power is the rate at which energy is expended.)

Energy The property of a system that enables it to do work.

Mechanical energy Energy due to the position of something or the movement of something.

Potential energy The energy that something possesses because of its position.

Kinetic energy Energy of motion, quantified by the relationship

$$\text{Kinetic energy} = \frac{1}{2}mv^2$$

Work-energy theorem The work done on an object equals the change in kinetic energy of the object.

$$\text{Work} = \Delta\text{KE}$$

(Work can also transfer other forms of energy to a system.)

Conservation of energy Energy cannot be created or destroyed; it may be transformed from one form into another, but the total amount of energy never changes.

Machine A device, such as a lever or pulley, that increases (or decreases) a force or simply changes the direction of a force.

Conservation of energy for machines The work output of any machine cannot exceed the work input. In an ideal machine, where no energy is transformed into thermal energy, $\text{work}_{\text{input}} = \text{work}_{\text{output}}$; $(Fd)_{\text{input}} = (Fd)_{\text{output}}$.

Lever Simple machine consisting of a rigid rod pivoted at a fixed point called the fulcrum.

Efficiency The percentage of the work put into a machine that is converted into useful work output. (More generally, useful energy output divided by total energy input.)

SUMMARY OF EQUATIONS

Work = force × distance: $W = Fd$

Power = $\frac{\text{work}}{\text{time}}$: $P = \frac{W}{t}$

Gravitational potential energy = weight × height: $PE = mgh$

Kinetic energy = $\frac{1}{2}$ mass × speed^2: $KE = \frac{1}{2}mv^2$

Work energy theorem: Work = ΔKE

REVIEW QUESTIONS

1. When is energy most evident?

Work

2. A force sets an object in motion. When the force is multiplied by the time of its application, we call the quantity *impulse*, which changes the *momentum* of that object. What do we call the quantity force × distance?

3. Cite an example in which a force is exerted on an object without doing work on the object.

4. Which requires more work—lifting a 50-kg sack a vertical distance of 2 m or lifting a 25-kg sack a vertical distance of 4 m?

Power

5. If both sacks in the preceding question are lifted their respective distances in the same time, how does the power required for each compare? How about for the case in which the lighter sack is moved its distance in half the time?

Mechanical Energy

6. Exactly what is it that enables an object to do work?

Potential Energy

7. A car is raised a certain distance in a service-station lift and therefore has potential energy relative to the floor. If it were raised twice as high, how much potential energy would it have relative to the floor?

8. Two cars are raised to the same elevation on service-station lifts. If one car is twice as massive as the other, how do their gains of potential energies compare?

9. When is the potential energy of something significant?

Kinetic Energy

10. A moving car has kinetic energy. If it speeds up until it is going 4 times as fast, how much kinetic energy does it have in comparison?

Work-Energy Theorem

11. Compared with some original speed, how much work must the brakes of a car supply to stop a car that is moving 4 times as fast? How will the stopping distance compare?

12. If you push a crate horizontally with 100 N across a 10-m factory floor and friction between the crate and the floor is a steady 70 N, how much kinetic energy is gained by the crate?

13. How does speed affect the friction between a road and a skidding tire?

Conservation of Energy

14. What will be the kinetic energy of a pile driver ram when it undergoes a 10-kJ decrease in potential energy?

15. An apple hanging from a limb has potential energy because of its height. If it falls, what becomes of this energy just before it hits the ground? When it hits the ground?

16. What is the source of energy in sunshine?

Machines

17. Can a machine multiply input force? Input distance? Input energy? (If your three answers are the same, seek help, for the last question is especially important.)

18. If a machine multiplies force by a factor of 4, what other quantity is diminished, and by how much?

19. A force of 50 N is applied to the end of a lever, which is moved a certain distance. If the other end of the lever moves one-third as far, how much force can it exert?

Efficiency

20. What is the efficiency of a machine that miraculously converts all the input energy to useful output energy?

21. If an input of 100 J in a pulley system increases the potential energy of a load by 60 J, what is the efficiency of the system?

Recycled Energy

22. What is recycled energy?

Energy for Life

23. In what sense are our bodies machines?

Sources of Energy

24. What is the ultimate source of energy for fossil fuels, dams, and windmills?

25. What is the ultimate source of geothermal energy?

26. Can we correctly say that hydrogen is a new source of energy? Why or why not?

PLUG AND CHUG

Work = force × distance: $W = Fd$

1. Calculate the work done when a force of 1 N moves a book 2 m.
2. Calculate the work done when a 20-N force pushes a cart 3.5 m.
3. Calculate the work done in lifting a 500-N barbell 2.2 m above the floor. (What is the gain of potential energy of the barbell when it is lifted to this height?)

Power = work/time: $P = W/t$

4. Calculate the watts of power expended when a force of 2 N moves a book 2 m in a time interval of 1 s.
5. Calculate the power expended when a 20-N force pushes a cart 3.5 m in a time of 0.5 s.
6. Calculate the power expended when a 500-N barbell is lifted 2.2 m in 2 s.

Gravitational potential energy = weight × height: $PE = mgh$

7. How many joules of potential energy does a 1-kg book gain when it is elevated 4 m? When it is elevated 8 m?
8. Calculate the increase in potential energy when a 20-kg block of ice is lifted a vertical distance of 2 m.
9. Calculate the change in potential energy of 8 million kg of water dropping 50 m over Niagara Falls.

Kinetic energy = $\frac{1}{2}$ mass × speed^2: $KE = \frac{1}{2}mv^2$

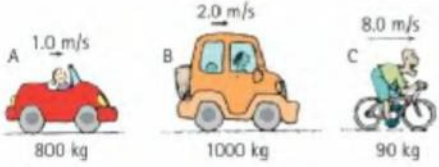
10. Calculate the number of joules of kinetic energy a 1-kg book has when tossed at a speed of 2 m/s.
11. Calculate the kinetic energy of a 3-kg toy cart that moves at 4 m/s.
12. Calculate the kinetic energy of the same cart moving at twice the speed.

Work-energy theorem: Work = ΔKE

13. How much work is required to increase the kinetic energy of a car by 5000 J?
14. What change in kinetic energy does an airplane experience on takeoff if it is moved a distance of 500 m by a sustained net force of 5000 N?

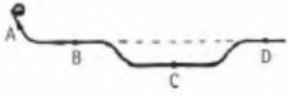
RANKING

1. The mass and speed of the three vehicles, A, B, and C, are shown. Rank them from greatest to least for



a. momentum.
b. kinetic energy.
c. work done to bring them up to their respective speeds from rest.

2. A ball is released from rest at the left of the metal track shown here. Assume it has only enough friction to roll, but not to lessen its speed. Rank these quantities from greatest to least at each point:

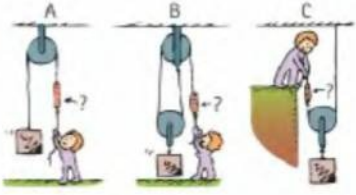


a. Momentum
b. KE
c. PE

3. The roller coaster ride starts from rest at point A. Rank these quantities from greatest to least at each point:

a. Speed
b. KE
c. PE

4. Rank the scale readings from most to least. (Ignore friction.)



EXERCISES

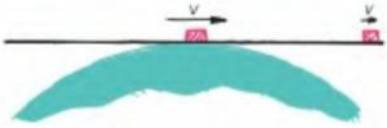
1. Why is it easier to stop a lightly loaded truck than a heavier one that has equal speed?
2. Why do you do no work on a 25-kg backpack when you walk a horizontal distance of 100 mm?
3. If your friend pushes a lawnmower 4 times as far as you do while exerting only half the force, which one of you does more work? How much more?
4. Why does one get tired when pushing against a stationary wall when no work is done on the wall?
5. Which requires more work: stretching a strong spring a certain distance or stretching a weak spring the same distance? Defend your answer.
6. Two people who weigh the same climb a flight of stairs. The first person climbs the stairs in 30 s, and the second person climbs them in 40 s. Which person does more work? Which uses more power?
7. The Sun puts out twice as much solar energy in 2 hours as it does in 1 hour. But the solar *power* of the Sun is the same from one hour to the next. Distinguish between the terms *solar energy* and *solar power*.
8. In determining the potential energy of Tenny's drawn bow (Figure 7.9), would it be an underestimate or an overestimate to multiply the force with which she holds the arrow in its drawn position by the distance she pulled it? Why do we say the work done is the *average* force × distance?
9. When a rifle with a longer barrel is fired, the force of expanding gases acts on the bullet for a longer distance. What effect does this have on the velocity of the emerging bullet? (Do you see why long-range cannons have such long barrels?)
10. Your friend says that the kinetic energy of an object depends on the reference frame of the observer. Explain why you agree or disagree.
11. You and a flight attendant toss a ball back and forth in an airplane in flight. Does the KE of the ball depend on the speed of the airplane? Carefully explain.
12. You watch your friend take off in a jet plane, and you comment on the kinetic energy she has acquired. But she says she experiences no such increase in kinetic energy. Who is correct?
13. When a jumbo jet slows and descends on approach to landing, there is a decrease in both its kinetic and potential energy. Where does this energy go?
14. Explain how "elastic potential energy" dramatically changed the sport of pole vaulting when flexible fiberglass poles replaced stiffer wooden poles.
15. At what point in its motion is the KE of a pendulum bob at a maximum? At what point is its PE at a maximum? When its KE is at half its maximum value, how much PE does it have relative to its PE at the center of the swing?
16. A physics instructor demonstrates energy conservation by releasing a heavy pendulum bob, as shown in the sketch, allowing it to swing to and fro. What would happen if, in his exuberance, he gave the bob a slight shove as it left his nose? Explain.

17. Does the International Space Station have gravitational PE? KE? Explain.
18. What does the work-energy theorem say about the speed of a satellite in circular orbit?
19. A moving hammer hits a nail and drives it into a wall. If the hammer hits the nail with twice the speed, how much deeper will the nail be driven? If it hits with 3 times the speed?
20. Why does the force of gravity do no work on (a) a bowling ball rolling along a bowling alley and (b) a satellite in circular orbit about Earth?
21. Why does the force of gravity do work on a car that rolls down a hill but no work when it rolls along a level part of the road?
22. Does the string that supports a pendulum bob do work on the bob as its swings to and fro? Does the force of gravity do any work on the bob?
23. A crate is pulled across a horizontal floor by a rope. At the same time, the crate pulls back on the rope, in accord with Newton's third law. Does the work done on the crate by the rope then equal zero? Explain.
24. On a playground slide, a child has potential energy that decreases by 1000 J while her kinetic energy increases by 900 J. What other form of energy is involved, and how much?
25. Someone wanting to sell you a Superball claims that it will bounce to a height greater than the height from which it is dropped. Can this be?
26. Why can't a Superball released from rest reach its original height when it bounces from a rigid floor?
27. Consider a ball thrown straight up in the air. At what position is its kinetic energy at a maximum? Where is its gravitational potential energy at a maximum?
28. Discuss the design of the roller coaster shown in the sketch in terms of the conservation of energy.

29. Suppose that you and two classmates are discussing the design of a roller coaster. One classmate says that each summit must be lower than the previous one. Your other classmate says this is nonsense, for as long as the first one is the highest, it doesn't matter what height the others are. What do you say?
30. Consider the identical balls released from rest on Tracks A and B, as shown. When they reach the right ends of the tracks, which will have the greater speed? Why is this question easier to answer than the similar one (Exercise 40) in Chapter 3?

31. Does a car burn more gasoline when its lights are turned on? Does the overall consumption of gasoline depend on whether or not the engine is running while the lights are on? Defend your answer.

32. Suppose an object is set sliding, with a speed less than escape velocity, on an infinite frictionless plane in contact with the surface of Earth, as shown. Describe its motion. (Will it slide forever at a constant velocity? Will it slide to a stop? In what way will its energy changes be similar to that of a pendulum?)



33. If a golf ball and a Ping-Pong ball both move with the same kinetic energy, can you say which has the greater speed? Explain in terms of the definition of KE. Similarly, in a gaseous mixture of heavy molecules and light molecules with the same average KE, can you say which have the greater speed?
34. Running a car's air conditioner usually increases fuel consumption. But, at certain speeds, a car with its windows open and with the air conditioner turned off can consume more fuel. Explain.
35. Why bother using a machine if it cannot multiply work input to achieve greater work output?
36. When the girl in Figure 7.16 jacks up a car, how can applying so little force produce sufficient force to raise the car?
37. What famous equation describes the relationship between mass and energy?
38. You tell your friend that no machine can possibly put out more energy than is put into it, and your friend states that a nuclear reactor puts out more energy than is put into it. What do you say?
39. This may seem like an easy question for a physics type to answer: With what force does a rock that weighs 10 N strike the ground if dropped from a rest position 10 m high? In fact, the question cannot be answered unless you know more. Why?
40. Your friend is confused about ideas discussed in Chapter 4 that seem to contradict ideas discussed in this chapter. For example, in Chapter 4, we learned that the net force is zero for a car traveling along a level road at constant velocity, and, in this chapter, we learned that work is done in such a case. Your friend asks, "How can work be done when the net force equals zero?" Explain.
41. In the absence of air resistance, a ball thrown vertically upward with a certain initial KE will return to its original level with the same KE. When air resistance is a factor affecting the ball, will it return to its original level with the same, less, or more KE? Does your answer contradict the law of energy conservation?
42. You're on a rooftop and you throw one ball downward to the ground below and another upward. The second ball, after rising, falls and also strikes the ground below. If air resistance can be neglected, and if your downward and upward initial speeds are the same, how will the speeds of the balls compare upon striking the ground? (Use the idea of energy conservation to arrive at your answer.)
43. Going uphill, the gasoline engine in a gasoline–electric hybrid car provides 75 horsepower while the total power propelling the car is 90 horsepower. Burning gasoline provides the 75 horsepower. What provides the other 15 horsepower?
44. When a driver applies brakes to keep a car going downhill at constant speed and constant kinetic energy, the potential energy of the car decreases. Where does this energy go? Where does most of it go with a hybrid vehicle?
45. Does the KE of a car change more when it goes from 10 to 20 km/h or when it goes from 20 to 30 km/h?
46. Can something have energy without having momentum? Explain. Can something have momentum without having energy? Defend your answer.
47. When the mass of a moving object is doubled with no change in speed, by what factor is its momentum changed? By what factor is its kinetic energy changed?
48. When the velocity of an object is doubled, by what factor is its momentum changed? By what factor is its kinetic energy changed?
49. Which, if either, has greater momentum: a 1-kg ball moving at 2 m/s or a 2-kg ball moving at 1 m/s? Which has greater kinetic energy?
50. A car has the same kinetic energy when traveling north as when it turns around and travels south. Is the momentum of the car the same in both cases?
51. If an object's KE is zero, what is its momentum?
52. If your momentum is zero, is your kinetic energy necessarily zero also?
53. If two objects have equal kinetic energies, do they necessarily have the same momentum? Defend your answer.
54. Two lumps of clay with equal and opposite momenta have a head-on collision and come to rest. Is momentum conserved? Is kinetic energy conserved? Why are your answers the same or different?
55. Scissors for cutting paper have long blades and short handles, whereas metal-cutting shears have long handles and short blades. Bolt cutters have very long handles and very short blades. Why is this so?
56. Consider the swinging-balls apparatus. If two balls are lifted and released, momentum is conserved as two balls pop out the other side with the same speed as the released balls at impact. But momentum would also be conserved if one ball popped out at twice the speed. Can you explain why this never happens? (And can you explain why this exercise is in Chapter 7 rather than in Chapter 6?)

57. An inefficient machine is said to "waste energy." Does this mean that energy is actually lost? Explain.
58. If an automobile were to have a 100% efficient engine, transferring all of the fuel's energy to work, would the

engine be warm to your touch? Would its exhaust heat the surrounding air? Would it make any noise? Would it vibrate? Would any of its fuel go unused?

59. To combat wasteful habits, we often speak of "conserving energy," by which we mean turning off lights and hot water when they are not being used and keeping thermostats at a moderate level. In this chapter, we also speak of "energy conservation." Distinguish between these two usages.

60. When an electric company can't meet its customers' demand for electricity on a hot summer day, should the problem be called an "energy crisis" or a "power crisis"? Explain.

61. Your friend says that one way to improve air quality in a city is to have traffic lights synchronized so that motorists can travel long distances at constant speed. What physics principle supports this claim?

62. The energy we require to live comes from the chemically stored potential energy in food, which is transformed into other energy forms during the metabolism process. What happens to a person whose combined work and heat output is less than the energy consumed? What happens when the person's work and heat output is greater than the energy consumed? Can an undernourished person perform extra work without extra food? Defend your answers.

63. Once used, can energy be regenerated? Is your answer consistent with the common term *renewable energy*?

64. What do international peace, cooperation, and security have to do with addressing the world's energy needs?

PROBLEMS

1. The second floor of a house is 6 m above the street level. How much work is required to lift a 300-kg refrigerator to the second-story level?

2. (a) How much work is done when you push a crate horizontally with 100 N across a 10-m factory floor? (b) If the force of friction on the crate is a steady 70 N, show that the KE gained by the crate is 300 J. (c) Show that 700 J is turned into heat.

3. This question is typical on some driver's license exams: A car moving at 50 km/h skids 15 m with locked brakes. How far will the car skid with locked brakes at 150 km/h?

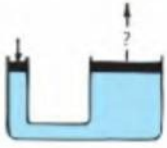
4. Belly-flop Bernie dives from atop a tall flagpole into a swimming pool below. His potential energy at the top is 10,000 J (relative to the surface of the pool). What is his kinetic energy when his potential energy reduces to 1000 J?

5. Nellie Newton applies a force of 50 N to the end of a lever, which is moved a certain distance. If the other end of the lever moves one-third as far, show that the force it exerts is 150 N.

6. Consider an ideal pulley system. If you pull one end of the rope 1 m downward with a 50-N force, show that you can lift a 200-N load one-quarter of a meter high.

7. In raising a 5000-N piano with a pulley system, the workers note that for every 2 m of rope pulled downward, the piano rises 0.2 m. Ideally, show that 500 N is required to lift the piano.

8. In the hydraulic machine shown, you observe that when the small piston is pushed down 10 cm, the large piston is raised 1 cm. If the small piston is pushed down with a force of 100 N, what is the most weight that the large piston can support?



9. How many watts of power do you expend when you exert a force of 1 N that moves a book 2 m in a time interval of 1 s?

•10. Emily holds a banana of mass m over the edge of a bridge of height h. She drops the banana and it falls to the river below. Use conservation of energy to show that the speed of the banana just before hitting the water is $v = \sqrt{2gh}$.

CHAPTER 7 ONLINE RESOURCES

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Interactive Figures

- 7.11, 7.14, 7.17, 7.18, 7.19

Tutorial

- Energy

Videos

- Bowling Ball and Conservation of Energy
- Machines: Pulleys
- Conservation of Energy: Numerical Example

Quizzes

Flashcards

Links

8 Rotational Motion

1 Burl Grey, my sign-painting buddy, stimulated my interest in science at the impressionable age of 25. 2 He introduced me to futurist Jacque Fresco, the most passionate teacher I have ever met, who inspired my love of teaching. 3 Jacque also positively influenced my lifelong friend, cartoonist Ernie Brown, who among many things, designed the *Conceptual Physics* cover logos that go back to the first edition.

Futurist thinker Jacque Fresco was the foremost influence in my transition from being a sign painter to pursuing a life in physics. I met Fresco through my sign-painting partner, Burl Grey, in Miami, Florida. With my wife Millie and with Ernie Brown, a close friend and cartoonist, I attended Fresco's dynamic series of weekly lectures in Miami Beach and sometimes at his home in Coral Gables. Charismatic Jacque has always been a futurist, believing that the best path to a better future is via science and technology and that a community with more engineers than lawyers is more likely to be a better one. His topics revolved around the importance of expanded technology to better living, locally and globally. As a teacher, Jacque was and is the very best. He certainly was an enormous influence in my own teaching. He taught me to introduce concepts new to a student by first comparing them to familiar ones—teaching by analogy. He felt that little or nothing would be learned if not tied to something similar, familiar, and already understood. He had a built-in "crap detector" that ensured emphasis on the central parts of an idea. After every lecture, I, my wife, and Ernie left with knowledge that was valued. The experience convinced me to take advantage of the GI Bill (I was a noncombat Korean War vet), get a college education, and pursue a career in science.

Jacque Fresco, with his associate, Roxanne Meadows, founded *The Venus Project* and the nonprofit organization *Future By Design* that reflect the culmination of Fresco's life work: the integration of the best of science and technology into a comprehensive plan for a new society based on human and environmental concerns—a global vision of hope for the future of humankind in our technological age. His vision is well stated in his many books and publications, on the web, and most recently in a movie, *Zeitgeist Addendum*, that features his visionary ideas. Now in his 90s, he continues to inspire young and old worldwide.

In typical lecture lessons, Jacque treated the distinctions between closely related ideas as well as their similarity. I recall one of his lessons distinguishing between

linear motion and rotational motion. Where does a child move faster on a merry-go-round—near the outside rail or near the inside rail—or do they have the same speed? Because the distinction between linear speed and rotational speed is poorly understood, Jacque said that asking this question to different people results in different answers. Just as "tail-end Charlie" at the end of a line of skaters making a turn moves faster than skaters near the center of the curve, so it is that railroad-train wheels on the outside track of a curve travel faster than wheels on the inside track. Jacque explained how slight tapering of the wheel rims make this possible. This and other similarities and distinctions are treated in this chapter.

Circular Motion

Linear speed, which we simply called *speed* in previous chapters, is the distance traveled per unit of time. A point on the outside edge of a merry-go-round or turntable travels a greater distance in one complete rotation than a point nearer the center. Traveling a greater distance in the same time means a greater speed. Linear speed is greater on the outer edge of a rotating object than it is closer to the axis. The linear speed of something moving along a circular path can be called **tangential speed** because the direction of motion is tangent to the circumference of the circle. For circular motion, we can use the terms *linear speed* and *tangential speed* interchangeably. Units of linear or tangential speed are usually m/s or km/h.

Rotational speed (sometimes called *angular speed*) involves the number of rotations or revolutions per unit of time. All parts of the rigid merry-go-round and turntable turn about the axis of rotation in the same amount of time. Thus, all parts share the same rate of rotation, or the same *number of rotations* or *revolutions per unit of time*. It is common to express rotational rates in revolutions per minute (RPM).[1] For example, most phonograph turntables, which were common in mom and dad's time, rotate at $33\frac{1}{3}$ RPM. A ladybug sitting anywhere on the surface of the turntable revolves at $33\frac{1}{3}$ RPM.

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Tutorial
Rotational Motion

fyi

- When an object turns about an internal axis, the motion is a *rotation*, or spin. A merry-go-round or a turntable rotates about a central internal axis. When an object turns about an external axis, the motion is a *revolution*. Earth makes one revolution about the Sun each year, while it rotates about its polar axis once per day.

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Rotational Speed

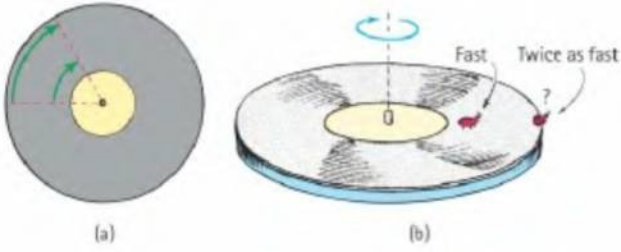

FIGURE 8.1
INTERACTIVE FIGURE
(a) When the turntable rotates, a point farther from the center travels a longer path in the same time and has a greater tangential speed. (b) A ladybug twice as far from the center moves twice as fast.

Tangential speed and rotational speed are related. Have you ever ridden on a big, round, rotating platform in an amusement park? The faster it turns, the faster your tangential speed. This makes sense; the greater the RPMs, the faster your speed in meters per second. We say that tangential speed is *directly proportional* to rotational speed at any fixed distance from the axis of rotation.

FIGURE 8.2
INTERACTIVE FIGURE
The tangential speed of each person is proportional to the rotational speed of the platform multiplied by the distance from the central axis.

[1]Physics types usually describe rotational speed, ω, in terms of the number of "radians" turned in a unit of time. There are a little more than 6 radians in a full rotation (2π radians, to be exact). When a direction is assigned to rotational speed, we call it *rotational velocity* (often called *angular velocity*). Rotational velocity is a vector whose magnitude is the rotational speed. By convention, the rotational velocity vector lies along the axis of rotation, and points in the direction of advance of a conventional right-handed screw.

When a row of people, locked arm in arm at the skating rink, makes a turn, the motion of "tail-end Charlie" is evidence of a greater tangential speed.

Tangential speed, unlike rotational speed, depends on radial distance (the distance from the axis). At the very center of the rotating platform, you have no speed at all; you merely rotate. But, as you approach the edge of the platform, you find yourself moving faster and faster. Tangential speed is directly proportional to distance from the axis for any given rotational speed.

So we see that tangential speed is proportional to both radial distance and rotational speed.[2]

$$\text{Tangential speed} \sim \text{radial distance} \times \text{rotational speed}$$

In symbol form,

$$v \sim r\omega$$

where v is tangential speed and ω (Greek letter omega) is rotational speed. You move faster if the rate of rotation increases (bigger ω). You also move faster if you move farther from the axis (bigger r). Move out twice as far from the rotational axis at the center and you move twice as fast. Move out 3 times as far and you have 3 times as much tangential speed. If you find yourself in any kind of rotating system, your tangential speed depends on how far you are from the axis of rotation.

Why will a person with one leg shorter than the other tend to walk in circles when lost?

CHECK POINT

1. Imagine a ladybug sitting halfway between the rotational axis and the outer edge of the turntable in Figure 8.1b. When the turntable has a rotational speed of 20 RPM and the bug has a tangential speed of 2 cm/s, what will be the rotational and tangential speeds of her friend who sits at the outer edge?
2. Trains ride on a pair of tracks. For straight-line motion, both tracks are the same length. Not so for tracks along a curve. Which track is longer, the one on the outside of the curve or the one on the inside?

Check Your Answers

1. Since all parts of the turntable have the same rotational speed, her friend also rotates at 20 RPM. Tangential speed is a different story. Since she is twice as far from the axis of rotation, she moves twice as fast—4 cm/s.
2. Similar to Figure 8.1, the track on the outside of the curve is longer—just as the circumference of a circle of greater radius is longer.

FIGURE 8.3
Cathy Candler asks her class which set of cups will self-correct when she rolls them along a pair of "meterstick tracks."

When tangential speed undergoes change, we speak of a *tangential acceleration*. Any change in tangential speed indicates an acceleration parallel to tangential motion. For example, a person on a rotating platform that speeds up or slows down undergoes a tangential acceleration. We'll soon see that anything moving in a curved path undergoes another kind of acceleration—one directed to the center of curvature. This is *centripetal acceleration*. In the interest of "information overload," we'll not go into the details of tangential or centripetal acceleration.

[2]If you take a follow-up physics course, you will learn that when the proper units are used for tangential speed v, rotational speed ω, and radial distance r, the direct proportion of v to both r and ω becomes the exact equation $v = r\omega$. So the tangential speed will be directly proportional to r when all parts of a system simultaneously have the same ω, as for a wheel or disk (or a flyswatter!).

Wheels on Railroad Trains

Why does a moving railroad train stay on the tracks? Most people assume that the wheel flanges keep the wheels from rolling off. But if you look at these flanges, you'll likely note they are rusty. They seldom touch the track, except when they follow slots that switch the train from one set of tracks to another. So how do the wheels of a train stay on the tracks? They stay on the track because their rims are slightly tapered.

If you roll a tapered cup across a surface, it makes a curved path (Figure 8.4). The wider part of the cup has a greater radius, rolls a greater distance per revolution, and therefore has a greater tangential speed than the narrower end. If you fasten a pair of cups together at their wide ends (simply taping them together) and roll the pair along a pair of parallel tracks (Figure 8.5), the cups will remain on the track and center themselves whenever they roll off center. This occurs because when the pair rolls to the left of center, say, the wider part of the left cup rides on the left track while the narrow part of the right cup rides on the right track. This steers the pair toward the center. If it "overshoots" toward the right, the process repeats, this time toward the left, as the wheels tend to center themselves. Likewise for a railroad train, where passengers feel the train swaying as these corrective actions occur.

This tapered shape is essential on the curves of railroad tracks. On any curve, the distance along the outer part is longer than the distance along the inner part (as we saw in Figure 8.1a). So, whenever a vehicle follows a curve, its outer wheels travel faster than its inner wheels. For an automobile, this is not a problem because the wheels are freewheeling and roll independently of each other. For a train, however, like the pair of fastened cups, pairs of wheels are firmly connected and rotate together. Opposite wheels have the same RPM at any time. But, due to the slightly tapered rim of the wheel, its tangential speed along the track depends on whether it rides on the narrow part of the rim or the wide part. On the wide part, it travels faster. So, when a train rounds a curve, wheels on the outer track ride on the wider part of the tapered rims, while opposite wheels ride on their narrow parts. In this way, the wheels have different tangential speeds for the same rotational speed. This is $v \sim r\omega$ in action! Can you see that if the wheels were not tapered, scraping would occur and the wheels would squeal when a train rounds a curve?

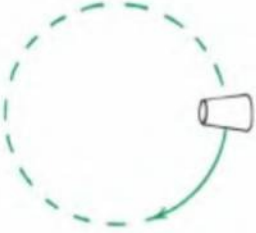

FIGURE 8.4
Because the wide part of the cup rolls faster than the narrow part, the cup rolls in a curve.

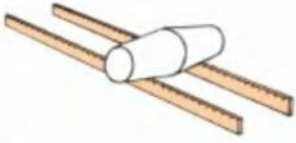

FIGURE 8.5
Two fastened cups stay on the tracks as they roll because, when they roll off center, the different tangential speeds due to the taper cause them to self-correct toward the center of the track.

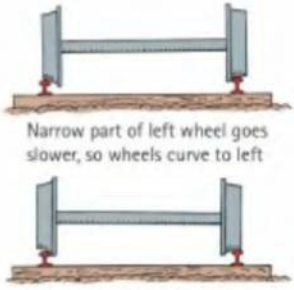

FIGURE 8.7
(Top) Along a track that curves to the left, the right wheel rides on its wide part and goes faster while the left wheel rides on its narrow part and goes slower. (Bottom) The opposite is true when the track curves to the right.

FIGURE 8.6
Wheels of a railroad train are slightly tapered (shown exaggerated here).

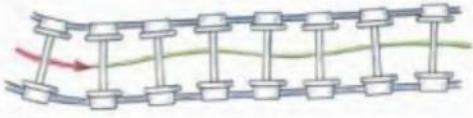

FIGURE 8.8
After rounding a curve, a train often oscillates on the straightaway as the wheels self-correct.

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- An idea put forward in past years for boosting efficiency in electric rail travel was massive rotor disks—flywheels—beneath the flooring of railroad cars. When brakes were applied, rather than slowing the cars by converting braking energy to heat via friction, the braking energy would be diverted to revving the flywheels, which then could operate generators to supply electric energy for operating the train. The massiveness of the rotors turned out to make the scheme impractical. But the idea hasn't been lost. Today's hybrid automobiles do much the same thing—not mechanically, but electrically. Braking energy is diverted to electric batteries, which are then used for operating the automobile.

Rotational Inertia

Just as an object at rest tends to stay at rest and an object in motion tends to remain moving in a straight line, *an object rotating about an axis tends to remain rotating about the same axis unless interfered with by some external influence.* (We shall see shortly that this external influence is properly called a *torque*.) The property of an object to resist changes in its rotational state of motion is called **rotational inertia.**[3] Bodies that are rotating tend to remain rotating, while nonrotating bodies tend to remain nonrotating. In the absence of outside influences, a rotating top keeps rotating, while a top at rest remains at rest.

Like inertia for linear motion, rotational inertia depends on mass. The thick stone disk that rotates beneath a potter's wheel is very massive, and, once it is spinning, it tends to remain spinning. But, unlike linear motion, rotational inertia depends on the distribution of the mass about the axis of rotation. The greater the distance between an object's mass concentration and the axis, the greater the rotational inertia. This is evident in industrial flywheels that are constructed so that most of their mass is concentrated far from the axis, along the rim. Once rotating, they have a greater tendency to remain rotating. When at rest, they are more difficult to get rotating.

Industrial flywheels provide a practical means of storing energy in electric power plants. When the plants generate continuous electricity, energy not needed when power demand is low is diverted to massive flywheels, which are the counterpart of electric batteries—but environmentally sound with no toxic metals nor hazardous waste. The whirling wheels are then connected to generators to release the power when it's needed. When combined with other flywheels, banks of ten or more of them connected to power grids offset fluctuations between supply and demand and help them run more smoothly. Cheers for rotational inertia!

The greater the rotational inertia of an object, the greater the difficulty in changing its rotational state. This fact is employed by a circus tightrope walker who carries a long pole to aid balance. Much of the mass of the pole is far from the axis of rotation, its midpoint. The pole, therefore, has considerable rotational inertia. If the tightrope walker starts to topple over, a tight grip on the pole rotates the pole. But the rotational inertia of the pole resists, giving the tightrope walker time to readjust his or her balance. The longer the pole, the better. And better still if massive objects are attached to the ends. But a tightrope walker with no pole can at least extend his or her arms full length to increase the body's rotational inertia.

The rotational inertia of the pole, or of any object, depends on the axis about which it rotates.[4] Compare the different rotations of a pencil (Figure 8.11). Consider

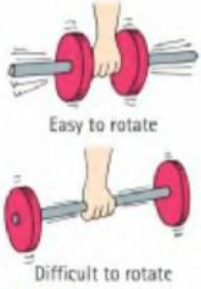

FIGURE 8.9

Rotational inertia depends on the distribution of mass relative to the axis of rotation.

FIGURE 8.10

The tendency of the pole to resist rotation aids the acrobat.

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Rotational Inertia Using Weighted Pipes
Rotational Inertia Using a Hammer
Rotational Inertia with a Weighted Rod

[3]Often called *moment of inertia*.

three axes—one about its central core parallel to the length of the pencil, where the lead is; the second about the perpendicular midpoint axis; and the third about an axis perpendicular to one end. Rotational inertia is very small about the first position, and it's easy to rotate the pencil between your fingertips because most all the mass is very close to the axis. About the second axis, like that used by the tightrope walker in the preceding illustration, rotational inertia is greater. About the third axis, at the end of the pencil so that it swings like a pendulum, rotational inertia is greater still.

FIGURE 8.11
The pencil has different rotational inertias about different rotational axes.

A long baseball bat held near its end has more rotational inertia than a short bat. Once it is swinging, it has a greater tendency to keep swinging, but it is harder to bring it up to speed. A short bat, with less rotational inertia, is easier to swing—which explains why baseball players sometimes "choke up" on a bat by grasping it closer to the more massive end. Similarly, when you run with your legs bent, you reduce their rotational inertia so you can rotate them back and forth more quickly. A long-legged person tends to walk with slower strides than a person with short legs. The different strides of creatures with different leg lengths are especially evident in animals. Giraffes, horses, and ostriches run with a slower gait than dachshunds, mice, and bugs.

FIGURE 8.12
You bend your legs when you run to reduce rotational inertia.

FIGURE 8.13
Short legs have less rotational inertia than long legs. An animal with short legs has a quicker stride than people with long legs, just as a baseball batter can swing a short bat more quickly than a long one.

Because of rotational inertia, a solid cylinder starting from rest will roll down an incline faster than a hoop. Both rotate about a central axis, and the shape that has most of its mass far from its axis is the hoop. So, for its weight, a hoop has more rotational inertia and is harder to start rolling. Any solid cylinder will outroll any hoop on the same incline. This doesn't seem plausible at first, but remember that any two objects, regardless of mass, will fall together when dropped. They will also slide together when released on an inclined plane. When rotation is introduced, the object with the larger rotational inertia *relative to its own mass* has the greater resistance to a change in its motion. Hence, any solid cylinder will roll down any incline with more acceleration than any hollow cylinder, regardless of mass or radius. A hollow cylinder has more "laziness per mass" than a solid cylinder. Try it and see!

FIGURE 8.14
A solid cylinder rolls down an incline faster than a hoop, whether or not they have the same mass or outer diameter. A hoop has greater rotational inertia relative to its mass than a cylinder does.

Figure 8.15 compares rotational inertias for various shapes and axes. It is not important for you to learn the equations shown in the figure, but can you see how they vary with the shape and axis?

[1]When the mass of an object is concentrated at the radius r from the axis of rotation (as for a simple pendulum bob or a thin ring), rotational inertia I is equal to the mass m multiplied by the square of the radial distance. For this special case, $I = mr^2$.

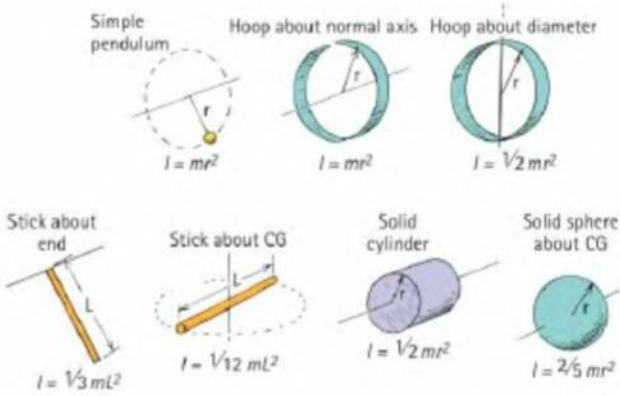

FIGURE 8.15
Rotational inertias of various objects, each of mass m, about indicated axes.

Note how rotational inertia very much depends on the location of the axis of rotation. A stick rotated about one end, for example, has 4 times the rotational inertia than when rotated about its center.

CHECK POINT

1. Consider balancing a hammer upright on the tip of your finger. The head is likely heavier than the handle. Is it easier to balance with the end of the handle on your fingertip, with the head at the top, or the other way around with the head at your fingertip and the end of the handle at the top?
2. Consider a pair of metersticks standing nearly upright against a wall. If you release them, they'll rotate to the floor in the same time. But what if one has a massive hunk of clay stuck to its top end? Will it rotate to the floor in a longer or shorter time?
3. Just for fun, and since we're discussing round things, why are manhole covers circular in shape?

Check Your Answers

1. Stand the hammer with the handle at your fingertip and the head at the top. Why? Because it will have more rotational inertia this way and be more resistant to a rotational change. (Try this yourself by trying to balance a spoon both ways on your fingertip.) Those acrobats you see on stage who balance a long pole have an easier task when their friends are at the top of the pole. A pole empty at the top has less rotational inertia and is more difficult to balance!
2. Try it and see! (If you don't have clay, fashion something equivalent.)
3. Not so fast on this one. Give it some thought. If you don't come up with an answer, *then* look to the end of the chapter for an answer.

FIGURE 8.16
Move the weight farther from your hand and feel the difference between force and torque.

Torque

Hold the end of a meterstick horizontally with your hand. Dangle a weight from it near your hand and you can feel the stick twist. Now slide the weight farther from your hand and you can feel that the twist is greater. But the weight is the same. The force acting on your hand is the same. What's different is the *torque*.

A torque (rhymes with *dork*) is the rotational counterpart of force. Force tends to change the motion of things; torque tends to twist or change the state of rotation of things. If you want to make a stationary object move or a moving object change speed, apply force. If you want to make a stationary object rotate or a rotating object change rotational speed, apply torque.

Just as rotational inertia differs from regular inertia, torque differs from force. Both rotational inertia and torque involve distance from the axis of rotation. In the case of torque, this distance, which provides leverage, is called the *lever arm*. It is the shortest distance between the applied force and the rotational axis. We define **torque** as the product of this lever arm and the force that tends to produce rotation:

$$\text{Torque} = \text{lever arm} \times \text{force}$$

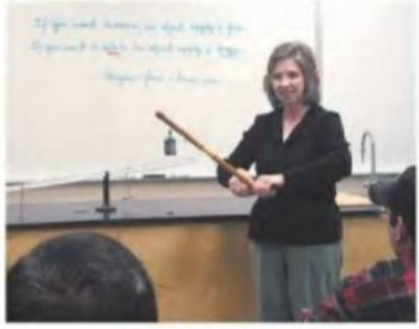

FIGURE 8.17

Mary Beth Monroe demonstrates a "torque feeler" before she passes it around for her students to try.

Torques are intuitively familiar to youngsters playing on a seesaw. Kids can balance a seesaw even when their weights are unequal. Weight alone doesn't produce rotation—torque does also—and children soon learn that the distance they sit from the pivot point is every bit as important as their weight. The torque produced by the boy on the right in Figure 8.18 tends to produce clockwise rotation, while torque produced by the girl on the left tends to produce counterclockwise rotation. If the torques are equal, making the net torque zero, no rotation is produced.

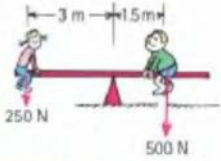

FIGURE 8.18

INTERACTIVE FIGURE

No rotation is produced when the torques balance each other.

Suppose that the seesaw is arranged so that the half-as-heavy girl is suspended from a 4-m rope hanging from her end of the seesaw (Figure 8.19). She is now 5 m from the fulcrum, and the seesaw is still balanced. We see that the lever-arm distance is still 3 m and not 5 m. The lever arm about any axis of rotation is the perpendicular distance from the axis to the line along which the force acts. This will always be the shortest distance between the axis of rotation and the line along which the force acts.

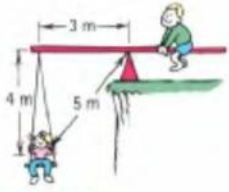

FIGURE 8.19

The lever arm is still 3 m.

This is why the stubborn bolt shown in Figure 8.20 is more likely to turn when the applied force is perpendicular to the handle, rather than at an oblique angle as shown in the first figure. In the first figure, the lever arm is shown by the dashed line and is less than the length of the wrench handle. In the second figure, the lever arm is equal to the length of the wrench handle. In the third figure, the lever arm is extended with a piece of pipe to provide more leverage and a greater torque.

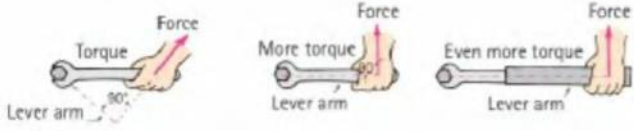

FIGURE 8.20

INTERACTIVE FIGURE

Although the magnitudes of the force are the same in each case, the torques are different.

If and when all clocks go digital, will clockwise and counterclockwise have meaning to future generations?

Recall the equilibrium rule in Chapter 2—that the sum of the forces acting on a body or any system must equal zero for mechanical equilibrium. That is, $\Sigma F = 0$. We now see an additional condition. The *net torque* on a body or on a system must also be zero for mechanical equilibrium, $\Sigma\tau = 0$, where τ stands for torque. Anything in mechanical equilibrium doesn't accelerate linearly or rotationally.

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Difference Between Torque and Weight

Why a Ball Rolls Down a Hill

CHECK POINT

1. If a pipe effectively extends a wrench handle to 3 times its length, by how much will the torque increase for the same applied force?
2. Consider the balanced seesaw in Figure 8.18. Suppose the girl on the left suddenly gains 50 N, such as by being handed a bag of apples. Where should she sit in order to balance, assuming the heavier boy does not move?

Check Your Answers

1. Three times more leverage for the same force produces 3 times more torque. (Caution: This method of increasing torque sometimes results in shearing off the bolt!)
2. She should sit $\frac{1}{2}$ m closer to the center. Then her lever arm is 2.5 m. This checks: 300 N × 2.5 m = 500 N × 1.5 m.

Center of Mass and Center of Gravity

Toss a baseball into the air, and it will follow a smooth parabolic trajectory. Toss a baseball bat spinning into the air, and its path is not smooth; its motion is wobbly, and it seems to wobble all over the place. But, in fact, it wobbles about a very special place, a point called the **center of mass (CM).**

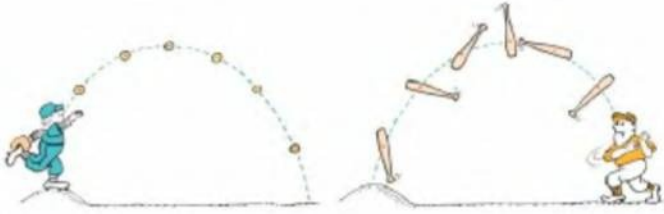

FIGURE 8.21
The center of mass of the baseball and that of the bat follow parabolic trajectories.

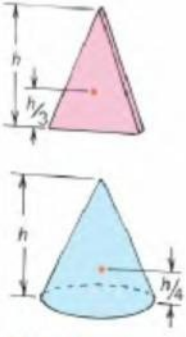

FIGURE 8.22
The center of mass for each object is shown by the red dot.

For a given body, the center of mass is the average position of all the mass that makes up the object. For example, a symmetrical object, such as a ball, has its center of mass at its geometrical center; by contrast, an irregularly shaped body, such as a baseball bat, has more of its mass toward one end. The center of mass of a baseball bat, therefore, is toward the thicker end. A solid cone has its center of mass exactly one-fourth of the way up from its base.

Center of gravity (CG) is a term popularly used to express center of mass. The center of gravity is simply the average position of weight distribution. Since weight and mass are proportional, center of gravity and center of mass refer to the same point of an object.[5] The physicist prefers to use the term *center of mass*, for an object has a center of mass whether or not it is under the influence of gravity. However, we shall use either term to express this concept, and we shall favor the term *center of gravity* when weight is part of the picture.

[5]For almost all objects on and near Earth's surface, these terms are interchangeable. A small difference between center of gravity and center of mass can occur for an object large enough so that gravity varies from one part to another. For example, the center of gravity of the Empire State Building is about 1 millimeter below its center of mass. This is due to the lower stories being pulled a little more strongly by Earth's gravity than the upper stories. For everyday objects (including tall buildings), we can use the terms *center of gravity* and *center of mass* interchangeably.

The multiple-flash photograph (Figure 8.23) shows a top view of a wrench sliding across a smooth horizontal surface. Note that its center of mass, indicated by the white dot, follows a straight-line path, while other parts of the wrench wobble as they move across the surface. Since there is no external force acting on the wrench, its center of mass moves equal distances in equal time intervals. The motion of the spinning wrench is the combination of the straight-line motion of its center of mass and the rotational motion about its center of mass.

FIGURE 8.23
The center of mass of the spinning wrench follows a straight-line path.

If the wrench were instead tossed into the air, no matter how it rotates, its center of mass (or center of gravity) would follow a smooth parabolic arc. The same is true for an exploding cannonball (Figure 8.24). The internal forces that act in the explosion do not change the center of gravity of the projectile. Interestingly enough, if air resistance can be neglected, the center of gravity of the dispersed fragments as they fly though the air will be in the same location as the center of gravity would have been if the explosion hadn't occurred.

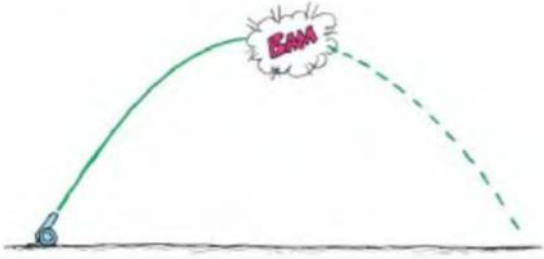

FIGURE 8.24
The center of mass of the cannonball and its fragments moves along the same path before and after the explosion.

CHECK POINT

1. Where is the CG of a donut?
2. Can an object have more than one CG?

Check Your Answers

1. In the center of the hole!
2. No. A rigid object has one CG. If it is nonrigid, such as a piece of clay or putty, and is distorted into different shapes, then its CG may change as its shape changes. Even then, it has one CG for any given shape.

LOCATING THE CENTER OF GRAVITY

The center of gravity of a uniform object, such as a meterstick, is at its midpoint, for the stick acts as if its entire weight were concentrated there. If you support that single point, you support the entire stick. Balancing an object provides a simple method of locating its center of gravity. In Figure 8.25, the many small arrows represent the pull of gravity all along the meterstick. All of these can be combined into a resultant force acting through the center of gravity. The entire weight of the stick may be thought of as acting at this single point. Hence, we can balance the stick by applying a single upward force in a direction that passes through this point.

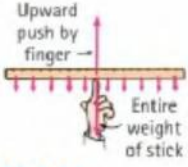

FIGURE 8.25
The weight of the entire stick behaves as if it were concentrated at the stick's center.

FIGURE 8.26
Finding the center of gravity for an irregularly shaped object.

The center of gravity of any freely suspended object lies directly beneath (or at) the point of suspension (Figure 8.26). If a vertical line is drawn through the point of suspension, the center of gravity lies somewhere along that line. To determine exactly where it lies along the line, we have only to suspend the object from some other point and draw a second vertical line through that point of suspension. The center of gravity lies where the two lines intersect.

The center of mass of an object may be a point where no mass exists. For example, the center of mass of a ring or a hollow sphere is at the geometrical center where no matter exists. Similarly, the center of mass of a boomerang is outside the physical structure, not within the material of the boomerang (Figure 8.27).

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Learning the Center of Gravity

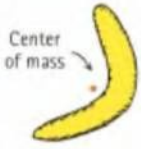
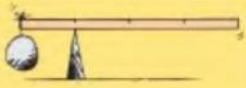


FIGURE 8.27
The center of mass can be outside the mass of a body.

FIGURE 8.28
The athlete executes a "Fosbury flop" to clear the bar while her center of gravity passes beneath the bar.

CHECK POINT

1. Where is the center of mass of Earth's atmosphere?
2. A uniform meterstick supported at the 25-cm mark balances when a 1-kg rock is suspended at the 0-cm end. What is the mass of the meterstick?



Check Your Answers

1. Like a giant basketball, Earth's atmosphere is a spherical shell with its center of mass at Earth's center.
2. The mass of the meterstick is 1 kg. Why? The system is in equilibrium, so any torques must be balanced. The torque produced by the weight of the rock is balanced by the equal but oppositely directed torque produced by the weight of the stick *applied at its CG, the 50-cm mark*. The support force at the 25-cm mark is applied midway between the rock and the stick's CG, so the lever arms about the support point are equal (25 cm). This means that the weights (and hence the masses) of the rock and stick are also equal. (Note that we don't have to go through the laborious task of considering the fractional parts of the stick's weight on either side of the fulcrum, for the CG of the whole stick really is at one point—the 50-cm mark!) Interestingly, the CG of the rock + stick system is at the 25-cm mark—directly above the fulcrum.

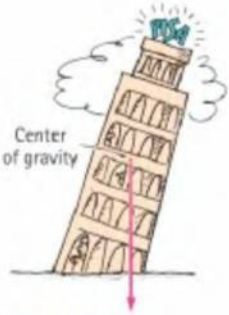


FIGURE 8.29

The center of gravity of the Leaning Tower of Pisa lies above its base of support, so the tower is in stable equilibrium.

FIGURE 8.30

When you stand, your center of gravity is somewhere above the base area bounded by your feet. Why do you keep your legs far apart when you have to stand in the aisle of a bumpy-riding bus?

STABILITY

The location of the center of gravity is important for stability (Figure 8.29). If we draw a line straight down from the center of gravity of an object of any shape and it falls inside the base of the object, it is in stable **equilibrium**; it will balance. If it falls outside the base, it is unstable. Why doesn't the famous Leaning Tower of Pisa topple over? As we can see in Figure 8.29, a line from the center of gravity of the tower to the level of the ground falls inside its base, so the Leaning Tower has stood for several centuries. If the tower leaned far enough so that the center of gravity extended beyond the base, an unbalanced torque would topple the tower.

When you stand erect (or lie flat), your center of gravity is within your body. Why is the center of gravity lower in an average woman than it is in an average man of the same height? Is your center of gravity always at the same point in your body? Is it always inside your body? What happens to it when you bend over?

If you are fairly flexible, you can bend over and touch your toes without bending your knees. Ordinarily, when you bend over and touch your toes, you extend your lower extremity as shown in the left half of Figure 8.31, so that your center of gravity is above a base of support, your feet. If you attempt to do this when standing against a wall, however, you cannot counterbalance yourself, and your center of gravity soon protrudes beyond your feet, as shown in the right half of Figure 8.31.

FIGURE 8.31

You can lean over and touch your toes without falling over only if your center of gravity is above the area bounded by your feet.

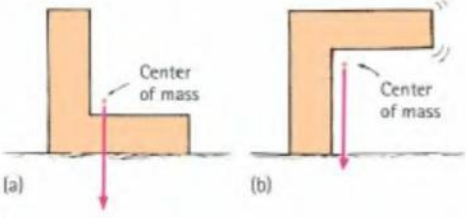


FIGURE 8.32

The center of mass of the L-shaped object is located where no mass exists. In (a), the center of mass is above the base of support, so the object is stable. In (b), it is not above the base of support, so the object is unstable and will topple over.

FIGURE 8.33
Where is Alexei's center of gravity relative to his hands?

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Video
Toppling

You rotate because of an unbalanced torque. This is evident in the two L-shaped objects shown in Figure 8.34. Both are unstable and will topple unless fastened to the level surface. It is easy to see that even if both shapes have the same weight, the one on the right is more unstable. This is because of the greater lever arm and, hence, a greater torque.

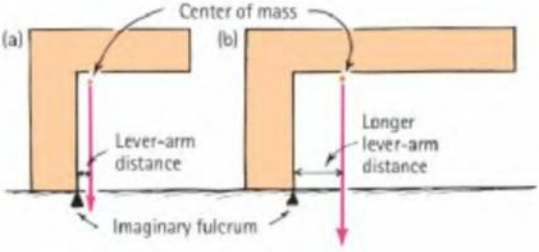

FIGURE 8.34
The greater torque acts on (b) for two reasons. What are they?

Try balancing the pole end of a broom upright on the palm of your hand. The support base is quite small and relatively far beneath the center of gravity, so it's difficult to maintain balance for very long. After some practice, you can do it if you learn to make slight movements of your hand to respond exactly to variations in balance. You learn to avoid underresponding or overresponding to the slightest variations in balance. The intriguing Segway Human Transporter (Figure 8.35) does much the same. Variations in balance are quickly sensed by gyroscopes, and an internal computer regulates a motor to keep the vehicle upright. The computer regulates corrective adjustments of the wheel speed in a way quite similar to the way in which your brain coordinates your adjustive action when balancing a long pole on the palm of your hand. Both feats are truly amazing.

FIGURE 8.35
Gyroscopes and computer-assisted motors make continual adjustments in the self-balancing electric scooters to keep the combined CGs of Mark, Tenny, and the vehicles above the wheelbase.

To reduce the likelihood of tipping, it is usually advisable to design objects with a wide base and low center of gravity. The wider the base, the higher the center of gravity must be raised before the object tips over.

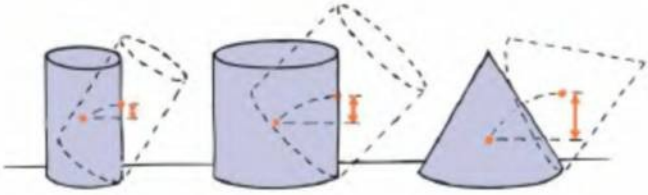

FIGURE 8.36
Stability is determined by the vertical distance that the center of gravity is raised in tipping. An object with a wide base and a low center of gravity is more stable.

CHECK POINT

1. Why is it dangerous to slide open the top drawers of a fully loaded file cabinet that is not secured to the floor?
2. When a car drives off a cliff, why does it rotate forward as it falls?

Check Your Answers

1. The filing cabinet is in danger of tipping because the CG may extend beyond the support base. If it does, then torque due to gravity tips the cabinet.
2. When all wheels are on the ground, the car's CG is above a support base and no tipping occurs. But when the car drives off a cliff, the front wheels are first to leave the ground and the car is supported only by the rear wheels. The CG then extends beyond the support base, and rotation occurs. Interestingly, the speed of the car relates to how much time the CG is not supported, and hence, the amount the car rotates while it falls.

Centripetal Force

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Video
Centripetal Force

Any force directed toward a fixed center is called a **centripetal force.** *Centripetal* means "center-seeking" or "toward the center." When we whirl a tin can on the end of a string, we find that we must keep pulling on the string—exerting a centripetal force (Figure 8.37). The string transmits the centripetal force, which pulls the can into a circular path. Gravitational and electrical forces can produce centripetal forces. The Moon, for example, is held in an almost circular orbit by gravitational force directed toward the center of Earth. The orbiting electrons in atoms experience an electrical force toward the central nuclei. Anything that moves in a circular path does so because it's acted upon by a centripetal force.

FIGURE 8.37
The force exerted on the whirling can is toward the center.

Centripetal force depends on the mass m, tangential speed v, and radius of curvature r of the circularly moving object. In lab, you'll likely use the exact relationship

$$F = \frac{mv^2}{r}$$

Notice that speed is squared, so twice the speed needs 4 times the force. The inverse relationship with the radius of curvature tells us that half the radial distance requires twice the force.

Centripetal force is not a basic force of nature; it is simply the name given to any force, whether string tension, gravitational, electrical, or whatever, that is directed toward a fixed center. If the motion is circular and executed at constant speed, this force is at right angles to the path of the moving object.

FIGURE 8.38
The centripetal force (adhesion of mud on the spinning tire) is not great enough to hold the mud on the tire, so it flies off in straight-line tangents.

When an automobile rounds a corner, the friction between the tires and the road provides the centripetal force that holds the car in a curved path (Figure 8.39).

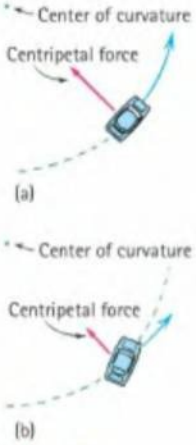

FIGURE 8.39

(a) When a car goes around a curve, there must be a force pushing the car toward the center of the curve. (b) A car skids on a curve when the centripetal force (friction of road on tires) is not great enough.

If this friction is insufficient (due to oil or gravel on the pavement, for example), the tires slide sideways and the car fails to make the curve; the car tends to skid tangentially off the road.

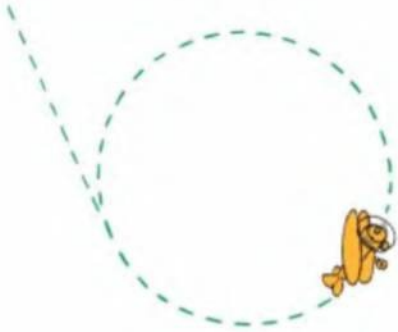

FIGURE 8.40

Large centripetal forces on the wings of an aircraft enable it to fly in circular loops. The acceleration away from the straight-line path the aircraft would follow in the absence of centripetal force is often several times greater than the acceleration due to gravity, g. For example, if the centripetal acceleration is 50 m/s^2 (5 times as great as 10 m/s^2), we say that the aircraft is undergoing 5 g's. For a pilot, the number of g's is defined by the force on the seat of his or her pants. So at the bottom of the loop where the pilot's weight lines up with the centripetal force, the pilot experiences 6 g's. Typical fighter aircraft are designed to withstand accelerations up to 8 or 9 g's. The pilot as well as the aircraft must withstand this amount of acceleration. Pilots of fighter aircraft wear pressure suits to prevent blood from flowing away from the head toward the legs, which could cause a blackout.

FIGURE 8.41

The clothes are forced into a circular path, but the water is not.

Centripetal force plays the main role in the operation of a centrifuge. A familiar example is the spinning tub in an automatic washing machine (Figure 8.41). In its spin cycle, the tub rotates at high speed and produces a centripetal force on the wet clothes, which are forced into a circular path by the inner wall of the tub. The tub exerts great force on the clothes, but the holes in the tub prevent the exertion of the same force on the water in the clothes. The water escapes tangentially out the holes. Strictly speaking, the clothes are forced away from the water; the water is not forced away from the clothes. Think about that.

Practicing Physics: Water-Bucket Swing

Half fill a bucket of water and swing it in a vertical circle, as Marshall Ellenstein demonstrates. The bucket and water accelerate toward the center of your swing. If you swing the bucket fast enough, the water won't fall out at the top. Interestingly, although it won't fall *out*, it still falls. The trick is to swing the bucket fast enough so that the bucket falls as fast as the water inside the bucket falls. Can you see that because the bucket is circling the water moves tangentially—and stays in the bucket? In Chapter 10, we'll learn that an orbiting space shuttle similarly falls while in orbit. The trick is to impart sufficient tangential velocity to the shuttle so that it falls around the curved Earth rather than into it.

Centrifugal Force

Although centripetal force is center directed, an occupant inside a rotating system seems to experience an outward force. This apparent outward force is called **centrifugal force.** *Centrifugal* means "center-fleeing" or "away from the center." In the case of the whirling can, it is a common misconception to believe that a centrifugal force pulls outward on the can. If the string holding the whirling can breaks (Figure 8.42), the can doesn't move radially outward, but goes off in a tangent straight-line path—because *no* force acts on it. We illustrate this further with another example.

FIGURE 8.42
When the string breaks, the whirling can moves in a straight line, tangent to—not outward from—the center of its circular path.

Suppose you are a passenger in a car that suddenly stops short. You pitch forward toward the dashboard. When this occurs, you don't say that something forced you forward. In accord with the law of inertia, you pitched forward because of the absence of a force, which seat belts would have provided. Similarly, if you are in a car that rounds a sharp corner to the left, you tend to pitch outward to the right—not because of some outward or centrifugal force, but because there is no centripetal force holding you in circular motion (again, the purpose of seat belts). The idea that a centrifugal force bangs you against the car door is a misconception. (Sure, you push out against the door, but only because the door pushes in on you—Newton's third law.)

FIGURE 8.43
The only force that is exerted on the whirling can (neglecting gravity) is directed *toward* the center of circular motion. This is a centripetal force. No *outward* force acts on the can.

Likewise, when you swing a tin can in a circular path, no force pulls the can outward—the only force on the can is the string pulling it inward. There is no outward force on the can. Now suppose there is a ladybug inside the whirling can (Figure 8.44). The can presses against the bug's feet and provides the centripetal force that holds it in a circular path. From our outside stationary frame of reference, we see no centrifugal force exerted on the ladybug, just as no centrifugal force banged us against the car door. The centrifugal force effect is caused not by a real force, but by inertia—the tendency of the moving object to follow a straight-line path. But try telling that to the ladybug!

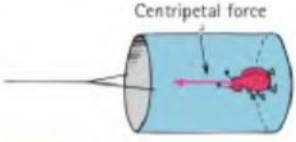

FIGURE 8.44
The can provides the centripetal force necessary to hold the ladybug in a circular path.

Centrifugal Force in a Rotating Reference Frame

If we stand at rest and watch somebody whirling a can overhead in a horizontal circle, we see that the force on the can is centripetal, just as it is on a ladybug inside the can. The bottom of the can exerts a force on the ladybug's feet. Neglecting gravity, no other force acts on the ladybug. But, as viewed from inside the frame of reference of the revolving can, things appear very different.[6]

In the rotating frame of the ladybug, in addition to the force of the can on the ladybug's feet, there is an apparent centrifugal force that is exerted on the ladybug. Centrifugal force *in a rotating reference frame* is a force in its own right, as real as the pull of gravity. However, there is a fundamental difference. Gravitational force is an

[6]A frame of reference wherein a free body exhibits no acceleration is called an *inertial* frame of reference. Newton's laws are seen to hold exactly in an inertial frame. A rotating frame of reference, in contrast, is an accelerating frame of reference. Newton's laws are not valid in an accelerating frame of reference.

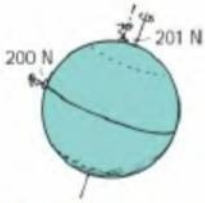

FIGURE 8.45
In the frame of reference of the spinning Earth, we experience a centrifugal force that slightly decreases our weight. Like an outside horse on a merry-go-round, we have the greatest tangential speed farthest from Earth's axis, at the equator. Centrifugal force is therefore maximum for us when we are at the equator and zero for us at the poles, where we have no tangential speed. So, strictly speaking, if you want to lose weight, walk toward the equator!

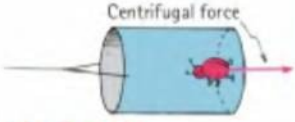

FIGURE 8.46
From the reference frame of the ladybug inside the whirling can, it is being held to the bottom of the can by a force that is directed away from the center of circular motion. The ladybug calls this outward force a *centrifugal* force, which is as real to it as gravity.

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Simulated Gravity

interaction between one mass and another. The gravity we experience is our interaction with Earth. But for centrifugal force in the rotating frame, no such agent exists—there is no interaction counterpart. Centrifugal force *feels* like gravity, but with no agent pulling. Nothing produces it; it is a result of rotation. For this reason, physicists call it an "inertial" force (or sometimes a *fictitious* force)—an *apparent* force—and not a real force like gravity, electromagnetic forces, and nuclear forces. Nevertheless, to observers who are in a rotating system, centrifugal force feels like, and is interpreted to be, a very real force. Just as gravity is ever present at Earth's surface, centrifugal force is ever present in a rotating system.

CHECK POINT

A heavy iron ball is attached by a spring to the rotating platform, as shown in the sketch. Two observers, one in the rotating frame and one on the ground at rest, observe its motion. Which observer sees the ball being pulled outward, stretching the spring? Which sees the spring pulling the ball into circular motion?

Check Your Answer

The observer in the reference frame of the rotating platform states that a centrifugal force pulls radially outward on the ball, which stretches the spring. The observer in the rest frame states that a centripetal force supplied by the stretched spring pulls the ball into circular motion. Only the observer in the rest frame can identify an action–reaction pair of forces, where action is spring on ball, reaction is ball on spring. The rotating observer can't identify a reaction counterpart to the centrifugal force because there isn't any!

Simulated Gravity

Consider a colony of ladybugs living inside a bicycle tire—a balloon tire with plenty of room inside. If we toss the bicycle wheel through the air or drop it from an airplane high in the sky, the ladybugs will be in a weightless condition. They will float freely while the wheel is in free fall. Now spin the wheel. The ladybugs will feel themselves pressed to the outer part of the tire's inner surface. If the wheel is spun at just the right speed, the ladybugs will experience *simulated gravity* that will feel like the gravity they are accustomed to. Gravity is simulated by centrifugal force. The "down" direction to the ladybugs will be what we would call radially outward, away from the center of the wheel.

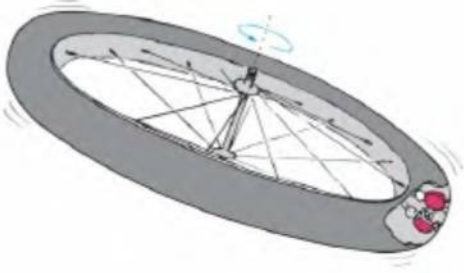

FIGURE 8.47
If the spinning wheel freely falls, the ladybugs inside will experience a centrifugal force that feels like gravity when the wheel spins at the appropriate rate. To the occupants, the direction "up" is toward the center of the wheel and "down" is radially outward.

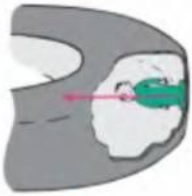

FIGURE 8.48

The interaction between the man and the floor, as seen from a stationary frame of reference outside the rotating system. The floor presses against the man (action) and the man presses back on the floor (reaction). The only force exerted on the man is by the floor. It is directed toward the center and is a centripetal force.

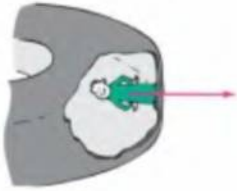

FIGURE 8.49

As seen from inside the rotating system, in addition to the man–floor interaction, there is a centrifugal force exerted on the man at his center of mass. It seems as real as gravity. Yet, unlike gravity, it has no reaction counterpart—there is nothing out there that he can pull back on. Centrifugal force is not part of an interaction, but it is a consequence of rotation. It is therefore called an apparent force, or a *fictitious force*.

Humans today live on the outer surface of this spherical planet and are held here by gravity. The planet has been the cradle of humankind. But we will not stay in the cradle forever. We are becoming a spacefaring people. Occupants of today's space vehicles feel weightless because they experience no *support force*. They're not pressed against a supporting floor by gravity, nor do they experience a centrifugal force due to spinning. Over extended periods, this can cause loss of muscle strength and detrimental changes in the body, such as loss of calcium from the bones. But future space travelers need not be subject to weightlessness. Their space habitats will probably spin, like the ladybug's spinning wheel, effectively supplying a support force and nicely simulating gravity.

The significantly smaller International Space Station doesn't rotate. Therefore, its crew members have to adjust to living in a weightless environment. Rotating habitats may follow later, perhaps in huge, lazily rotating structures where occupants will be held to the inner surfaces by centrifugal force. Such a rotating habitat supplies a simulated gravity so that the human body can function normally. Structures of small diameter would have to rotate at high rates to provide a simulated gravitational acceleration of 1 *g*. Sensitive and delicate organs in our inner ears sense rotation. Although there appears to be no difficulty at a single revolution per minute (RPM) or so, many people find it difficult to adjust to rates greater than 2 or 3 RPM (although some easily adapt to 10 or so RPM). To simulate normal Earth gravity at 1 RPM requires a large structure—one about 2 km in diameter. Centrifugal acceleration is directly proportional to the radial distance from the hub, so a variety of *g* states is possible. If the structure rotates so that inhabitants on the inside of the outer edge experience 1 *g*, then halfway to the axis they would experience 0.5 *g*. At the axis itself they would experience weightlessness (0 *g*). The variety of fractions of *g* possible from the rim of a rotating space habitat holds promise for a most different and (at this writing) as yet unexperienced environment. In this still very hypothetical structure, we would be able to perform ballet at 0.5 *g*, diving and acrobatics at 0.2 *g* and lower-*g* states, and three-dimensional soccer (and new sports not yet conceived) in very low *g* states.

A rotating habitat need not be a huge wheel. Gravity could be simulated in a pair of circling pods connected by a long cable.

CHECK POINT

If Earth were to spin faster about its axis, your weight would be less. If you were in a rotating space habitat that increased its spin rate, you'd "weigh" more. Explain why greater spin rates produce opposite effects in these cases.

Check Your Answer

You're on the *outside* of the spinning Earth, but you'd be on the *inside* of a spinning space habitat. A greater spin rate on the outside of the Earth tends to throw you *off* a weighing scale, causing it to show a decrease in weight, but *against* a weighing scale *inside* the space habitat to show an increase in weight.

Angular Momentum

Things that rotate, whether a colony in space, a cylinder rolling down an incline, or an acrobat doing a somersault, remain rotating until something stops them. A rotating object has an "inertia of rotation." Recall, from Chapter 6, that all moving objects have "inertia of motion" or *momentum*—the product of mass and velocity. This kind of momentum is **linear momentum.** Similarly, the "inertia of rotation" of rotating objects is called **angular momentum.** A planet orbiting the Sun, a rock whirling at the end of a string, and the tiny electrons whirling about atomic nuclei all have angular momentum.

Angular momentum is defined as the product of rotational inertia and rotational velocity:

$$\text{Angular momentum} = \text{rotational inertia} \times \text{rotational velocity}$$

It is the counterpart of linear momentum:

$$\text{Linear momentum} = \text{mass} \times \text{velocity}$$

Like linear momentum, angular momentum is a vector quantity and has direction as well as magnitude. In this book, we won't treat the vector nature of angular momentum (or even of torque, which also is a vector), except to acknowledge the remarkable action of the gyroscope. The rotating bicycle wheel in Figure 8.50 shows what happens when a torque caused by Earth's gravity acts to change the direction of its angular momentum (which is along the wheel's axle). The pull of gravity that normally acts to topple the wheel over and change its rotational axis causes it instead to *precess* about a vertical axis. You must do this yourself while standing on a turntable to fully believe it. You probably won't fully understand it unless you do follow-up study sometime in the future.

FIGURE 8.50

Angular momentum keeps the wheel axle nearly horizontal when a torque supplied by Earth's gravity acts on it. Instead of causing the wheel to topple, the torque causes the wheel's axle to turn slowly around the circle of students. This is called *precession.*

For the case of an object that is small compared with the radial distance to its axis of rotation, such as a tin can swinging from a long string or a planet orbiting in a circle around the Sun, the angular momentum can be expressed as the magnitude of its linear momentum, mv, multiplied by the radial distance, r (Figure 8.51). In shorthand notation,

$$\text{Angular momentum} = mvr$$

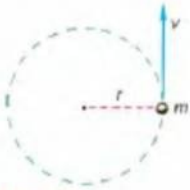

FIGURE 8.51
A small object of mass m whirling in a circular path of radius r with a speed v has angular momentum mvr.

Just as an external net force is required to change the linear momentum of an object, an external net torque is required to change the angular momentum of an object. We can state a rotational version of Newton's first law (the law of inertia):

An object or system of objects will maintain its angular momentum unless acted upon by an external net torque.

Our solar system has angular momentum that includes the Sun, the spinning and orbiting planets, and myriad other smaller bodies. The angular momentum of the solar system today will be its angular momentum for eons to come. Only an external torque from outside the solar system can change it. In the absence of such a torque, we say the angular momentum of the solar system is conserved.

Conservation of Angular Momentum

Just as the linear momentum of any system is conserved if no net force acts on the system, angular momentum is conserved if no net torque acts. The **law of conservation of angular momentum** states:

If no external net torque acts on a rotating system, the angular momentum of that system remains constant.

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Videos
Conservation of Angular Momentum Using a Rotating Platform

This means that, with no external torque, the product of rotational inertia and rotational velocity at one time will be the same as at any other time.

An interesting example illustrating the conservation of angular momentum is shown in Figure 8.52. The man stands on a low-friction turntable with weights extended. His rotational inertia, I, with the help of the extended weights, is relatively large in this position. As he slowly turns, his angular momentum is the product of his rotational inertia and rotational velocity, ω. When he pulls the weights inward, the rotational inertia of his body and the weights is considerably reduced. What is the result? His rotational speed increases! This example is best appreciated by the turning person who feels changes in rotational speed that seem to be mysterious. But it's straightforward physics! This procedure is used by a figure skater who starts to whirl with her arms and perhaps a leg extended and then draws her arms and leg in to obtain a greater rotational speed. Whenever a rotating body contracts, its rotational speed increases.

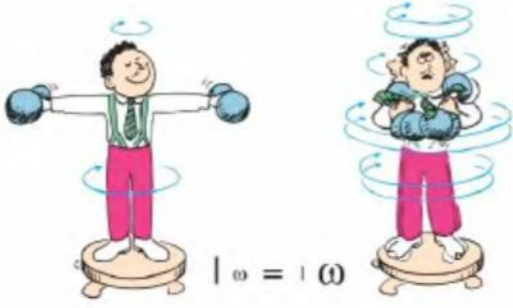


FIGURE 8.52
INTERACTIVE FIGURE
Conservation of angular momentum. When the man pulls his arms and the whirling weights inward, he decreases his rotational inertia I, and his rotational speed ω correspondingly increases.

Why do short acrobats have an advantage in tumbling or in other end-over-end rotational motions?

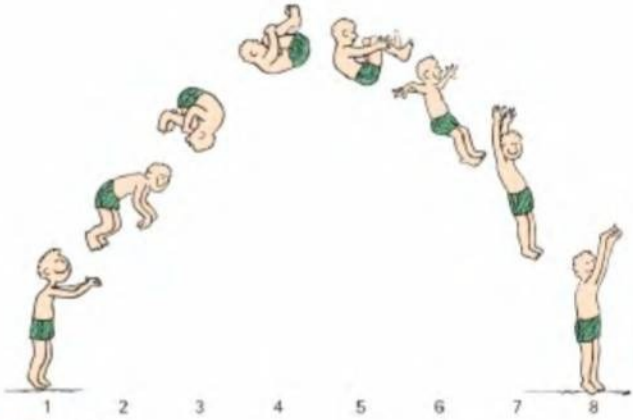


FIGURE 8.53
Rotational speed is controlled by variations in the body's rotational inertia as angular momentum is conserved during a forward somersault.

Similarly, when a gymnast is spinning freely in the absence of unbalanced torques on his or her body, angular momentum does not change. However, rotational speed can be changed by simply making variations in rotational inertia. This is done by moving some part of the body toward or away from the axis of rotation.

If a cat is held upside down and dropped, it is able to execute a twist and to land upright, even if it has no initial angular momentum. Zero-angular-momentum twists and turns are performed by turning one part of the body against the other. While falling, the cat rearranges its limbs and tail several times to change its rotational inertia repeatedly until it lands feet downward. During this maneuver the total angular momentum remains zero (Figure 8.54). When it is over, the cat is not turning. This maneuver rotates the body through an angle, but it does not create continuing rotation. To do so would violate angular momentum conservation.

Humans can perform similar twists without difficulty, though not as fast as a cat. Astronauts have learned to make zero-angular-momentum rotations as they orient their bodies in preferred directions when floating freely in space.

The law of conservation of angular momentum is seen in the motions of planets and the shapes of galaxies. It is fascinating to note that the conservation of angular momentum tells us that the Moon is getting farther away from Earth. This is because the Earth's daily rotation is slowly decreasing due to the friction of ocean waters on the ocean bottom, just as an automobile's wheels slow down when brakes are applied. This decrease in Earth's angular momentum is accompanied by an equal increase in the angular momentum of the Moon in its orbital motion about Earth, which results in the Moon's increasing distance from Earth and decreasing speed. This increase of distance amounts to one-quarter of a centimeter per rotation. Have you noticed that the Moon is getting farther away from us lately? Well, it is; each time we see another full Moon, it is one-quarter of a centimeter farther away!

Oh yes—before we end this chapter, we'll give an answer to Check Point Question 3 back on page 128. Manhole covers are circular because a circular cover is the only shape that can't fall into the hole. A square cover, for example, can be tilted vertically and turned so it can drop diagonally into the hole. Likewise for every other shape. If you're working in a manhole and some fresh kids are horsing around above, you'll be glad the cover is round!

FIGURE 8.54
Time-lapse photo of a falling cat.

SUMMARY OF TERMS

Tangential speed The linear speed tangent to a curved path, such as in circular motion.

Rotational speed The number of rotations or revolutions per unit of time; often measured in rotations or revolutions per second or per minute. (Scientists usually measure it in radians per second.)

Rotational inertia That property of an object that measures its resistance to any change in its state of rotation: if at rest, the body tends to remain at rest; if rotating, it tends to remain rotating and will continue to do so unless acted upon by an external net torque.

Torque The product of force and lever-arm distance, which tends to produce rotation.

$$\text{Torque} = \text{lever arm} \times \text{force}$$

Center of mass (CM) The average position of the mass of an object. The CM moves as if all the external forces acted at this point.

Center of gravity (CG) The average position of weight or the single point associated with an object where the force of gravity can be considered to act.

Equilibrium The state of an object in which it is not acted upon by a net force or a net torque.

Centripetal force A force directed toward a fixed point, usually the cause of circular motion:

$$F = mv^2/r$$

Centrifugal force An outward force apparent in a rotating frame of reference. It is apparent (fictitious) in the sense that it is not part of an interaction but is a result of rotation—with no reaction-force counterpart.

Angular momentum The product of a body's rotational inertia and rotational velocity about a particular axis. For an object that is small compared with the radial distance, it can be expressed as the product of mass, speed, and the radial distance of rotation.

Conservation of angular momentum When no external torque acts on an object or a system of objects, no change of angular momentum can occur. Hence, the angular momentum before an event involving only internal torques or no torques is equal to the angular momentum after the event.

REVIEW QUESTIONS

Circular Motion

1. What is meant by tangential speed?
2. Distinguish between tangential speed and rotational speed.
3. What is the relationship between tangential speed and distance from the center of the rotational axis? Give an example.
4. A tapered cup rolled on a flat surface makes a circular path. What does this tell you about the tangential speed of the rim of the wide end of the cup compared with that of the rim of the narrow end?
5. How does the tapered rim of a wheel on a railroad train allow one part of the rim to have a greater tangential speed than another part when it is rolling on a track?

Rotational Inertia

6. What is rotational inertia, and is it similar to inertia as studied in previous chapters?
7. Inertia depends on mass; rotational inertia depends on mass and something else. What?
8. Does the rotational inertia of a particular object differ for different axes of rotation? Can one object have more than one rotational inertia?
9. Consider three axes of rotation for a pencil: along the lead; at right angles to the lead at the middle; at right angles to the lead at one end. Rate the rotational inertias about each axis from small to large.
10. Which is easier to get swinging, a baseball bat held at the end or one held closer to the massive end (choked up)?
11. Why does bending your legs when running enable you to swing your legs to and fro more rapidly?
12. Which will have the greater acceleration rolling down an incline, a hoop or a solid disk?

Torque

13. What does a torque tend to do to an object?
14. What is meant by the "lever arm" of a torque?
15. How do clockwise and counterclockwise torques compare when a system is balanced?

Center of Mass and Center of Gravity

16. If you toss a stick into the air, it appears to wobble all over the place. Specifically, what place?
17. Where is the center of mass of a baseball? Where is its center of gravity? Where are these centers for a baseball bat?

Locating the Center of Gravity

18. If you hang at rest by your hands from a vertical rope, where is your center of gravity with respect to the rope?
19. Where is the center of mass of a soccer ball?

Stability

20. What is the relationship between center of gravity and support base for an object in stable equilibrium?
21. Why doesn't the Leaning Tower of Pisa topple over?
22. In terms of center of gravity, support base, and torque, why can you not stand with heels and back to a wall and then bend over to touch your toes and return to your stand-up position?

Centripetal Force

23. When you whirl a can at the end of a string in a circular path, what is the direction of the force you exert on the can?
24. Is it an inward force or an outward force that is exerted on the clothes during the spin cycle of an automatic washing machine?

Centrifugal Force

25. If the string that holds a whirling can in its circular path breaks, what kind of force causes it to move in a straight-line path—centripetal, centrifugal, or no force? What law of physics supports your answer?
26. If you are in a car that rounds a curve, and you are not wearing a seat belt, and you slide across your seat and slam against a car door, what kind of force is responsible for your slide—centripetal, centrifugal, or no force? Why is the correct answer "no force"?

Centrifugal Force in a Rotating Reference Frame

27. Why is centrifugal force in a rotating frame called a "fictitious force"?

Simulated Gravity

28. How can gravity be simulated in an orbiting space station?

Angular Momentum

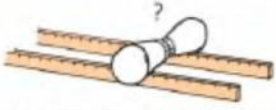
29. Distinguish between linear momentum and angular momentum.
30. What is the law of inertia for rotating systems in terms of angular momentum?

Conservation of Angular Momentum

31. What does it mean to say that angular momentum is conserved?
32. If a skater who is spinning pulls her arms in so as to reduce her rotational inertia by half, by how much will her angular momentum increase? By how much will her rate of spin increase? (Why are your answers different?)

PROJECTS

1. Write a letter to Grandpa and tell him how you're learning to distinguish between closely related concepts, using the examples of force and torque. Tell him how the two are similar, and how they're different. Suggest where he can find "hands-on" things in his home that can illustrate the difference between the two. Also cite an example that shows how the net force on an object can be zero while the net torque isn't, as well as an example showing vice versa. (Now make your Grandpa's day and *send* the letter to him!)
2. Fasten a pair of foam cups together at their wide ends and roll them along a pair of metersticks that simulate railroad tracks. Note how they self-correct whenever their path departs from the center. Question: If you taped the cups together at their narrow ends, so they tapered oppositely as shown, would the pair of cups self-correct or self-destruct when rolling slightly off center?



3. Fasten a fork, spoon, and wooden match together as shown. The combination will balance nicely—on the edge of a glass, for example. This happens because the center of gravity actually "hangs" below the point of support.

4. Stand with your heels and back against a wall and try to bend over and touch your toes. You'll find that you have to stand away from the wall to do so without toppling over. Compare the minimum distance of your heels from the wall with that of a friend of the opposite sex. Who can touch their toes with their heels nearer to the wall—males or females? On the average and in proportion to height, which sex has the lower center of gravity?
5. First ask a friend to stand facing a wall with her toes touching the wall, then ask her to stand on the balls of her feet without toppling backward. Your friend won't be able to do it. Now you explain why it can't be done.
6. Rest a meterstick on two extended forefingers as shown. Slowly bring your fingers together. At what part of the stick do your fingers meet? Can you explain why this always happens, no matter where you start your fingers?

7. Place the hook of a wire coat hanger over your finger. Carefully balance a coin on the straight wire on the bottom directly under the hook. You may have to flatten the wire with a hammer or fashion a tiny platform with tape. With a surprisingly small amount of practice you can swing the hanger and balanced coin back and forth and then in a circle. Centripetal force holds the coin in place.

PLUG AND CHUG

Torque = Lever Arm × Force

1. Calculate the torque produced by a 50-N perpendicular force at the end of a 0.2-m-long wrench.
2. Calculate the torque produced by the same 50-N force when a pipe extends the length of the wrench to 0.5 m.

Centripetal Force: $F = mv^2/r$

3. Calculate the tension in a horizontal string that whirls a 2-kg toy in a circle of radius 2.5 m when it moves at 3 m/s on an icy surface.
4. Calculate the force of friction that keeps a 75-kg person sitting on the edge of a horizontal rotating platform when the person sits 2 m from the center of the platform and has a tangential speed of 3 m/s.

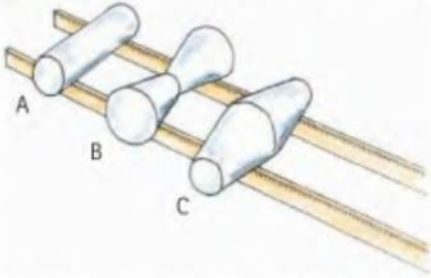
Angular Momentum = mvr

5. Calculate the angular momentum of the person in the previous problem.
6. If the person's speed doubles and all else remains the same, what will be the person's angular momentum?

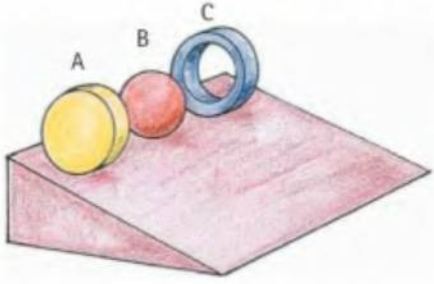
RANKING

1. The three cups are rolled on a level surface. Rank the cups by the amount they depart from a straight-line path (most curved to least curved).

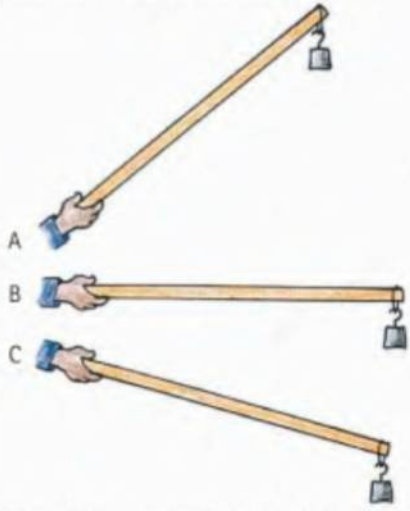
2. Three types of rollers are placed on slightly inclined parallel meterstick tracks as shown. From greatest to least, rank the rollers in terms of their ability to remain stable as they roll.



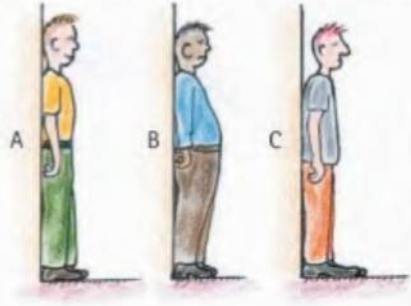
3. Beginning from a rest position, a solid disk A, a solid ball B, and a hoop C race down an inclined plane. Rank them in order for finishing: winner, second place, and third place.



4. You hold a meterstick horizontally with the same mass suspended at the end. Rank the torque needed to keep the stick steady, from largest to smallest.

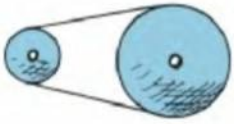


5. Three physics majors stand with their backs against a wall. They are all in good physical shape. Their task is to lean over and touch their toes without toppling over. Rank their chances for success from highest to lowest.



EXERCISES

1. While riding on a carnival Ferris wheel, Sam Nasty horses around and climbs out of his chair and along the spoke so he is halfway to the axis. How does his rotational speed compare with that of his friends who remain in the chair? How does his tangential speed compare? Why are your answers different?
2. An automobile speedometer is configured to read speed proportional to the rotational speed of its wheels. If larger wheels, such as those of snow tires, are used, will the speedometer reading be high, or low—or no different?
3. A large wheel is coupled to a wheel with half the diameter, as shown. How does the rotational speed of the smaller wheel compare with that of the larger wheel? How do the tangential speeds at the rims compare (assuming the belt doesn't slip)?



4. Dan and Sue cycle at the same speed. The tires on Dan's bike are larger in diameter than those on Sue's bike. Which wheels, if either, have the greater rotational speed?
5. Use the equation $v = r\omega$ to explain why the end of a fly-swatter moves much faster than your wrist when swatting a fly.
6. The wheels of railroad trains are tapered, a feature especially important on curves. How, if at all, does the amount of taper relate to the curving of the tracks?
7. Flamingos are frequently seen standing on one leg with the other lifted. Is rotational inertia enhanced with long legs? What can you say about the bird's center of mass with respect to the foot on which it stands?
8. The front wheels of a racing vehicle are located far out in front to help keep the vehicle from nosing upward when it accelerates. What physics concepts play a role here?

9. In this chapter, we learned that an object may *not* be in mechanical equilibrium even when $\Sigma F = 0$. Explain.
10. When a car drives off a cliff it rotates forward as it falls. For a higher speed off the cliff, will it rotate more, or less? (Consider the time that the unbalanced torque acts.)

11. Why does a car nose up when accelerating and nose down when braking?

12. Which will have the greater acceleration rolling down an incline—a bowling ball or a volleyball? Defend your answer.
13. A softball and a basketball start from rest and roll down an incline. Which ball reaches the bottom first? Defend your answer.
14. How would a ramp help you to distinguish between two identical-looking spheres of the same weight, one solid and the other hollow?
15. Which will roll down an incline faster—a can of water or a can of ice?
16. Why are lightweight tires preferred over lightweight frames in bicycle racing?
17. A youngster who has entered a soapbox derby (in which 4-wheel unpowered vehicles roll from rest down a hill) asks if large massive wheels or lightweight ones should be used. Also, should the wheels have spokes or be solid? What advice do you offer?
18. Is the net torque changed when a partner on a seesaw stands or hangs from her end instead of sitting? (Does the weight or the lever arm change?)

19. Can a force produce a torque when there is no lever arm?
20. When you pedal a bicycle, maximum torque is produced when the pedal sprocket arms are in the horizontal position, and no torque is produced when they are in the vertical position. Explain.

21. When the line of action of a force intersects the center of mass of an object, can that force produce a torque about the object's center of mass?
22. The spool is pulled in three ways, as shown. There is sufficient friction for rotation. In what direction will the spool roll in each case?

23. When a bowling ball leaves your hand, it may not spin. But farther along the alley, it does spin. What produces the spinning?

24. Why does sitting closest to the center of a vehicle provide the most comfortable ride in a bus traveling on a bumpy road, in a ship in a choppy sea, or in an airplane in turbulent air?

25. Which is more difficult—doing sit-ups with your knees bent, or with your legs straight out? Why?

26. Explain why a long pole is more beneficial to a tightrope walker if the pole droops.

27. Why must you bend forward when carrying a heavy load on your back?

28. Why is the wobbly motion of a single star an indication that the star has one or more planets orbiting around it?

29. Why is it easier to carry the same amount of water in two buckets, one in each hand, than in a single bucket?

30. Nobody at the playground wants to play with the obnoxious boy, so he fashions a seesaw as shown so he can play by himself. Explain how this is done.

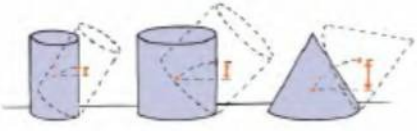
31. Where is the center of mass of Earth's atmosphere?

32. Using the ideas of torque and center of gravity, explain why a ball rolls down a hill.

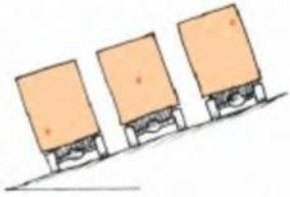
33. Why is it important to secure file cabinets to the floor, especially cabinets with heavy loads in top drawers?

34. How can the three bricks be stacked so that the top brick has maximum horizontal displacement from the bottom brick? For example, stacking them like the dotted lines suggest would be unstable and the bricks would topple. (*Hint:* Start with the top brick and work down. At every interface the CG of the bricks above must not extend beyond the end of the supporting brick.)

35. Describe the comparative stabilities of the three objects shown in terms of work and potential energy.



36. The centers of gravity of the three trucks parked on a hill are shown by the Xs. Which truck(s) will tip over?



37. A long track balanced like a seesaw supports a golf ball and a more massive billiard ball with a compressed spring between the two. When the spring is released, the balls move away from each other. Does the track tip clockwise, tip counterclockwise, or remain in balance as the balls roll outward? What principles do you use for your explanation?

38. When a long-range cannonball is fired toward the equator from a northern (or southern) latitude, it lands west of its "intended" longitude. Why? (*Hint:* Consider a flea jumping from partway out to the outer edge of a rotating turntable.)

39. A racing car on a flat circular track needs friction between the tires and the track to maintain its circular motion. How much more friction is required for twice the speed?

40. Can an object move along a curved path if no force acts on it? Defend your answer.

41. As a car speeds up when rounding a curve, does the centripetal force on the car also increase? Defend your answer.

42. When you are in the front passenger seat of a car turning to the left, you may find yourself pressed against the right-side door. Why do you press against the door? Why does the door press on you? Does your explanation involve a centrifugal force, or Newton's laws?

43. Friction is needed for a car rounding a curve. But, if the road is banked, friction may not be required at all. What, then, supplies the needed centripetal force? (*Hint:* Consider vector components of the normal force on the car.)

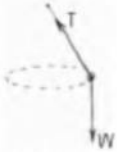
44. Under what conditions could a fast-moving car remain on a banked track covered with slippery ice?

45. Explain why a centripetal force does *not* do work on a circularly moving object.

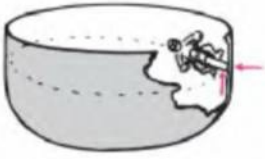
46. The occupant inside a rotating space habitat of the future feels that she is being pulled by artificial gravity against the outer wall of the habitat (which becomes the "floor"). Explain what is going on in terms of Newton's laws and centripetal force.

47. The sketch shows a coin at the edge of a turntable. The weight of the coin is shown by the vector **W**. Two other forces act on the coin—the normal force and a force of friction that prevents it from sliding off the edge. Draw in force vectors for both of these.

48. The sketch shows a conical pendulum. The bob swings in a circular path. The tension **T** and weight **W** are shown by vectors. Draw a parallelogram with these vectors and show that their resultant lies in the plane of the circle. (See the parallelogram rule in Chapter 5.) What is the name of this resultant force?



49. A motorcyclist is able to ride on the vertical wall of a bowl-shaped track as shown. Friction of the wall on the tires is shown by the vertical red vector. (a) How does the magnitude of this vertical vector compare with the weight of the motorcycle and rider? (b) Does the horizontal red vector represent the normal force acting on the bike and rider, the centripetal force, both, or neither? Defend your answer.



50. Consider a ball rolling around in a circular path on the inner surface of a cone. The weight of the ball is shown by the vector **W**. Without friction, only one other force acts on the ball—a normal force. (a) Draw in the vector for the normal force the length of the vector depends on the next step. (b). (b) Using the parallelogram rule, show that the resultant of the two vectors is along the radial direction of the ball's circular path. (Yes, the normal is appreciably larger than the weight!)

51. You sit at the middle of a large turntable at an amusement park as it is set spinning and then allowed to spin freely. When you crawl toward the edge of the turntable, does the rate of the rotation increase, decrease, or remain unchanged? What physics principle supports your answer?

52. A sizable quantity of soil is washed down the Mississippi River and deposited in the Gulf of Mexico each year. What effect does this tend to have on the length of a day? (Hint: Relate this to the previous exercise.)

53. If all of Earth's inhabitants moved to the equator, how would this affect Earth's rotational inertia? How would it affect the length of a day?

54. Strictly speaking, as more and more skyscrapers are built on the surface of Earth, does the day tend to become longer or shorter? And, strictly speaking, does the falling of autumn leaves tend to lengthen or shorten the 24-hour day? What physics principle supports your answers?

55. If the world's populations moved to the North Pole and the South Pole, would the 24-hour day become longer, shorter, or stay the same?

56. If the polar ice caps of Earth were to melt, the oceans would be deeper. Strictly speaking, what effect would this have on Earth's rotation?

57. Why does a typical small helicopter with a single main rotor have a second small rotor on its tail? Describe the consequence if the small rotor fails in flight.

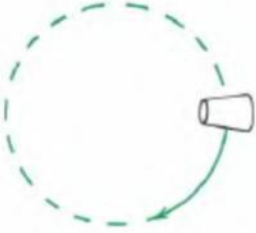
58. A toy train is initially at rest on a track fastened to a bicycle wheel, which is free to rotate. How does the wheel respond when the train moves clockwise? When the train backs up? Does the angular momentum of the wheel–train system change during these maneuvers? How would the resulting motions be affected if the train were much more massive than the track? Or vice versa?

59. We believe that our galaxy was formed from a huge cloud of gas. The original cloud was far larger than the present size of the galaxy, was more or less spherical, and was rotating very much more slowly than the galaxy is now. In this sketch, we see the original cloud and the galaxy as it is now (seen edgewise). Explain how the inward pull of gravity and the conservation of angular momentum contribute to the galaxy's present shape and why it rotates faster now than when it was a larger, spherical cloud.

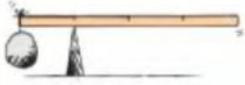
60. Earth is not spherical but bulges at the equator. Jupiter bulges more. What is the cause of these bulges?

PROBLEMS

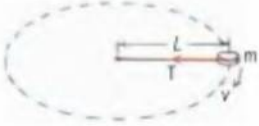
1. The diameter of the base of a tapered drinking cup is 6 cm. The diameter of its mouth is 9 cm. The path of the cup curves when you roll it on the top of a table. Which end, the base or the mouth, rolls faster? How much faster?



2. To tighten a bolt, you push with a force of 80 N at the end of a wrench handle that is 0.25 m from the axis of the bolt. (a) What torque are you exerting? (b) If you move your hand inward to be only 0.10 m from the bolt, to achieve the same torque show that you should exert 200 N of force. (c) Do your answers depend on the direction of your push relative to the direction of the wrench handle?
3. The rock and meterstick balance at the 25-cm mark, as shown. The meterstick has a mass of 1 kg. What must be the mass of the rock?



4. Mary Beth uses a torque feeler that consists of a meterstick held at the 0-cm end with a weight dangling from various positions along the stick (see Figure 8.17). When the stick is held horizontally, torque is produced when a 1-kg mass hangs from the 50-cm mark. How much more torque is exerted when it is hung from the 75-cm mark? The 100-cm mark?
5. An ice puck of mass m revolves on an icy surface in a circle at speed v at the end of a horizontal string of length L. The tension in the string is T.



   a. Write the equation for centripetal force, and substitute the values T and L appropriately. Then with a bit of elementary algebra, rearrange the equation so that it solves for mass.
   b. Show that the mass of the puck is 5 kg when the length of the string is 2 m, string tension is 10 N, and the tangential speed of the puck is 2 m/s.
6. If a trapeze artist rotates once each second while sailing through the air and contracts to reduce her rotational inertia to one-third of what it was, how many rotations per second will result?
• 7. A small space telescope at the end of a tether line of length L moves at linear speed v about a central space station.
   a. What will be the linear speed of the telescope if the length of the line is reduced to 0.33 L?
   b. If the initial linear speed of the telescope is 1.0 m/s, what is its speed when pulled in to one-third its initial distance from the space station?

CHAPTER 8 ONLINE RESOURCES

PhysicsPlace.com

Interactive Figures

- 8.1, 8.2, 8.18, 8.19, 8.20, 8.52

Tutorial

- Rotational Motion

Videos

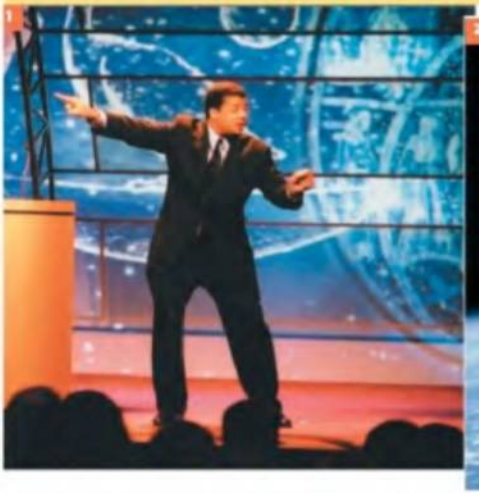
- Rotational Speed
- Rotational Inertia Using Weighted Pipes
- Rotational Inertia Using a Hammer
- Rotational Inertia with a Weighted Rod
- Difference Between Torque and Weight
- Why a Ball Rolls Down a Hill
- Locating the Center of Gravity
- Toppling
- Centripetal Force
- Simulated Gravity
- Conservation of Angular Momentum Using a Rotating Platform

Quizzes

Flashcards

Links

9 Gravity



1 Neil deGrasse Tyson emphasizes the universal nature of gravity in his standing-room-only lectures. 2 Contrary to what most people think, the gravitational force on the spacewalking astronaut is nearly as strong as it is when at Earth's surface. So why doesn't the astronaut fall to Earth? We'll see in the next chapter that the astronaut, like all Earth satellites, continually falls *around* Earth. 3 Tomas Brage uses a classroom model of a Cavendish apparatus to measure *G*.

According to popular legend, Isaac Newton was sitting under an apple tree when the idea struck him that what pulls apples from trees is the same force that keeps the Moon circling Earth. Newton didn't discover gravity, as is commonly thought. What he discovered is that gravity extends beyond Earth—that it is universal. It pulls any corners of planets inward to form spheres, pulls planets toward the Sun, raises ocean tides, and accounts for the shapes of galaxies. However, since he was very shy and sensitive to criticism, Newton put his writings about gravity in a drawer, untouched for some 20 years. As will be soon explained, Newton was prodded by a friend to publish his results.

Once Newton published his findings, he did much more than explain how the Sun pulls on planets and how planets pull on moons, and did much more than solve the mystery of ocean tides. Newton took a giant step further and showed that nature plays by natural rules and operates by natural laws—at a time when rules and laws were decreed by kings and other high officials. Newton's findings went on to show that natural law is neither capricious nor malevolent—nature is indifferent to the human condition. This was an enormous break with established tradition. Knowledge of nature's laws provided hope and inspiration to scientists, writers, artists, philosophers, and people of all walks of life. Newton's way of looking at nature ushered in the Age of Reason. The ideas and insights of Isaac Newton truly changed the world and elevated the human condition.

The Newtonian Synthesis

From the time of Aristotle, the circular motion of heavenly bodies was regarded as natural. The ancients believed that the stars, the planets, and the Moon moved in divine circles. As far as the ancients were concerned, this circular motion required no explanation. Isaac Newton, however, recognized that a force of some kind must act on the planets, whose orbits, he knew, were ellipses; otherwise, their paths would be straight lines. Others of his time, influenced by Aristotle, supposed that any force on a planet would be directed along its path. Newton, however, reasoned that the force on each planet would be directed toward a fixed central point—toward the Sun. This, the force of gravity, was the same force that pulls an apple off a tree. Newton's stroke of intuition, that the force between Earth and an apple is the same force that pulls moons and planets and everything else in our universe, was a revolutionary break with the prevailing notion that there were two sets of natural laws: one for earthly events, and another, altogether different, for motion in the heavens. This union of terrestrial laws and cosmic laws is called the Newtonian synthesis.

FIGURE 9.1
Could the gravitational pull on the apple reach to the Moon?

The Universal Law of Gravity

To test his hypothesis that Earth gravity reaches to the Moon, Newton compared the fall of an apple with the "fall" of the Moon. He realized that the Moon falls in the sense that *it falls away from the straight line it would follow if there were no forces acting on it.* Because of its tangential velocity, it "falls around" the round Earth (more about this in the next chapter). By simple geometry, the Moon's distance of fall per second could be compared with the distance that an apple or anything that far away would fall in 1 second. Newton's calculations didn't check. Disappointed, but recognizing that brute fact must always win over a beautiful hypothesis, he placed his papers in a drawer, where, as mentioned earlier, they remained for nearly 20 years. During this period, he founded and developed the field of optics, for which he first became famous.

The tangential velocity of a planet or moon moving in a circle is at right angles to the force of gravity.

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Tutorial
Motion and Gravity

Newton's interest in mechanics was rekindled with the advent of a spectacular comet in 1680 and another 2 years later. He returned to the Moon problem at the prodding of his astronomer friend Edmund Halley, for whom the second comet was later named. He made corrections in the experimental data used in his earlier method and obtained excellent results. Only then did he publish what is one of the most far-reaching generalizations of the human mind: the **law of universal gravitation.**[1]

Everything pulls on everything else in a beautifully simple way that involves only mass and distance. According to Newton, every body attracts every other body with a force that, for any two bodies, is directly proportional to the product of their masses and inversely proportional to the square of the distance separating them. This statement can be expressed as

$$\text{Force} \sim \frac{\text{mass}_1 \times \text{mass}_2}{\text{distance}^2}$$

[1]This is a dramatic example of the painstaking effort and cross-checking that go into the formulation of a scientific theory. Contrast Newton's approach with the failure to "do one's homework," the hasty judgments, and the absence of cross-checking that so often characterize the pronouncements of people advocating less-than-scientific theories.

FIGURE 9.2
The tangential velocity of the Moon about Earth allows it to fall around Earth rather than directly into it. If this tangential velocity were reduced to zero, what would be the fate of the Moon?

Expressed in symbol shorthand,

$$F \sim \frac{m_1 m_2}{d^2}$$

where m_1 and m_2 are the masses of the bodies and d is the distance between their centers. Thus, the greater the masses m_1 and m_1, the greater the force of attraction between them, in direct proportion to the masses.[2] The greater the distance of separation d, the weaker the force of attraction, in inverse proportion to the square of the distance between their centers of mass.

CHECK POINT

1. In Figure 9.2, we see that the Moon falls around Earth rather than straight into it. If the Moon's tangential velocity were zero, how would it move?
2. According to the equation for gravitational force, what happens to the force between two bodies if the mass of one of the bodies is doubled? If both masses are doubled?
3. Gravitational force acts on all bodies in proportion to their masses. Why, then, doesn't a heavy body fall faster than a light body?

Check Your Answers

1. If the Moon's tangential velocity were zero, it would fall straight down and crash into Earth!
2. When one mass is doubled, the force between it and the other one doubles. If both masses double, the force is 4 times as much.
3. The answer goes back to Chapter 4. Recall Figure 4.12, in which heavy and light bricks fall with the same acceleration because both have the same ratio of weight to mass. Newton's second law ($a = F/m$) reminds us that greater force acting on greater mass does not result in greater acceleration.

The Universal Gravitational Constant, *G*

The proportionality form of the universal law of gravitation can be expressed as an exact equation when the constant of proportionality G is introduced. G is called the *universal gravitational constant*. Then the equation is

$$F = G\frac{m_1 m_2}{d^2}$$

The units of G make the force come out in newtons. The magnitude of G is the same as the gravitational force between two 1-kilogram masses that are 1 meter apart: 0.0000000000667 newton.

$$G = 6.67 \times 10^{-11}\ \mathrm{N \cdot m^2/kg^2}$$

This is an extremely small number.[3] It shows that gravity is a very weak force compared with electrical forces. The large net gravitational force we feel as weight is because of the enormity of atoms in planet Earth that are pulling on us.

FIGURE 9.3
As the rocket gets farther from Earth, gravitational strength between the rocket and Earth decreases.

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Video
Von Jolly's Method of Measuring the Attraction Between Two Masses

[2]Note the different role of mass here. Thus far, we have treated mass as a measure of inertia, which is called *inertial mass*. Now we see mass as a measure of gravitational force, which in this context is called *gravitational mass*. It is experimentally established that the two are equal, and, as a matter of principle, the equivalence of inertial and gravitational mass is the foundation of Einstein's general theory of relativity.
[3]The numerical value of G depends entirely on the units of measurement we choose for mass, distance, and time. The international system of choice is: for mass, the kilogram; for distance, the meter; and for time, the second. Scientific notation is discussed in Appendix A at the end of this book.

Interestingly, Newton could calculate the product of G and Earth's mass, but not either one alone. Calculating G alone was first done by the English physicist Henry Cavendish in 1798, a century after Newton's time.

Cavendish measured G by measuring the tiny force between lead masses with an extremely sensitive torsion balance, as Professor Brage shows in the opening photo at the beginning of this chapter. A simpler method was later developed by Philipp von Jolly, who attached a spherical flask of mercury to one arm of a sensitive balance (Figure 9.4). After the balance was put in equilibrium, a 6-ton lead sphere was rolled beneath the mercury flask. The gravitational force between the two masses was measured by the weight needed on the opposite end of the balance to restore equilibrium. All the quantities, m_1, m_2, F, and d, were known, from which the constant G was calculated:

$$G = \frac{F}{\left(\frac{m_1 m_2}{d^2}\right)} = 6.67 \times 10^{-11}\ \mathrm{N/kg^2/m^2} = 6.67 \times 10^{-11}\ \mathrm{N \cdot m^2/kg^2}$$

Just as sheet music guides a musician playing music, equations guide a physics student to understand how concepts are connected.

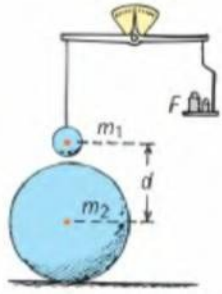

FIGURE 9.4

Jolly's method of measuring G. Balls of mass m_1 and m_2 attract each other with a force F provided by the weights needed to restore balance.

The value of G shows that gravity is the weakest of the presently known four fundamental forces. (The other three are the electromagnetic force and two kinds of nuclear forces.) We sense gravitation only when masses like that of Earth are involved. If you stand on a large ship, the force of attraction between you and the ship is too weak for ordinary measurement. The force of attraction between you and Earth, however, can be measured. It is your weight. Your weight depends not only on your mass but also on your distance from the center of Earth. At the top of a mountain, your mass is the same as it is anywhere else, but your weight is slightly less than it is at ground level. That's because your distance from Earth's center is greater.

Once the value of G was known, the mass of Earth was easily calculated. The force that Earth exerts on a mass of 1 kg at its surface is 10 N (more precisely, 9.8 N). The distance between the 1-kg mass and the center of Earth is Earth's radius, 6.4×10^6 m. Therefore, from $F = G\frac{m_1 m_2}{d^2}$, where m_1 is the mass of Earth,

$$9.8\ \mathrm{N} = 6.67 \times 10^{-11}\mathrm{N \cdot m^2/kg^2}\ \frac{1\ \mathrm{kg} \times m_1}{(6.4 \times 10^6\mathrm{m})^2}$$

which leads to $m_1 = 6 \times 10^{24}$ kg.

In the 18th century, when G was first measured, people all over the world were excited about it. That's because newspapers everywhere announced the discovery as one that measured the mass of the planet Earth. How exciting that Newton's formula gives the mass of the entire planet, with all its oceans, mountains, and inner parts yet to be discovered. G and the mass of Earth were measured when a great portion of Earth's surface was still undiscovered.

Just as π relates circumference and diameter for circles, G relates gravitational force to mass and distance.

CHECK POINT

If there is an attractive force between all objects, why do we not feel ourselves gravitating toward massive buildings in our vicinity?

Check Your Answer

Gravity certainly does pull us to massive buildings and everything else in the universe. The forces between buildings and us are relatively small because their masses are small compared with the mass of Earth. The forces due to the stars are extremely tiny because of their great distances from us. These tiny forces escape our notice when they are overwhelmed by the overpowering attraction to Earth. Physicist Paul A. M. Dirac, 1933 Nobel Prize recipient, put it this way: "Pick a flower on Earth and you move the farthest star!"

You can never change only one thing! Every equation reminds us of this—you can't change a term on one side without affecting the other side.

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Video
Inverse-Square Law

Gravity and Distance: The Inverse-Square Law

We can better understand how gravity weakens with distance by considering how paint from a paint gun spreads with increasing distance (Figure 9.5). Suppose we position a paint gun at the center of a sphere with a radius of 1 meter, and a burst of paint spray travels 1 m to produce a square patch of paint that is 1 mm thick. How thick would the patch be if the experiment were done in a sphere with twice the radius? If the same amount of paint travels in straight lines for 2 m, it will spread to a patch twice as tall and twice as wide. The paint would then be spread over an area 4 times as big, and its thickness would be only 1/4 mm.

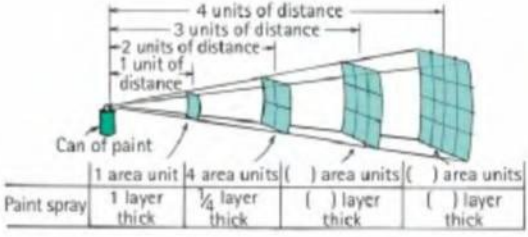

FIGURE 9.5
The inverse-square law. Paint spray travels radially away from the nozzle of the can in straight lines. Like gravity, the "strength" of the spray obeys the inverse-square law.

Can you see from the figure that, for a sphere of radius 3 m, the thickness of the paint patch would be only 1/9 mm? Can you see the thickness of the paint decreases as the square of the distance increases? This is known as the **inverse-square law.** The inverse-square law holds for gravity and for all phenomena wherein the effect from a localized source spreads uniformly throughout the surrounding space: the electric field about an isolated electron, light from a match, radiation from a piece of uranium, and sound from a cricket.

Newton's law of gravity as written applies to particles and spherical bodies, as well as to nonspherical bodies sufficiently far apart. The distance term d in Newton's equation is the distance between the centers of masses of the objects. Note in Figure 9.6 that the apple that normally weighs 1 N at Earth's surface weighs only 1/4 as much when it is twice the distance from Earth's center. The greater the distance

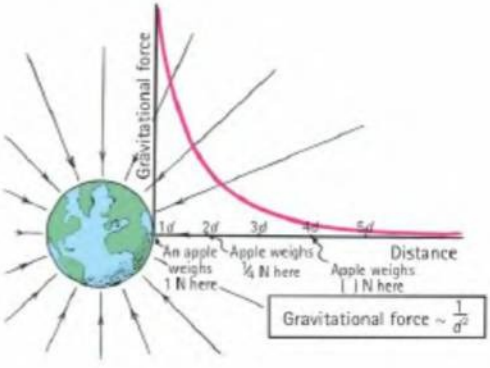

FIGURE 9.6
INTERACTIVE FIGURE
If an apple weighs 1 N at Earth's surface, it would weigh only 1/4 N twice as far from the center of Earth. At 3 times the distance, it would weigh only 1/9 N. Gravitational force versus distance is plotted in color. What would the apple weigh at 4 times the distance? Five times the distance?

from Earth's center, the less the weight of an object. A child who weighs 300 N at sea level will weigh only 299 N atop Mt. Everest. For greater distances, force is less. For very great distances, Earth's gravitational force approaches zero. The force *approaches* zero, but never reaches zero. Even if you were transported to the far reaches of the universe, the gravitational field of home would still be with you. It may be overwhelmed by the gravitational fields of nearer and/or more massive bodies, but it is there. The gravitational field of every material object, however small or however far, extends through all of space.

FIGURE 9.7
According to Newton's equation, her weight (not her mass) decreases as she increases her distance from Earth's center.

CHECK POINT

1. By how much does the gravitational force between two objects decrease when the distance between their centers is doubled? Tripled? Increased tenfold?
2. Consider an apple at the top of a tree that is pulled by Earth's gravity with a force of 1 N. If the tree were twice as tall, would the force of gravity be 1/4 as strong? Defend your answer.

Check Your Answers

1. It decreases to 1/4, 1/9, and 1/100 the original value.
2. No, because an apple at the top of the twice-as-tall apple tree is not twice as far from Earth's center. The taller tree would need a height equal to the Earth's radius (6,370 km) for the apple's weight at its top to reduce to 1/4 N. Before its weight decreases by 1%, an apple or any object must be raised 32 km—nearly 4 times the height of Mt. Everest. So, as a practical matter, we disregard the effects of everyday changes in elevation.

Weight and Weightlessness

The force of gravity, like any force, can produce acceleration. Objects under the influence of gravity accelerate toward each other. Because we are almost always in contact with Earth, we think of gravity as something that presses us against Earth rather than as something that accelerates us. The pressing against Earth is the sensation we interpret as **weight.**

Stand on a bathroom scale that is supported on a stationary floor. The gravitational force between you and Earth pulls you against the supporting floor and the scale. By Newton's third law, at the same time, the floor and scale push upward on you. Located in between you and the supporting floor are springs inside the bathroom scale. Compression of the springs is read as your weight. If you repeat this weighing procedure in a moving elevator, your weight reading would vary—not during steady motion, but during accelerated motion. If the elevator accelerates upward, the bathroom scale and floor push harder against your feet. So the springs inside the scale are compressed even more. The scale shows an increase in your weight. If the elevator accelerates downward, you sense a decrease in your weight.

In Chapters 2 and 4, we treated the weight of an object as the force due to gravity upon it. When in equilibrium on a firm surface, weight is evidenced by a support force, or, when in suspension, by a supporting rope tension. In either case, with no acceleration, weight equals mg. Then, when we discussed rotating environments in Chapter 8, we learned that a support force can occur without regard to gravity. So a broader definition of the weight of something is the force it exerts against a supporting floor or a weighing scale. According to this definition, you are as heavy as

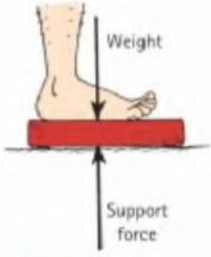

FIGURE 9.8
When you step on a weighing scale, two forces act on it: a downward force of gravity, mg, and an upward support force. These two forces are equal and opposite when no acceleration occurs, and they squeeze a spring-like device inside the scale that is calibrated to show your weight.

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Videos
Apparent Weightlessness
Weight and Weightlessness

Astronauts inside an orbiting space vehicle have no weight, even though the force of gravity between them and Earth is only slightly less than at ground level.

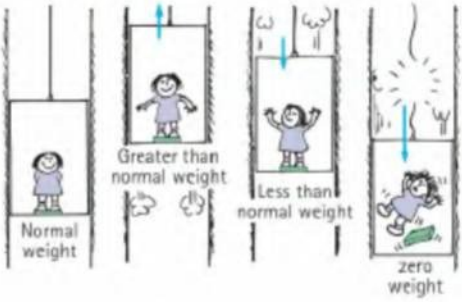

FIGURE 9.9

INTERACTIVE FIGURE

Your weight equals the force with which you press against the supporting floor. If the floor accelerates up or down, your weight varies (even though the gravitational force mg that acts on you remains the same).

FIGURE 9.10

These astronauts are in free fall. They feel weightless because they aren't pressed against anything that would provide a support force.

you feel; so, in an elevator that accelerates downward, the supporting force of the floor is less and you weigh less. If the elevator is in free fall, the reading on a weighing scale would be zero. According to the reading, you would be **weightless** (Figure 9.9). Even in this weightless condition, however, there is still a gravitational force acting on you, causing your downward acceleration. But gravity now is not felt as weight because there is no support force.

Astronauts in orbit are without a support force. They are in a sustained state of *weightlessness*, which isn't the absence of gravity, but the absence of a support force. Astronauts sometimes experience "space sickness" until they become accustomed to a state of sustained weightlessness. Astronauts in orbit are in a state of continual free fall.

The International Space Station in Figure 9.12 provides a weightless environment. The station facility and astronauts all accelerate equally toward Earth, at somewhat less than 1 g because of their altitude. This acceleration is not sensed at all; with respect to the station, the astronauts experience 0 g. Over extended periods of time, this causes loss of muscle strength and other detrimental changes in the body. Future space travelers, however, need not be subjected to weightlessness. As mentioned in the previous chapter, lazily rotating giant wheels or pods at the

FIGURE 9.11

Both are weightless.

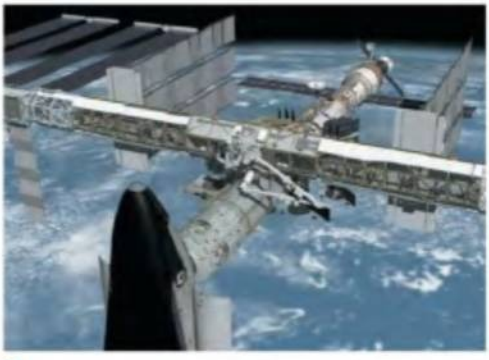

FIGURE 9.12

The inhabitants in this laboratory and docking facility continually experience weightlessness. They are in free fall around Earth. Does a force of gravity act on them?

end of a tether will likely take the place of today's nonrotating space habitats. Rotation effectively supplies a support force and nicely provides weight.

CHECK POINT

In what sense is drifting in space far away from all celestial bodies like stepping down off a stepladder?

Check Your Answer

In both cases, you'd experience weightlessness. Drifting in deep space, you would remain weightless because no discernable force acts on you. Stepping from a stepladder, you would be only momentarily weightless because of a momentary lapse of support force.

Ocean Tides

Seafaring people have always known that there is a connection between the ocean tides and the Moon, but no one could offer a satisfactory theory to explain the two high tides per day. Newton produced the explanation: Ocean tides are caused by *differences* in the gravitational pull between the Moon and Earth on opposite sides of Earth. Gravitational force between the Moon and Earth is stronger on the side of Earth nearer to the Moon, and it is weaker on the side of Earth that is farther from the Moon. This is simply because the gravitational force is weaker with increased distance.

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Tutorial
Tides

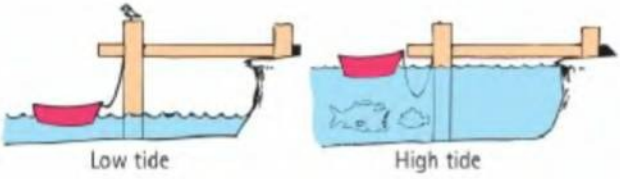

FIGURE 9.13
Ocean tides.

To understand why these different pulls produce tides, let's look at a ball of Jell-O (Figure 9.14). If you exerted the same force on every part of the ball, the ball would remain perfectly round as it accelerated. But if you pull harder on one side than the other, the different pulls would stretch the ball. That's what's happening to this big ball on which we live. Different pulls of the Moon stretch Earth, most notably in its oceans. This stretch is evident in ocean bulges on opposite sides of

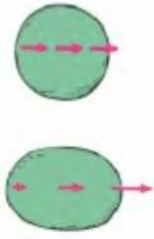

FIGURE 9.14
A ball of Jell-O stays spherical when all parts are pulled equally in the same direction. When one side is pulled more than the other, it is elongated.

FIGURE 9.15
The two tidal bulges produced by differences in gravitational pulls remain relatively fixed relative to the Moon, while Earth spins daily beneath them.

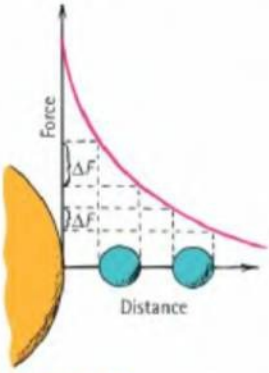

FIGURE 9.16

A plot of gravitational force versus distance (not to scale). The greater the distance from the Sun, the smaller the force F, which varies as $1/d^2$, and the smaller the difference in gravitational pulls on opposite sides of a planet, ΔF.

Earth. Hence we experience two sets of ocean tides per day—two high tides and two low tides.

On a world average, the ocean bulges are nearly 1 m above the average surface level of the ocean. Earth spins once per day, so a fixed point on Earth passes beneath both of these bulges each day. This produces two sets of ocean tides per day. Any part of Earth that passes beneath one of the bulges has a high tide. When Earth has made a quarter turn 6 hours later, the water level at the same part of the ocean is nearly 1 m below the average sea level. This is low tide. The water that "isn't there" is under the bulges that make up the high tides. A second high tidal bulge is experienced when Earth makes another quarter turn. So we have two high tides and two low tides daily. Interestingly, while Earth spins, the Moon moves in its orbit and appears at the same position in our sky every 24 hours and 50 minutes, so the two-high-tide cycle is actually at 24-hour-and-50-minute intervals. That is why tides do not occur at the same time every day.

The Sun also contributes to ocean tides, but it's about half as effective as the Moon. Interestingly, the Sun pulls 180 times as hard on Earth as on the Moon. Why aren't tides due to the Sun 180 times as large as tides due to the Moon? Because of the Sun's great distance, the *difference* in gravitational pulls on opposite sides of Earth is very small. In other words, the Sun pulls almost as hard on the far side of Earth as it does on the near side. You'll understand tides more when you tackle "Ocean Tides" in the *Conceptual Physics Practice Book*.[4]

When the Sun, Earth, and Moon are aligned, the tides due to the Sun and the Moon coincide. Then we have higher-than-average high tides and lower-than-average low tides. These are called **spring tides** (Figure 9.17). (Spring tides have

FIGURE 9.17

When the attractions of the Sun and the Moon are lined up with each other, spring tides occur.

nothing to do with the spring season.) You can tell when the Sun, Earth, and Moon are aligned by the full Moon or by the new Moon. When the Moon is full, Earth is between the Sun and Moon. (If all three are *exactly* in line, then we have a lunar eclipse, for the full Moon passes into Earth's shadow.) A new Moon occurs when the Moon is between the Sun and Earth, when the nonilluminated hemisphere of the Moon faces Earth. (When this alignment is perfect, the Moon blocks the Sun and we have a solar eclipse.) Spring tides occur at the times of a new or full Moon.

All spring tides are not equally high because Earth–Moon and Earth–Sun distances vary; the orbital paths of Earth and the Moon are elliptical rather than circular. The Moon's distance from Earth varies by about 10% and its effect in raising tides varies by about 30%. Highest spring tides occur when the Moon and Sun are closest to Earth.

When the Moon is halfway between a new Moon and a full Moon, in either direction (Figure 9.18), the tides due to the Sun and the Moon partly cancel each other. Then, the high tides are lower than average and the low tides are not as low as average low tides. These are called **neap tides.**

FIGURE 9.18

When the attractions of the Sun and the Moon are about 90° apart (at the time of a half Moon), neap tides occur.

[4]Newton deduced that *differences* in tidal pulls decrease as the *cube* of the distance between the centers of the bodies. Hence, only relatively close distances result in appreciable tides.

Another factor that affects the tides is the tilt of Earth's axis (Figure 9.19). Even though the opposite tidal bulges are equal, Earth's tilt causes the two daily high tides experienced in most parts of the ocean to be unequal most of the time.

Tides don't occur in ponds because no part of the pond is significantly closer to the Moon or Sun than any other part. With no differences in pulls, no tides are produced. Similarly for the fluids in your body; any tides in your body fluids that are caused by the Moon are negligible. You're not tall enough for tides. What microtides the Moon may produce in your body are only about one two-hundredth the tides produced by a 1-kg melon held 1 m above your head (Figure 9.20).

Our treatment of tides is quite simplified here, for tides are actually more complicated. Interfering land masses and friction with the ocean floor, for example, complicate tidal motions. In many places, the tides break up into smaller "basins of circulation," where a tidal bulge travels like a circulating wave that moves around in a small basin of water that is tilted. For this reason, the high tide may be hours away from an overhead Moon. In mid-ocean, where the range between high and low tide is usually about a meter, variations in range occur in different parts of the world. The range is greatest in some Alaskan fjords and is most notable in the basin of the Bay of Fundy, between New Brunswick and Nova Scotia in eastern Canada, where tidal differences sometimes exceed 15 m. This is largely due to the ocean floor, which funnels shoreward in a V-shape. The tide often comes in faster than a person can run. Don't dig clams near the water's edge at low tide in the Bay of Fundy!

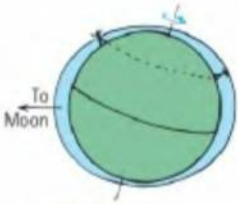

FIGURE 9.19
The inequality of the two high tides per day. Because of Earth's tilt, a person may find the tide nearest the Moon much lower (or higher) than the tide half a day later. Inequalities of tides vary with the positions of the Moon and the Sun.

FIGURE 9.20
The tidal force difference due to a 1-kg body 1 m over the head of an average height person is about 60 trillionths (6×10^{-11}) N/kg. For an overhead Moon, it is about 0.3 trillionth (3×10^{-13}) N/kg. So holding a melon over your head produces about 200 times as much tidal effect in your body as the Moon does.

CHECK POINT

We know that both the Moon and the Sun produce our ocean tides. And we know the Moon plays the greater role because it is closer. Does its closeness mean that it pulls on Earth's oceans with more gravitational force than the Sun?

Check Your Answer

No, the Sun's pull is much stronger. But the *difference* in lunar pulls is more than the *difference* in solar pulls. So our tides are due primarily to the Moon.

TIDES IN EARTH AND ATMOSPHERE

Earth is not a rigid solid but, for the most part, is a semimolten liquid covered by a thin, solid, and pliable crust. As a result, the Moon–Sun tidal forces produce Earth tides as well as ocean tides. Twice each day, the solid surface of Earth rises and falls as much as 1/4 m! As a result, earthquakes and volcanic eruptions have a slightly higher probability of occurring when Earth is experiencing an Earth spring tide—that is, near a full or new Moon.

We live at the bottom of an ocean of air that also experiences tides. Being at the bottom of the atmosphere, we don't notice these tides (just as creatures in deep water likely don't notice ocean tides). In the upper part of the atmosphere is the ionosphere, so named because it contains many ions—electrically charged atoms that are the result of ultraviolet light and intense cosmic ray bombardment. Tidal effects in the ionosphere produce electric currents that alter the magnetic field that surrounds Earth. These are magnetic tides. They, in turn, regulate the degree to which cosmic rays penetrate into the lower atmosphere. The cosmic-ray penetration is evident in subtle changes in the behaviors of living things. The highs and lows of magnetic tides are greatest when the atmosphere is having its spring tides—again, near the full and new Moon.

In addition to ocean tides, the Moon and Sun make atmospheric tides—highest then lowest during a full Moon. Does this explain why some of your friends are weird when the Moon is full?

TIDAL BULGES ON THE MOON

There are two tidal bulges on the Moon for the same reason there are two tidal bulges on Earth—the near and far sides of each body are pulled differently. So the

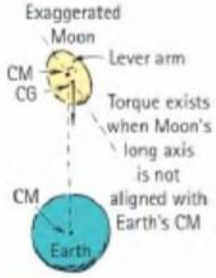

FIGURE 9.21

Earth's pull on the Moon at its center of gravity produces a torque about the Moon's center of mass, which tends to rotate the long axis of the Moon into alignment with Earth's gravitational field (like a compass needle that aligns with a magnetic field). That's why only one side of the Moon faces Earth.

Moon is pulled slightly away from a spherical shape into a football shape, with its long axis pointing toward Earth. But unlike Earth's tides, the tidal bulges remain in fixed locations, with no "daily" rising and falling of Moon tides. Since the Moon takes 27.3 days to make a single revolution about its own axis (and also about the Earth–Moon axis), the same lunar hemisphere faces Earth all the time. This is not a coincidence; it occurs because the elongated Moon's center of gravity is slightly displaced from its center of mass. So whenever the Moon's long axis is not lined up toward Earth (Figure 9.21), Earth exerts a small torque on the Moon. This tends to twist the Moon toward aligning with Earth's gravitational field, like the torque that aligns a compass needle with a magnetic field. So we see there is a reason why the Moon always shows us its same face.

Interestingly enough, this "tidal lock" is also working on Earth. Our days are getting longer at the rate of 2 milliseconds per century. In a few billion years, our day will be as long as a month, and Earth will always show the same face to the Moon. How about that!

Gravitational Fields

Earth and the Moon pull on each other. This is *action at a distance,* because Earth and Moon interact with each other without being in contact. We can look at this in a different way: We can regard the Moon as being in contact and interacting with the *gravitational field* of Earth. The properties of the space surrounding any massive body can be looked at as altered in such a way that another massive body in this region experiences a force. This alteration of space is a **gravitational field.** It is common to think of rockets and distant space probes being influenced by the gravitational field at their locations in space, rather than by Earth and other planets or stars. The field concept plays an in-between role in our thinking about the forces between different masses.

A gravitational field is an example of a *force field,* for any body with mass experiences a force in the field. Another force field, perhaps more familiar, is a magnetic field. Have you ever seen iron filings lined up in patterns around a magnet? (Look ahead to Figure 24.2 on page 427, for example.) The pattern of the filings shows the strength and direction of the magnetic field at different points in the space around the magnet. Where the filings are closest together, the field is strongest. The direction of the filings shows the direction of the field at each point.

FIGURE 9.22

Field lines represent the gravitational field about Earth. Where the field lines are closer together, the field is stronger. Farther away, where the field lines are farther apart, the field is weaker.

The pattern of Earth's gravitational field can be represented by field lines (Figure 9.22). Like the iron filings around a magnet, the field lines are closer together where the gravitational field is stronger. At each point on a field line, the direction of the field is along the line. Arrows show the field direction. A particle, astronaut, spaceship, or any body in the vicinity of Earth will be accelerated in the direction of the field line at that location.

The strength of Earth's gravitational field, like the strength of its force on objects, follows the inverse-square law. It is strongest near Earth's surface and weakens with increasing distance from Earth.[5]

The gravitational field at Earth's surface varies slightly from location to location. Above large subterranean lead deposits, for example, the field is slightly stronger than average. Above large caverns, the field is slightly weaker. To predict what lies beneath Earth's surface, geologists and prospectors of oil and minerals make precise measurements of Earth's gravitational field.

[5]The strength of the gravitational field g at any point is equal to the force F per unit of mass placed there. So $g = F/m$, and its units are newtons per kilogram (N/kg). The field g also equals the free-fall acceleration of gravity. The units N/kg and m/s^2 are equivalent.

GRAVITATIONAL FIELD INSIDE A PLANET[6]

The gravitational field of Earth exists inside Earth as well as outside. Imagine a hole drilled completely through Earth from the North Pole to the South Pole. Forget about impracticalities, such as the high-temperature molten interior, and consider the motion you would undergo if you fell into such a hole. If you started at the North Pole end, you'd fall and gain speed all the way down to the center, then lose speed all the way "up" to the South Pole. Without air drag, the one-way trip would take nearly 45 minutes. If you failed to grab the edge of the hole when you reached the South Pole, you'd fall back toward the center, and return to the North Pole in the same time.

Your acceleration, a, will be progressively less as you continue toward the center of Earth. Why? Because, as you fall toward Earth's center, there is less mass pulling you toward the center. When you are at the center of Earth, the pull down is balanced by the pull up, so the net force on you as you whiz with maximum speed past Earth's center is zero. That's right: you'd have maximum velocity and minimum acceleration at Earth's center! The gravitational field of Earth at its center is zero![7]

The composition of Earth varies, being most dense at its core and least dense at the surface. Inside a hypothetical planet of uniform density, however, the field inside increases linearly—that is, at a steady rate—from zero at its center to g at the surface. We won't go into why this is so, but perhaps your instructor will provide the explanation. In any event, a plot of the gravitational field intensity inside and outside a solid planet of uniform density is shown in Figure 9.24.

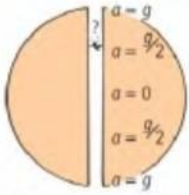

FIGURE 9.23
As you fall faster and faster in a hole bored completely through Earth, your acceleration decreases because the part of Earth's mass beneath you becomes smaller and smaller. Less mass means less attraction until, at the center, where you are pulled equally in all directions, the net force is zero and acceleration is zero. Momentum carries you past the center and against a growing acceleration to the opposite end of the tunnel, where acceleration is again g, directed back toward the center.

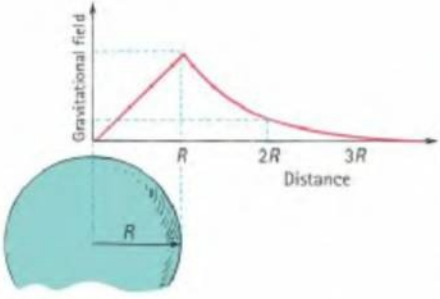

FIGURE 9.24
The gravitational field intensity inside a planet of uniform density is directly proportional to the radial distance from its center and is maximum at its surface. Outside, it is inversely proportional to the square of the distance from its center.

Imagine a spherical cavern at the center of a planet. The cavern would be gravity-free because of the cancellation of gravitational forces in every direction. Amazingly, the size of the cavern doesn't change this fact—even if it constitutes most of the volume of the planet! A hollow planet, like a huge basketball, would have no gravitational field anywhere inside it. Complete cancellation of gravitational forces occurs everywhere inside. To see why, consider the particle P in Figure 9.25, which is twice as far from the left side of the planet as it is from the right side. If gravity depended only on distance, P would be attracted only 1/4 as much to the left side as to the right side (according to the inverse-square law). But gravity also depends on mass. Imagine a cone reaching to the left from P to encompass region A in the figure, and an equal-angle cone reaching to the right encompassing region B. Region A has 4 times the area and therefore 4 times the mass of region B. Since 1/4 of 4 is equal to 1,

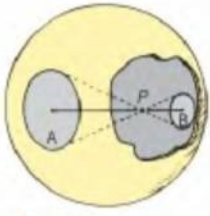

FIGURE 9.25
The gravitational field anywhere inside a spherical shell of uniform thickness and composition is zero, because the field components from all the particles of mass in the shell cancel one another. A mass at point P, for example, is attracted just as much to the larger but farther region A as it is to the smaller but closer region B.

[6]This section may be skipped for a brief treatment of gravitational fields.

[7]Interestingly enough, during the first few kilometers beneath Earth's surface, you'd actually gain acceleration because the density of the compact center is much greater than the density of the surface material. So gravity would be slightly stronger during the first part of a fall. Farther in, gravitation would decrease and would diminish to zero at Earth's center.

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Gravitational Field Inside a Hollow Planet
The Weight of an Object Inside a Hollow Planet but Not at Its Center

P is attracted to the farther but more massive region A with just as much force as it is to the closer but less massive region B. Cancellation occurs. More thought will show that cancellation will occur anywhere inside a planetary shell having uniform density and thickness. A gravitational field would exist within and beyond the shell. At its outer surface and in the space beyond the gravitational field would be the same as if all the mass of the planet were concentrated at its center. Everywhere inside the hollow part, the gravitational field is zero. Anyone inside would be weightless. I call this "yum-yum" physics!

CHECK POINT

1. Suppose you stepped into a hole bored clear through the center of Earth and made no attempt to grab the edges at either end. Neglecting air drag, what kind of motion would you experience?
2. Halfway to the center of Earth, would the force of gravity on you be less than at the surface of Earth?

Check Your Answers

1. You would oscillate back and forth. If Earth were an ideal sphere of uniform density and there were no air drag, your oscillation would be what is called *simple harmonic motion*. Each round-trip would take nearly 90 minutes. Interestingly, we will see in the next chapter that an Earth satellite in close orbit about Earth also takes the same 90 minutes to make a complete round-trip. (This is no coincidence: If you study physics further, you'll learn that "back-and-forth" simple harmonic motion is simply the vertical component of uniform circular motion—interesting stuff.)
2. Gravitational force on you would be less, because there is less mass of Earth below you, which pulls you with less force. If Earth were a uniform sphere of uniform density, gravitational force halfway to the center would be exactly half that at the surface. But since Earth's core is so dense (about 7 times the density of surface rock), gravitational force halfway down would be somewhat more than half. Exactly how much depends on how Earth's density varies with depth, which is information that is unknown today.

Neil deGrasse Tyson nicely describes a falling-through-Earth scenario on *NOVA*.

Although gravity can be canceled inside a body or between bodies, it cannot be shielded in the same way that electric forces can. In Chapter 22, we will see that electric forces can repel as well as attract, which makes shielding possible. Since gravitation only attracts, a similar kind of shielding cannot occur. Eclipses provide convincing evidence for this. The Moon is in the gravitational field of both the Sun and Earth. During a lunar eclipse, Earth is directly between the Moon and the Sun, and any shielding of the Sun's field by Earth would result in a deviation of the Moon's orbit. Even a very slight shielding effect would accumulate over a period of years and show itself in the timing of subsequent eclipses. But there have been no such discrepancies; past and future eclipses are calculated to a high degree of accuracy using only the simple law of gravitation. No shielding effect in gravitation has ever been found.

Einstein's Theory of Gravitation

In the early part of the 20th century, a model for gravity quite unlike Newton's was presented by Einstein in his general theory of relativity. Einstein perceived a gravitational field as a geometrical warping of 4-dimensional space and time; he realized that bodies put dents in space and time somewhat like a massive ball

placed in the middle of a large waterbed dents the 2-dimensional surface (Figure 9.26). The more massive the ball, the greater the dent or warp. If we roll a marble across the top of the bed but well away from the ball, the marble will roll in a straight-line path. But if we roll the marble near the ball, it will curve as it rolls across the indented surface of the waterbed. If the curve closes on itself, the marble will orbit the ball in either an oval or a circular path. If you put on your Newtonian glasses, so that you see the ball and marble but not the bed, you might conclude that the marble curves because it is attracted to the ball. If you put on your Einsteinian glasses, so that you see the marble and the indented waterbed but not the "distant" ball, you would likely conclude that the marble curves because the surface on which it moves is curved—in 2 dimensions for the waterbed and in 4 dimensions for space and time.[8] In Chapter 36, we will treat Einstein's theory of gravitation in more detail.

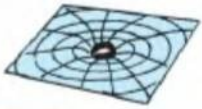

FIGURE 9.26

Warped space-time. Space-time near a star is curved in 4 dimensions in a way similar to the 2-dimensional surface of a waterbed when a heavy ball rests on it.

Black Holes

Suppose you were indestructible and could travel in a spaceship to the surface of a star. Your weight on the star would depend both on your mass and the star's mass and on the distance between the star's center and your belly button. If the star were to burn out and collapse to half its radius with no change in its mass, your weight at its surface, determined by the inverse-square law, would be 4 times as much (Figure 9.27). If the star were to collapse to a tenth of its radius, your weight at its surface would be 100 times as much. If the star kept shrinking, the gravitational field at the surface would become stronger. It would be more and more difficult for a starship to leave. The velocity required to escape, the *escape velocity*, would increase. If a star such as our Sun collapsed to a radius of less than 3 km, the escape velocity from its surface would exceed the speed of light, and nothing—not even light—could escape! The Sun would be invisible. It would be a **black hole.**

fyi

- Contrary to stories about black holes, they're nonaggressive and don't reach out and swallow innocents at a distance. Their gravitational fields are no stronger than the original fields about the stars before collapse—except at distances smaller than the original star radius. Except when they are too close, black holes shouldn't worry future astronauts.

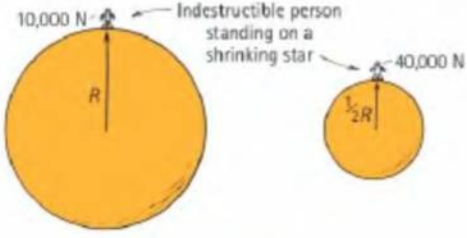

FIGURE 9.27

If a star collapses to half its radius and there is no change in its mass, gravitation at its surface is multiplied by 4.

The Sun, in fact, has too little mass to experience such a collapse, but when some stars with greater mass—now estimated to be at least 1.5 solar masses or more—reach the end of their nuclear resources, they undergo collapse and, unless rotation is high enough, the collapse continues until the stars reach infinite densities. Gravitation near these shrunken stars is so enormous that light cannot escape from their vicinity. They have crushed themselves out of visible existence. The results are black holes, which are completely invisible.

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Tutorial
Black Holes

[8]Don't be discouraged if you cannot visualize 4-dimensional space-time. Einstein himself often told his friends, "Don't try. I can't do it either." Perhaps we are not too different from the great thinkers around Galileo who couldn't visualize a moving Earth!

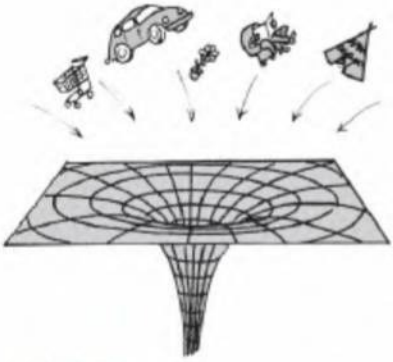

FIGURE 9.28

Anything that falls into a black hole is crushed out of existence. Only mass, angular momentum, and electric charge are retained by the black hole.

A black hole is no more massive than the star from which it collapsed, so the gravitational field in regions at and greater than the original star's radius is no different after the star's collapse than before. But, at closer distances near the vicinity of a black hole, the gravitational field can be enormous—a surrounding warp into which anything that passes too close—light, dust, or a spaceship—is drawn. Astronauts could enter the fringes of this warp and, if they were in a powerful spaceship, they could still escape. After a certain distance, however, they could not, and they would disappear from the observable universe. Any object falling into a black hole would be torn to pieces. No feature of the object would survive except its mass, its angular momentum (if any), and its electric charge (if any).

A theoretical entity with some similarity to a black hole is the "wormhole" (Figure 9.29). Like a black hole, a wormhole is an enormous distortion of space and time. But instead of collapsing toward an infinitely dense point, the wormhole opens out again in some other part of the universe—or even, conceivably, in some other universe! Whereas the existence of black holes has been confirmed, the wormhole remains an exceedingly speculative notion. Some science buffs imagine that the wormhole opens up the possibility of time travel.[9]

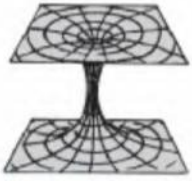

FIGURE 9.29

A speculative wormhole may be the portal to another part of our universe or even to another universe.

How can a black hole be detected if there is literally no way to "see" it? It makes itself felt by its gravitational influence on nearby matter and on neighboring stars. There is now good evidence that some binary star systems consist of a luminous star and an invisible companion with black-hole-like properties orbiting around each other. Even stronger evidence points to more massive black holes at the centers of many galaxies. In a young galaxy, observed as a "quasar," the central black hole sucks in matter that emits great quantities of radiation as it plunges to oblivion. In an older galaxy, stars are observed circling in a powerful gravitational field around an apparently empty center. These galactic black holes have masses ranging from millions to more than 1 billion times the mass of our Sun. The center of our own galaxy, although not so easy to see as the centers of some other galaxies, almost surely hosts a black hole. Discoveries are coming faster than textbooks can report. Check your astronomy web site for the latest update.

Universal Gravitation

We all know that Earth is round. But why is Earth round? It is round because of gravitation. Everything attracts everything else, and so Earth has attracted itself together as far as it can! Any "corners" of Earth have been pulled in; as a result, every part of the surface is equidistant from the center of gravity. This makes it a sphere. Therefore, we see from the law of gravitation that the Sun, the Moon, and Earth are spherical because they have to be (although rotational effects make them slightly ellipsoidal).

If everything pulls on everything else, then the planets must pull on each other. The force that controls Jupiter, for example, is not just the force from the Sun; there are also the pulls from the other planets. Their effect is small in comparison with

[9]Stephen Hawking, a pioneering expert on black holes, was one of the first to speculate about the existence of wormholes. But, in 2003, to the dismay of many science buffs, he announced his belief that they cannot exist.

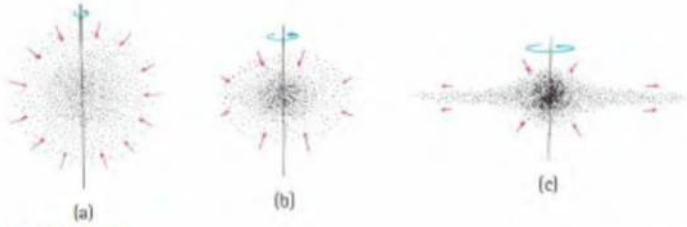

FIGURE 9.30

Formation of the solar system. A slightly rotating ball of interstellar gas (a) contracts due to mutual gravitation and (b) conserves angular momentum by speeding up. The increased momentum of individual particles and clusters of particles causes them (c) to sweep in wider paths about the rotational axis, producing an overall disk shape. The greater surface area of the disk promotes cooling and condensation of matter in swirling eddies—the birthplace of the planets.

the pull of the much more massive Sun, but it still shows. When Saturn is near Jupiter, its pull disturbs the otherwise smooth path traced by Jupiter. Both planets "wobble" in their orbits. The interplanetary forces causing this wobbling are called *perturbations*. By the 1840s, studies of the most recently discovered planet at the time, Uranus, showed that the deviations of its orbit could not be explained by perturbations from all other known planets. Either the law of gravitation was failing at this great distance from the Sun or an unknown eighth planet was perturbing the orbit of Uranus. An Englishman and a Frenchman, J. C. Adams and Urbain Leverrier, each assumed Newton's law to be valid, and they independently calculated where an eighth planet should be. At about the same time, Adams sent a letter to the Greenwich Observatory in England and Leverrier sent a letter to the Berlin Observatory in Germany, both suggesting that a certain area of the sky be searched for a new planet. The request by Adams was delayed by misunderstandings at Greenwich, but Leverrier's request was heeded immediately. The planet Neptune was discovered that very night!

Subsequent tracking of the orbits of both Uranus and Neptune led to the prediction and discovery of Pluto in 1930 at the Lowell Observatory in Arizona. Whatever you may have learned in your early schooling, astronomers now regard Pluto as a *dwarf planet*, a new category of certain asteroids in the Kuiper belt. Regardless of its status, Pluto takes 248 years to make a single revolution about the Sun, so no one will see it in its discovered position again until the year 2178.

Recent evidence suggests that the universe is expanding and accelerating outward, pushed by an antigravity *dark energy* that makes up some 73% of the universe. Another 23% is composed of the yet-to-be-discovered particles of exotic *dark matter*. Ordinary matter, the stuff of stars, cabbages, and kings, makes up only about 4%. The concepts of dark energy and dark matter are late-20th- and 21st-century discoveries. The present view of the universe has progressed appreciably beyond the universe as Newton perceived it.

Yet few theories have affected science and civilization as much as Newton's theory of gravity. The successes of Newton's ideas ushered in the Age of Enlightenment. Newton had demonstrated that, by observation and reason, people could uncover the workings of the physical universe. How profound that all the moons and planets and stars and galaxies have such a beautifully simple rule to govern them, namely,

$$F = G\frac{m_1 m_2}{d^2}$$

A sphere has the smallest surface area for any volume of matter.

fyi

- A widespread assumption is that when Earth ceased to be regarded as the center of the universe, its place and humankind were demoted and no longer considered special. On the contrary, writings of the time suggest most Europeans viewed humans as filthy and sinful because of Earth's lowly position—farthest from heaven, with hell at its center. Human elevation didn't occur until the Sun, viewed positively, took a center position. We became special by showing we're not so special.

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Video

Discovery of Neptune

The formulation of this simple rule is one of the major reasons for the success in science that followed, for it provided hope that other phenomena of the world might also be described by equally simple and universal laws.

This hope nurtured the thinking of many scientists, artists, writers, and philosophers of the 1700s. One of these was the English philosopher John Locke, who argued that observation and reason, as demonstrated by Newton, should be our best judge and guide in all things. Locke urged that all of nature and even society should be searched to discover any "natural laws" that might exist. Using Newtonian physics as a model of reason, Locke and his followers modeled a system of government that found adherents in the thirteen British colonies across the Atlantic. These ideas culminated in the Declaration of Independence and the Constitution of the United States of America.

SUMMARY OF TERMS

Law of universal gravitation 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 separating them:

$$F = G\frac{m_1 m_2}{d^2}$$

Inverse-square law A law relating the intensity of an effect to the inverse square of the distance from the cause. Gravity follows an inverse-square law, as do the effects of electric, magnetic, light, sound, and radiation phenomena.

Weight The force that an object exerts on a supporting surface (or, if suspended, on a supporting string), which is often, but not always, due to the force of gravity.

Weightless Being without a support force, as in free fall.

Spring tides High or low tides that occur when the Sun, Earth, and the Moon are all lined up so that the tides due to the Sun and the Moon coincide, making the high tides higher than average and the low tides lower than average.

Neap tides Tides that occur when the Moon is midway between new and full, in either direction. Tides due to the Sun and the Moon partly cancel, making the high tides lower than average and the low tides higher than average.

Gravitational field The influence that a massive body extends into the space around itself, producing a force on another massive body. It is measured in newtons per kilogram (N/kg).

Black hole A concentration of mass resulting from gravitational collapse, near which gravity is so intense that not even light can escape.

REVIEW QUESTIONS

1. What did Newton discover about gravity?
2. What is the Newtonian synthesis?

The Universal Law of Gravity

3. In what sense does the Moon "fall"?
4. State Newton's law of universal gravitation in words. Then do the same with one equation.

The Universal Gravitational Constant, *G*

5. What is the magnitude of gravitational force between two 1-kg bodies that are 1 m apart?
6. What is the magnitude of the gravitational force between Earth and a 1-kg body?
7. What do we call the gravitational force between Earth and your body?
8. When *G* was first measured by Henry Cavendish, newspapers of the time hailed his experiment as the "weighing Earth experiment." Why?

Gravity and Distance: The Inverse-Square Law

9. How does the force of gravity between two bodies change when the distance between them is doubled?
10. How does the thickness of paint sprayed on a surface change when the sprayer is held twice as far away?
11. Where do you weigh more—at the bottom of Death Valley or atop one of the peaks of the Sierra Nevada? Why?

Weight and Weightlessness

12. Would the springs inside a bathroom scale be more compressed or less compressed if you weighed yourself in an elevator that accelerated upward? Downward?
13. Would the springs inside a bathroom scale be more compressed or less compressed if you weighed yourself in an elevator that moved upward at *constant velocity?* Downward at *constant velocity?*
14. When is your weight equal to *mg*?
15. Give an example of when your weight is more than *mg*. Give an example of when it's zero.

Ocean Tides

16. Do tides depend more on the strength of gravitational pull or on the *difference* in strengths? Explain.
17. Why do both the Sun and the Moon exert a greater gravitational force on one side of Earth than the other?
18. Distinguish between *spring tides* and *neap tides*.

Tides in Earth and Atmosphere

19. Do tides occur in the molten interior of Earth for the same reason that tides occur in the oceans?
20. Why are all tides greatest at the time of a full Moon or new Moon?

Tidal Bulges on the Moon

21. Why is there a torque about the Moon's center of mass when the Moon's long axis is not aligned with Earth's gravitational field?
22. Is there a torque about the Moon's center of mass when the Moon's long axis is aligned with Earth's gravitational field? Explain how this compares with a magnetic compass.

Gravitational Fields

23. What is a gravitational field, and how can its presence be detected?

Gravitational Field Inside a Planet

24. What is the magnitude of the gravitational field at Earth's center?
25. For a planet of uniform density, how would the magnitude of the gravitational field halfway to the center compare with the field at the surface?
26. What would be the magnitude of the gravitational field anywhere inside a hollow, spherical planet?

Einstein's Theory of Gravitation

27. Newton viewed the curving of the path of a planet as being caused by a force acting upon the planet. How did Einstein view the curved path of a planet?

Black Holes

28. If Earth shrank with no change in its mass, what would happen to your weight at the surface?
29. What happens to the strength of the gravitational field at the surface of a star that shrinks?
30. Why is a black hole invisible?

Universal Gravitation

31. What was the cause of perturbations discovered in the orbit of the planet Uranus? What greater discovery did this lead to?
32. What percentage of the universe is presently speculated to be composed of dark matter and dark energy?

PROJECTS

1. Hold your hands outstretched in front of you, one twice as far from your eyes as the other, and make a casual judgment as to which hand looks bigger. Most people see them to be about the same size, although many see the nearer hand as slightly bigger. Almost no one, upon casual inspection, sees the nearer hand as 4 times as big, but, by the inverse-square law, the nearer hand should appear to be twice as tall and twice as wide and therefore seem to occupy 4 times as much of your visual field as the farther hand. Your belief that your hands are the same size is so strong that you likely overrule this information. Now, if you overlap your hands slightly and view them with one eye closed, you'll see the nearer hand as clearly bigger. This raises an interesting question: What other illusions do you have that are not so easily checked?

2. Repeat the eyeballing experiment, only this time use two dollar bills—one regular, and the other folded along its middle lengthwise, and again widthwise, so it has 1/4 the area. Now hold the two in front of your eyes. Where do you hold the folded one so that it looks the same size as the unfolded one? Nice?

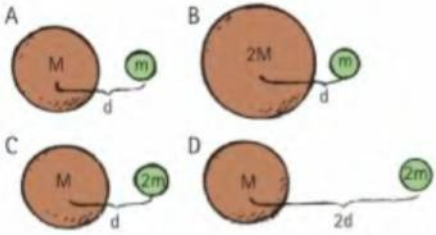
PLUG AND CHUG

$$F = G\frac{m_1 m_2}{d^2}$$

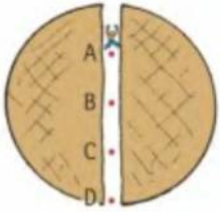
1. Calculate the force of gravity on a 1-kg mass at Earth's surface. The mass of Earth is 6.0×10^{24} kg, and its radius is 6.4×10^6 m.
2. Calculate the force of gravity on the same 1-kg mass if it were 6.4×10^6 m above Earth's surface (that is, if it were two Earth radii from Earth's center).
3. Calculate the force of gravity between Earth (mass = 6.0×10^{24} kg) and the Moon (mass = 7.4×10^{22} kg). The average Earth–Moon distance is 3.8×10^8 m.
4. Calculate the force of gravity between Earth and the Sun (the Sun's mass = 2.0×10^{30} kg; average Earth–Sun distance = 1.5×10^{11} m).
5. Calculate the force of gravity between a newborn baby (mass = 3 kg) and the planet Mars (mass = 6.4×10^{23} kg) when Mars is at its closest to Earth (distance = 5.6×10^{10} m).
6. Calculate the force of gravity between a newborn baby of mass 3 kg and the obstetrician of mass 100 kg, who is 0.5 m from the baby. Which exerts more gravitational force on the baby, Mars or the obstetrician? By how much?

RANKING

1. The planet and its moon gravitationally attract each other. Rank the force of attraction between each pair from greatest to least.



2. Consider the light of multiple candle flames, each of the same brightness. Rank from brightest to dimmest the light that enters your eye for the following situations.
   a. 3 candles seen from a distance of 3 m.
   b. 2 candles seen from a distance of 2 m.
   c. 1 candle seen from a distance of 1 m.
3. Pretend you fall into a hole bored completely through the Earth. Discounting friction and rotational effects, rank, from most to least, at positions A, B, C, and D your



   a. speed of fall.
   b. acceleration of fall.
4. Rank the average gravitational forces from greatest to least between
   a. Sun and Mars.
   b. Sun and the Moon.
   c. Sun and Earth.
5. Rank the microtidal forces on your own body, from greatest to least, produced by the
   a. Moon.
   b. Earth.
   c. Sun.

EXERCISES

1. Comment on whether or not the following label on a consumer product should be cause for concern: *CAUTION: The mass of this product pulls on every other mass in the universe, with an attracting force that is proportional to the product of the masses and inversely proportional to the square of the distance between them.*
2. Gravitational force acts on all bodies in proportion to their masses. Why, then, doesn't a heavy body fall faster than a light body?
3. What would be the path of the Moon if somehow all gravitational forces on it vanished to zero?
4. Is the force of gravity stronger on a piece of iron than on a piece of wood if both have the same mass? Defend your answer.
5. Is the force of gravity stronger on a crumpled piece of paper than on an identical piece of paper that has not been crumpled? Defend your answer.
6. What is the relationship between force and distance in an inverse-square law?
7. A friend says that up above the atmosphere, in space shuttle territory, Earth's gravitational field is zero. Explain how your friend has a misconception, and use the equation for gravitational force in your explanation.
8. A friend says that, since Earth's gravity is so much stronger than the Moon's gravity, rocks on the Moon could be dropped to Earth. What is wrong with this assumption?
9. Another friend says that the Moon's gravity would prevent rocks dropping from the Moon to Earth, but that if the Moon's gravity somehow no longer pulled on its own rocks, then rocks on the Moon would fall to Earth. What is wrong with this assumption?
10. A friend says that the International Space Station shown on the cover of this book is beyond the pull of Earth's gravity. Correct your friend's misconception.
11. Somewhere between Earth and the Moon, gravity from these two bodies on a space pod would cancel. Is this location nearer Earth or the Moon?
12. An apple falls because of the gravitational attraction to Earth. How does the gravitational attraction of Earth to the apple compare? (Does force change when you interchange m_1 and m_2 in the equation for gravity—m_2m_1 instead of m_1m_2?)
13. Larry weighs 300 N at the surface of Earth. What is the weight of Earth in the gravitational field of Larry?
14. Earth and the Moon are attracted to each other by gravitational force. Does the more massive Earth attract the less massive Moon with a force that is greater, smaller, or the same as the force with which the Moon attracts Earth? (With an elastic band stretched between your thumb and forefinger, which is pulled more strongly by the band, your thumb or your forefinger?)
15. If the Moon pulls Earth as strongly as Earth pulls the Moon, why doesn't Earth rotate around the Moon, or

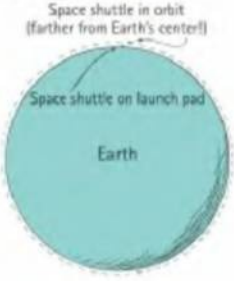
why don't both rotate around a point midway between them?

16. Is the acceleration due to gravity more or less atop Mt. Everest than at sea level? Defend your answer.
17. An astronaut lands on a planet that has the same mass as Earth but twice the diameter. How does the astronaut's weight differ from that on Earth?
18. An astronaut lands on a planet that has twice the mass as Earth and twice the diameter. How does the astronaut's weight differ from that on Earth?
19. If Earth somehow expanded to a larger radius, with no change in mass, how would your weight be affected? How would it be affected if Earth instead shrunk? (*Hint:* Let the equation for gravitational force guide your thinking.)
20. The intensity of light from a central source varies inversely as the square of the distance. If you lived on a planet only half as far from the Sun as our Earth, how would Sun's light intensity compare with that on Earth? How about a planet 10 times farther away than Earth?
21. A small light source located 1 m in front of a 1-m^2 opening illuminates a wall behind. If the wall is 1 m behind the opening (2 m from the light source), the illuminated area covers 4 m^2. How many square meters will be illuminated if the wall is 3 m from the light source? 5 m? 10 m?
22. The planet Jupiter is more than 300 times as massive as Earth, so it might seem that a body on the surface of Jupiter would weigh 300 times as much as on Earth. But it so happens that a body would scarcely weigh 3 times as much on the surface of Jupiter as it would on the surface of Earth. Can you think of an explanation for why this is so? (*Hint:* Let the terms in the equation for gravitational force guide your thinking.)
23. Why does a person in free fall experience weightlessness, while a person falling at terminal velocity does not?
24. Why do the passengers in high-altitude jet planes feel the sensation of weight while passengers in an orbiting space vehicle, such as a space shuttle, do not?
25. Is gravitational force acting on a person who falls off a cliff? On an astronaut inside an orbiting space shuttle?
26. If you were in a car that drove off the edge of a cliff, why would you be momentarily weightless? Would gravity still be acting on you?
27. What two forces act on you while you are in a moving elevator? When are these forces of equal magnitude and when are they not?
28. If you were in a freely falling elevator and you dropped a pencil, it would hover in front of you. Is there a force of gravity acting on the pencil? Defend your answer.
29. Why does a bungee jumper feel weightless during the jump?
30. Since your weight when standing on Earth is the gravitational attraction between you and Earth, would your weight be greater if Earth gained mass? If the Sun gained mass? Why are your answers the same or different?
31. Your friend says that the primary reason astronauts in orbit feel weightless is that they are beyond the main pull of Earth's gravity. Why do you agree or disagree?
32. Explain why the following reasoning is wrong. "The Sun attracts all bodies on Earth. At midnight, when the Sun is directly below, it pulls on you in the same direction as Earth pulls on you; at noon, when the Sun is directly overhead, it pulls on you in a direction opposite to Earth's pull on you. Therefore, you should be somewhat heavier at midnight and somewhat lighter at noon."
33. When will the gravitational force between you and the Sun be greater—today at noon, or tomorrow at midnight? Defend your answer.
34. If the mass of Earth increased, your weight would correspondingly increase. But, if the mass of the Sun increased, your weight would not be affected at all. Why?
35. If somebody tugged hard on your shirt sleeve, it would likely tear. But if all parts of your shirt were tugged equally, no tearing would occur. How does this relate to tidal forces?
36. Most people today know that the ocean tides are caused principally by the gravitational influence of the Moon, and most people therefore think that the gravitational pull of the Moon on Earth is greater than the gravitational pull of the Sun on Earth. What do you think?
37. Would ocean tides exist if the gravitational pull of the Moon (and the Sun) were somehow equal on all parts of the world? Explain.
38. Why aren't high ocean tides exactly 12 hours apart?
39. With respect to spring and neap ocean tides, when are the tides lowest? That is, when is it best for digging clams?
40. Whenever the ocean tide is unusually high, will the following low tide be unusually low? Defend your answer in terms of "conservation of water." (If you slosh water in a tub so that it is extra deep at one end, will the other end be extra shallow?)
41. The Mediterranean Sea has very little sediment churned up and suspended in its waters, mainly because of the absence of any substantial ocean tides. Why do you suppose the Mediterranean Sea has practically no tides? Similarly, are there tides in the Black Sea? In the Great Salt Lake? Your county reservoir? A glass of water? Explain.
42. The human body is composed mostly of water. Why does the Moon overhead cause appreciably less tidal effect in the fluid compartment of your body than a 1-kg melon held over your head?
43. Does the fact that one side of the Moon always faces Earth mean that the Moon rotates about its axis (like a top) or that it doesn't rotate about its axis? Defend your answer.
44. What would be the effect on Earth's tides if the diameter of Earth were very much larger than it is? If Earth were as it presently is, but the Moon were very much larger and had the same mass?
45. Which would produce the greatest microtides in your body, the Earth, the Moon, or the Sun? Why?
46. Exactly why do tides occur in Earth's crust and in Earth's atmosphere?
47. The value of g at Earth's surface is about 9.8 m/s^2. What is the value of g at a distance of twice Earth's radius?
48. If Earth were of uniform density (same mass/volume throughout), what would the value of g be inside Earth at half its radius?
49. If Earth were of uniform density, would your weight increase or decrease at the bottom of a deep mine shaft? Defend your answer.
50. It so happens that an actual *increase* in weight is found even in the deepest mine shafts. What does this tell us about how Earth's density changes with depth?

51. Which requires more fuel—a rocket going from Earth to the Moon or a rocket coming from the Moon to Earth? Why?
52. If you could somehow tunnel inside a uniform-density star, would your weight increase or decrease? If, instead, you somehow stood on the surface of a shrinking star, would your weight increase or decrease? Why are your answers different?
53. If our Sun shrank in size to become a black hole, show from the gravitational force equation that Earth's orbit would not be affected.
54. If Earth were hollow but still had the same mass and same radius, would your weight in your present location be more, less, or the same as it is now? Explain.
55. Some people dismiss the validity of scientific theories by saying that they are "only" theories. The law of universal gravity is a theory. Does this mean that scientists still doubt its validity? Explain.
56. Make up two multiple-choice questions—one that would check a classmate's understanding of the inverse-square law and another that would check a distinction between weight and weightlessness.

PROBLEMS

1. Suppose you stood atop a ladder so tall that you were 3 times as far from Earth's center as you presently are. Show that your weight would be one-ninth of its present value.
2. Show that the gravitational force between two planets is quadrupled if the masses of both planets are doubled but the distance between them stays the same.
3. Show that there is no change in the force of gravity between two objects when their masses are doubled and the distance between them is also doubled.
4. Find the change in the force of gravity between two planets when distance between them is *decreased* by 10.
5. Many people mistakenly believe that the astronauts that orbit Earth are "above gravity." Calculate g for space shuttle territory, 200 km above Earth's surface. Earth's mass is 6.0×10^{24} kg, and its radius is 6.38×10^6 m (6380 km). Your answer is what percentage of 10 m/s^2?



• 6. Newton's universal law of gravity tells us that $F = G\frac{m_1 m_2}{d^2}$. Newton's second law tells us that $a = \frac{F_{net}}{m}$.

a. With a bit of algebraic reasoning show that your gravitational acceleration toward any planet of mass M a distance d from its center is $a = \frac{GM}{d^2}$.

b. How does this equation tell you whether or not your gravitational acceleration depends on your mass?

CHAPTER 9 ONLINE RESOURCES

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- 9.6, 9.9

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- Tides
- Black Holes

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- Weight and Weightlessness
- Gravitational Field Inside a Hollow Planet
- The Weight of an Object Inside a Hollow Planet but Not at Its Center
- Discovery of Neptune

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10 Projectile and Satellite Motion

1 Topographic globes that show the relative heights of mountains and valleys are greatly exaggerated. Truly scaled, the surface of Earth is as smooth as the globe that Emily Abrams holds. And Earth's atmosphere is a small fraction of the width of her fingers, with space shuttles orbiting about the distance to her smallest fingernail! 2 In the dust-free "clean room" of the Jet Propulsion Laboratory, Ben Thoma and Tenny Lim stand beside the Mars Science Laboratory Descent Stage that is scheduled for a 2011 launch to Mars. 3 Tenny with a scale model of her design.

A teacher's influence knows no bounds. Our influence on students goes beyond what feedback makes its way to us. When I'm asked about which of my many students I take most pride in, and whom I most influenced, my answer is quick: Tenny Lim. In addition to being bright, she is artistic and very dexterous with her hands. She was the top-scoring student in my Conceptual Physics class in 1980 and earned an AS degree in Dental Laboratory Technology. With my encouragement and support, she continued at City College with courses in math and science and decided to pursue an engineering career. Two years later, she transferred to California Polytechnic Institute in San Luis Obispo. While earning her BS degree in mechanical engineering, a recruiter from the Jet Propulsion Laboratory in Pasadena was impressed that she concurrently took art classes to balance her technical studies. When asked about this, she replied that art was one of her passions. What the recruiter was looking for was someone talented in both art and engineering for JPL's design team. Tenny was hired and became part of the space program. Her current project is the Mars Science Laboratory, where she is the lead designer for the Descent Stage (see photo above). She also continues to pursue her art and has her work shown in local galleries.

Tenny's story exemplifies my advice to young people: Excel at more than one thing.

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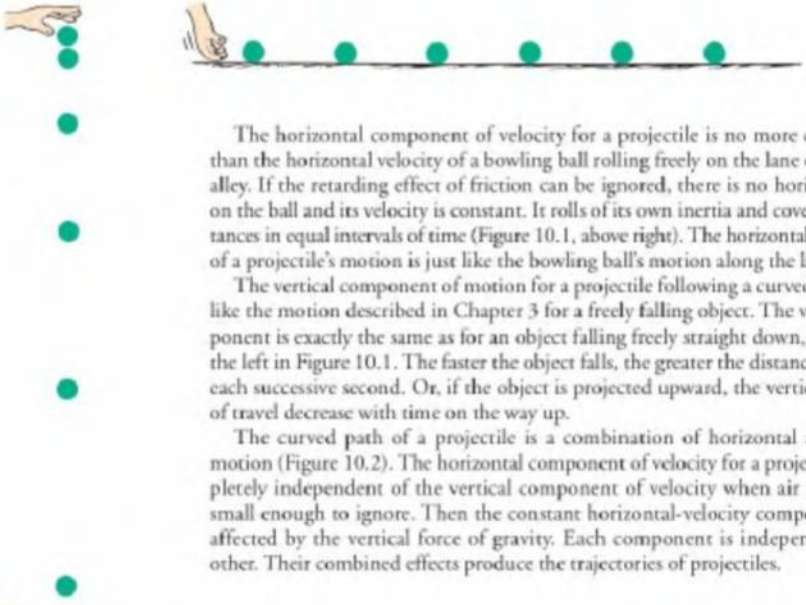
Projectile Motion

Without gravity, you could toss a rock at an angle skyward and it would follow a straight-line path. Because of gravity, however, the path curves. A tossed rock, a cannonball, or any object that is projected by some means and continues in motion by its own inertia is called a **projectile.** To the cannoneers of earlier centuries, the curved paths of projectiles seemed very complex. Today these paths are surprisingly simple when we look at the horizontal and vertical components of velocity separately.



The horizontal component of velocity for a projectile is no more complicated than the horizontal velocity of a bowling ball rolling freely on the lane of a bowling alley. If the retarding effect of friction can be ignored, there is no horizontal force on the ball and its velocity is constant. It rolls of its own inertia and covers equal distances in equal intervals of time (Figure 10.1, above right). The horizontal component of a projectile's motion is just like the bowling ball's motion along the lane.

The vertical component of motion for a projectile following a curved path is just like the motion described in Chapter 3 for a freely falling object. The vertical component is exactly the same as for an object falling freely straight down, as shown at the left in Figure 10.1. The faster the object falls, the greater the distance covered in each successive second. Or, if the object is projected upward, the vertical distances of travel decrease with time on the way up.

The curved path of a projectile is a combination of horizontal and vertical motion (Figure 10.2). The horizontal component of velocity for a projectile is completely independent of the vertical component of velocity when air resistance is small enough to ignore. Then the constant horizontal-velocity component is not affected by the vertical force of gravity. Each component is independent of the other. Their combined effects produce the trajectories of projectiles.

FIGURE 10.1
(Above right) Roll a ball along a level surface, and its velocity is constant because no component of gravitational force acts horizontally. (Above) Drop it, and it accelerates downward and covers a greater vertical distance each second.

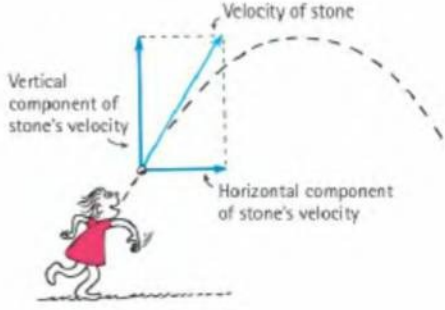
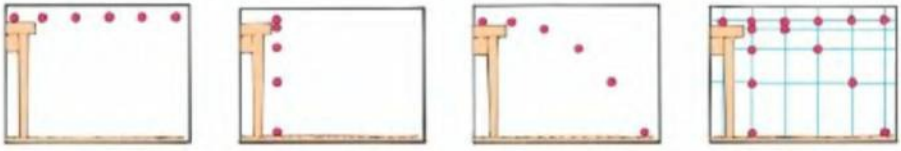


FIGURE 10.2
Vertical and horizontal components of a stone's velocity.

PROJECTILES LAUNCHED HORIZONTALLY

Projectile motion is nicely analyzed in Figure 10.3, which shows a simulated multiple flash exposure of a ball rolling off the edge of a table. Investigate it carefully, for there's a lot of good physics there. At the left we notice equally timed

sequential positions of the ball without the effect of gravity. Only the effect of the ball's horizontal component of motion is shown. Next we see vertical motion without a horizontal component. The curved path in the third view is best analyzed by considering the horizontal and vertical components of motion separately. Notice two important things. The first is that the ball's horizontal component of velocity doesn't change as the falling ball moves forward. The ball travels the same horizontal distance in equal times between each flash. That's because there is no component of gravitational force acting horizontally. Gravity acts only *downward*, so the only acceleration of the ball is *downward*. The second thing to notice is that the vertical positions become farther apart with time. The vertical distances traveled are the same as if the ball were simply dropped. Notice the curvature of the ball's path is the combination of constant horizontal motion, and accelerated vertical motion.



Horizontal motion with no gravity | Vertical motion only with gravity | Combined horizontal and vertical motion | Superposition of the preceding cases

FIGURE 10.3

INTERACTIVE FIGURE

Simulated photographs of a moving ball illuminated with a strobe light.

The trajectory of a projectile that accelerates only in the vertical direction while moving at a constant horizontal velocity is a **parabola.** When air resistance is small enough to neglect, as it is for a heavy object without great speed, the trajectory is parabolic.

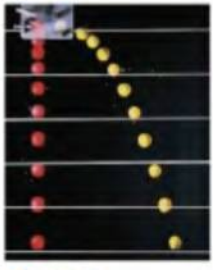


FIGURE 10.4

INTERACTIVE FIGURE

A strobe-light photograph of two golf balls released simultaneously from a mechanism that allows one ball to drop freely while the other is projected horizontally.

CHECK POINT

At the instant a cannon fires a cannonball horizontally over a level range, another cannonball held at the side of the cannon is released and drops to the ground. Which ball, the one fired downrange or the one dropped from rest, strikes the ground first?

Check Your Answer

Both cannonballs hit the ground at the same time, for both fall *the same vertical distance*. Notice that the physics is the same as shown in Figures 10.3 and 10.4. We can reason this another way by asking which one would hit the ground first if the cannon were pointed at an *upward* angle. Then the dropped cannonball would hit first, while the fired ball remains airborne. Now consider the cannon pointing *downward*. In this case, the fired ball hits first. So projected upward, the dropped one hits first; downward, the fired one hits first. Is there some angle at which there is a dead heat, where both hit at the same time? Can you see that this occurs when the cannon is horizontal?

FIGURE 10.5

Chuck Stone releases a ball near the top of a track. His students make measurements to predict where a can on the floor should be placed to catch the ball after it rolls off the table.

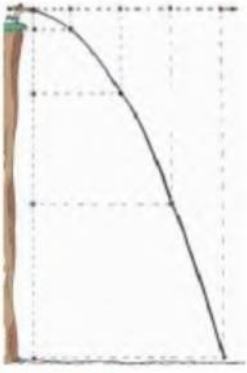


FIGURE 10.6

The vertical dashed line is the path of a stone dropped from rest. The horizontal dashed line would be its path if there were no gravity. The curved solid line shows the resulting trajectory that combines horizontal and vertical motion.

PROJECTILES LAUNCHED AT AN ANGLE

In Figure 10.7, we see the paths of stones thrown at an angle upward (left) and downward (right). The dashed straight lines show the ideal trajectories of the stones if there were no gravity. Notice that the vertical distance beneath the idealized straight-line paths is the same for equal times. This vertical distance is independent of what's happening horizontally.

Figure 10.8 shows specific vertical distances for a cannonball shot at an upward angle. If there were no gravity the cannonball would follow the straight-line path shown by the dashed line. But there is gravity, so this doesn't occur. What really happens is that the cannonball continuously falls beneath the imaginary line until it finally strikes the ground. Note that the vertical distance it falls beneath any point on the dashed line is the same vertical distance it would fall if it were dropped from rest and had been falling for the same amount of time. This distance, as introduced in Chapter 3, is given by $d = \frac{1}{2}gt^2$, where t is the elapsed time.

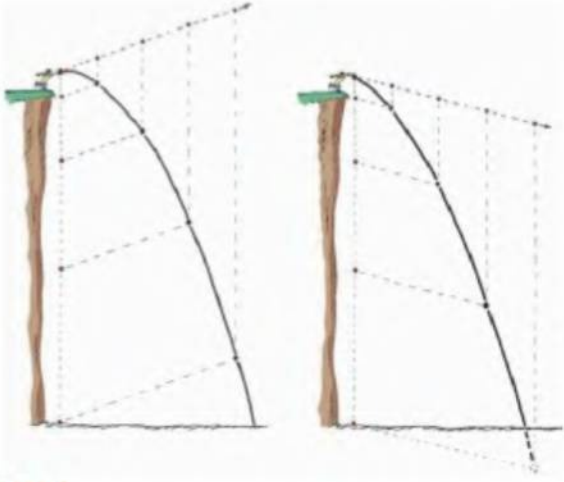


FIGURE 10.7

Whether launched at an angle upward or downward, the vertical distance of fall beneath the idealized straight-line path is the same for equal times.

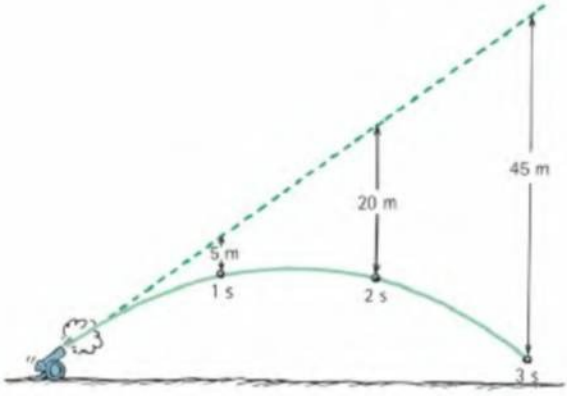


FIGURE 10.8

With no gravity, the projectile would follow a straight-line path (dashed line). But, because of gravity, the projectile falls beneath this line the same vertical distance it would fall if it were released from rest. Compare the distances fallen with those given in Table 3.3 in Chapter 3. (With $g = 9.8\ \text{m/s}^2$, these distances are more precisely 4.9 m, 19.6 m, and 44.1 m.)

We can put it another way: Shoot a projectile skyward at some angle and pretend there is no gravity. After so many seconds t, it should be at a certain point along a straight-line path. But, because of gravity, it isn't. Where is it? The answer is that it's directly below this point. How far below? The answer in meters is $5t^2$ (or, more precisely, $4.9t^2$). How about that!

Note another thing from Figure 10.8 and previous figures. The ball moves equal horizontal distances in equal time intervals. That's because no acceleration takes place horizontally. The only acceleration is vertical, in the direction of Earth's gravity.

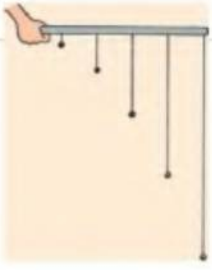
CHECK POINT

1. Suppose the cannonball in Figure 10.8 were fired faster. How many meters below the dashed line would it be at the end of the 5 s?
2. If the horizontal component of the cannonball's velocity is 20 m/s, how far downrange will the cannonball be in 5 s?

Check Your Answers

1. The vertical distance beneath the dashed line at the end of 5 s is 125 m [$d = 5t^2 = 5(5)^2 = 5(25) = 125$ m]. Interestingly enough, this distance doesn't depend on the angle of the cannon. If air drag is neglected, any projectile will fall $5t^2$ m below where it would have reached if there were no gravity.
2. With no air drag, the cannonball will travel a horizontal distance of 100 m [$d = \bar{v}t = (20\ \text{m/s})(5\ \text{s}) = 100$ m]. Note that, since gravity acts only vertically and there is no acceleration in the horizontal direction, the cannonball travels equal horizontal distances in equal times. This distance is simply its horizontal component of velocity multiplied by the time (and not $5t^2$, which applies only to vertical motion under the acceleration of gravity).

Practicing Physics: Hands-On Dangling Beads



Make your own model of projectile paths. Divide a ruler or a stick into five equal spaces. At position 1, hang a bead from a string that is 1 cm long, as shown. At position 2, hang a bead from a string that is 4 cm long. At position 3, do the same with a 9-cm length of string. At position 4, use 16 cm of string, and for position 5, use 25 cm of string. If you hold the stick horizontally, you will have a version of Figure 10.6. Hold it at a slight upward angle to show a version of Figure 10.7, left. Hold it at a downward angle to show a version of Figure 10.7, right.

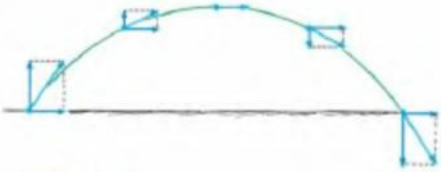


FIGURE 10.9

INTERACTIVE FIGURE

The velocity of a projectile at various points along its trajectory. Note that the vertical component changes and that the horizontal component is the same everywhere.

In Figure 10.9, we see vectors representing both horizontal and vertical components of velocity for a projectile following a parabolic trajectory. Notice that the horizontal component everywhere along the trajectory is the same, and only the vertical component changes. Note also that the actual velocity is represented by the vector that forms the diagonal of the rectangle formed by the vector components. At the top of the trajectory, the vertical component is zero, so the velocity at the zenith is only the horizontal component of velocity. Everywhere else along the trajectory, the magnitude of velocity is greater (just as the diagonal of a rectangle is greater than either of its sides).

Figure 10.10 shows the trajectory traced by a projectile launched with the same speed at a steeper angle. Notice the initial velocity vector has a greater vertical component than when the launch angle is smaller. This greater component results in a trajectory that reaches a greater height. But the horizontal component is less, and the range is less.

Figure 10.11 shows the paths of several projectiles, all with the same initial speed but different launching angles. The figure neglects the effects of air drag, so the trajectories are all parabolas. Notice that these projectiles reach different *altitudes*, or heights above the ground. They also have different *horizontal ranges*, or distances traveled horizontally. The remarkable thing to note from Figure 10.11 is that the same range is obtained from two different launching angles when the angles add up to 90°! An object thrown into the air at an angle of 60°, for example, will have the same range as if it were thrown at the same speed at an angle of 30°. For the smaller angle, of course, the object remains in the air for a shorter time. The greatest range occurs when the launching angle is 45°—when air drag is negligible.

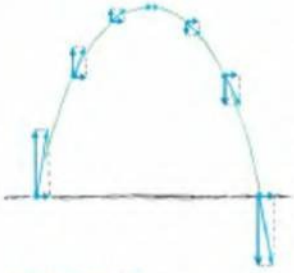


FIGURE 10.10

Trajectory for a steeper projection angle.

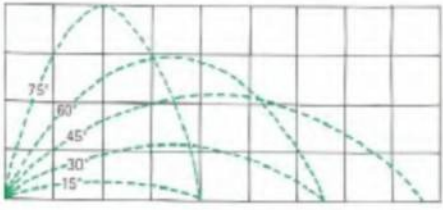


FIGURE 10.11

INTERACTIVE FIGURE

Ranges of a projectile shot at the same speed at different projection angles.

FIGURE 10.12

Maximum range would be attained when a ball is batted at an angle of nearly 45°—but only in the absence of air drag.

CHECK POINT

1. A baseball is batted at an angle into the air. Once airborne, and neglecting air drag, what is the ball's acceleration vertically? Horizontally?
2. At what part of its trajectory does the baseball have minimum speed?
3. Consider a batted baseball following a parabolic path on a day when the Sun is directly overhead. How does the speed of the ball's shadow across the field compare with the ball's horizontal component of velocity?

Check Your Answers

1. Vertical acceleration is g because the force of gravity is vertical. Horizontal acceleration is zero because no horizontal force acts on the ball.
2. A ball's minimum speed occurs at the top of its trajectory. If it is launched vertically, its speed at the top is zero. If launched at an angle, the vertical component of velocity is zero at the top, leaving only the horizontal component. So the speed at the top is equal to the horizontal component of the ball's velocity at any point. Doesn't this make sense?
3. They are the same!

Without the effects of air, the maximum range for a baseball would occur when it is batted 45° above the horizontal. Without air drag, the ball rises just like it falls, covering the same amount of ground while rising as while falling. But not so when air drag slows the ball. Its horizontal speed at the top of its path is less than its horizontal speed when leaving the bat, so it covers less ground while falling than when rising. As a result, for maximum range the ball must leave the bat with more horizontal speed than vertical speed—at about 25° to 34°, considerably less than 45°. Likewise for golf balls. (As Chapter 14 will show, spin of the ball also affects range.) For heavy projectiles like javelins and the shot, air has less effect on range. A javelin, being heavy and presenting a very small cross section to the air, follows an almost perfect parabola when thrown. So does a shot. Aha, but *launching speeds* are not equal for heavy projectiles thrown at different angles. In throwing a javelin or putting a shot, a significant part of the launching *force* goes into lifting—combating gravity—so launching at 45° means less launching speed. You can test this yourself: Throw a heavy boulder horizontally, then at an angle upward—you'll find the horizontal throw to be considerably faster. So maximum range for heavy projectiles thrown by humans is attained for angles of less than 45°—and not because of air drag.

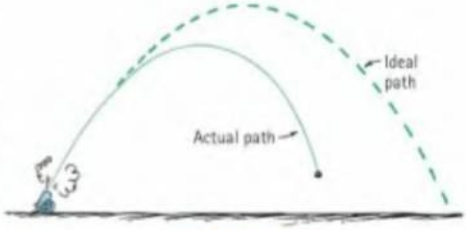


FIGURE 10.13

INTERACTIVE FIGURE

In the presence of air resistance, the trajectory of a high-speed projectile falls short of the idealized parabolic path.

When air resistance is small enough to be negligible, a projectile will rise to its maximum height in the same time it takes to fall from that height to its initial level (Figure 10.14). This is because its deceleration by gravity while going up is the same as its acceleration by gravity while coming down. The speed it loses while going up is therefore the same as the speed gained while coming down. So the projectile arrives at its initial level with the same speed it had when it was initially projected.

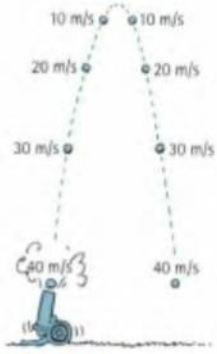


FIGURE 10.14

Without air drag, speed lost while going up equals speed gained while coming down: Time going up equals time coming down.

Baseball games normally take place on level ground. For the short-range projectile motion on the playing field, Earth can be considered to be flat because the flight of the baseball is not affected by Earth's curvature. For very long-range projectiles, however, the curvature of Earth's surface must be taken into account. We'll now see that if an object is projected fast enough, it will fall all the way around Earth and become an Earth satellite.

CHECK POINT

The boy on the tower throws a ball 20 m downrange, as shown in Figure 10.15. What is his pitching speed?

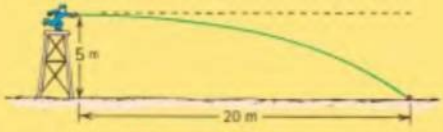


FIGURE 10.15

Check Your Answer

The ball is thrown horizontally, so the pitching speed is horizontal distance divided by time. A horizontal distance of 20 m is given, but the time is not stated. However, knowing the vertical drop is 5 m, you remember that a 5-m drop takes 1 s! From the equation for constant speed (which applies to horizontal motion), $v = d/t = (20\text{ m})/(1\text{ s}) = 20\text{ m/s}$. It is interesting to note that the equation for constant speed, $v = d/t$, guides our thinking about the crucial factor in this problem—the *time*.

Hang Time Revisited

In Chapter 3, we stated that airborne time during a jump is independent of horizontal speed. Now we see why this is so—horizontal and vertical components of motion are independent of each other. The rules of projectile motion apply to jumping. Once one's feet are off the ground, only the force of gravity acts on the jumper (neglecting air resistance). Hang time depends only on the vertical component of lift-off velocity. It so happens, however, that the action of running can make a difference. When running, the lift-off force during jumping can be appreciably increased by pounding of the feet against the ground (and the ground pounding against the feet in action–reaction fashion), so hang time for a running jump can exceed hang time for a standing jump. But again for emphasis: Once the runner's feet are off the ground, only the vertical component of lift-off velocity determines hang time.

Fast-Moving Projectiles—Satellites

Consider the baseball pitcher on the tower in Figure 10.15. If gravity did not act on the ball, the ball would follow a straight-line path shown by the dashed line. But gravity does act, so the ball falls below this straight-line path. In fact, as just discussed, 1 s after the ball leaves the pitcher's hand it will have fallen a vertical distance of 5 m below the dashed line—whatever the pitching speed. It is important to understand this, for it is the crux of satellite motion.

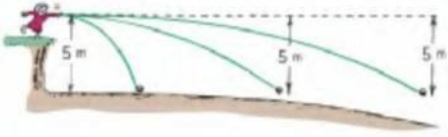


FIGURE 10.16
If you throw a ball at any speed, 1 s later it will have fallen 5 m below where it would have been without gravity.

Earth's curvature, dropping 5 m for each 8-km tangent, means that if you were floating in a calm ocean, you'd be able to see only the top of a 5-m mast on a ship 8 km away.

An Earth **satellite** is simply a projectile that falls *around* Earth rather than *into* it. The speed of the satellite must be great enough to ensure that its falling distance matches Earth's curvature. A geometrical fact about the curvature of Earth is that its surface drops a vertical distance of 5 m for every 8000 m tangent to the surface (Figure 10.17). If a baseball could be thrown fast enough to travel a horizontal distance of 8 km during the 1 s it takes to fall 5 m, then it would follow the curvature of Earth. This is a speed of 8 km/s. If this doesn't seem fast, convert it to kilometers per hour and you get an impressive 29,000 km/h (or 18,000 mi/h)!

FIGURE 10.17
Earth's curvature—not to scale!

FIGURE 10.18
If the speed of the stone is great enough, the stone may become a satellite.

At this speed, atmospheric friction would burn the baseball—or even a piece of iron—to a crisp. This is the fate of bits of rock and other meteorites that enter Earth's atmosphere and burn up, appearing as "falling stars." That is why satellites, such as the space shuttles, are launched to altitudes of 150 km or more—to be above almost all of the atmosphere and to be nearly free of air resistance. A common misconception is that satellites orbiting at high altitudes are free from gravity. Nothing could be further from the truth. The force of gravity on a satellite 200 km above

Earth's surface is nearly as strong as it is at the surface. The high altitude is to position the satellite beyond Earth's atmosphere, where air resistance is almost totally absent, but not beyond Earth's gravity.

Satellite motion was understood by Isaac Newton, who reasoned that the Moon was simply a projectile circling Earth under the attraction of gravity. This concept is illustrated in a drawing by Newton (Figure 10.19). He compared the motion of the Moon to a cannonball fired from the top of a high mountain. He imagined that the mountaintop was above Earth's atmosphere so that air resistance would not impede the motion of the cannonball. If fired with a low horizontal speed, a cannonball would follow a curved path and soon hit Earth below. If it were fired faster, its path would be less curved and it would hit Earth farther away. If the cannonball were fired fast enough, Newton reasoned, the curved path would become a circle and the cannonball would circle Earth indefinitely. It would be in orbit.

Both cannonball and Moon have tangential velocity (parallel to Earth's surface) sufficient to ensure motion *around* the Earth rather than *into* it. If there is no resistance to reduce its speed, the Moon or any Earth satellite "falls" around and around the Earth indefinitely. Similarly, the planets continuously fall around the Sun in closed paths. Why don't the planets crash into the Sun? They don't because of their tangential velocities. What would happen if their tangential velocities were reduced to zero? The answer is simple enough: Their falls would be straight toward the Sun, and they would indeed crash into it. Any objects in the solar system without sufficient tangential velocities have long ago crashed into the Sun. What remains is the harmony we observe.

FIGURE 10.19

"The greater the velocity . . . with which (a stone) is projected, the farther it goes before it falls to the Earth. We may therefore suppose the velocity to be so increased, that it would describe an arc of 1, 2, 5, 10, 100, 1000 miles before it arrived at the Earth, till at last, exceeding the limits of the Earth, it should pass into space without touching." — Isaac Newton, *System of the World*.

FIGURE 10.20

A space shuttle is a projectile in a constant state of free fall. Because of its tangential velocity, it falls around the Earth rather than vertically into it.

CHECK POINT

One of the beauties of physics is that there are usually different ways to view and explain a given phenomenon. Is the following explanation valid? Satellites remain in orbit instead of falling to Earth because they are beyond the main pull of Earth's gravity.

Check Your Answer

No, no, a thousand times no! If any moving object were beyond the pull of gravity, it would move in a straight line and would not curve around Earth. Satellites remain in orbit because they *are* being pulled by gravity, not because they are beyond it. For the altitudes of most Earth satellites, Earth's gravitational field is only a few percent weaker than it is at Earth's surface.

Circular Satellite Orbits

An 8-km/s cannonball fired horizontally from Newton's mountain would follow Earth's curvature and glide in a circular path around Earth again and again (provided the cannoneer and the cannon got out of the way). Fired at a slower speed, the cannonball would strike Earth's surface; fired at a faster speed, it would overshoot a circular orbit, as we will discuss shortly. Newton calculated the speed for circular orbit, and because such a cannon-muzzle velocity was clearly impossible, he did not

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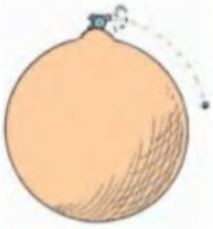


FIGURE 10.21

INTERACTIVE FIGURE

Fired fast enough, the cannonball will go into orbit.

foresee the possibility of humans launching satellites (and likely didn't consider multistage rockets).

Note that, in circular orbit, the speed of a satellite is not changed by gravity: Only the direction changes. We can understand this by comparing a satellite in circular orbit with a bowling ball rolling along a bowling lane. Why doesn't the gravity that acts on the bowling ball change its speed? The answer is that gravity pulls straight downward with no component of force acting forward or backward.

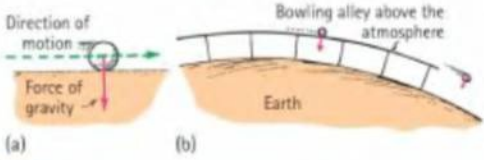


FIGURE 10.22

(a) The force of gravity on the bowling ball is at 90° to its direction of motion, so it has no component of force to pull it forward or backward, and the ball rolls at constant speed. (b) The same is true even if the bowling alley is larger and remains "level" with the curvature of Earth.

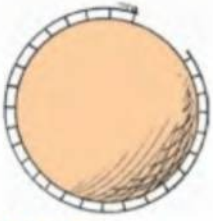


FIGURE 10.23

What speed will allow the ball to clear the gap?

Consider a bowling lane that completely surrounds the Earth, elevated high enough to be above the atmosphere and air resistance. The bowling ball will roll at constant speed along the lane. If a part of the lane were cut away, the ball would roll off its edge and would hit the ground below. A faster ball encountering the gap would hit the ground farther along the gap. Is there a speed at which the ball will clear the gap (like a motorcyclist who drives off a ramp and clears a gap to meet a ramp on the other side)? The answer is yes: 8 km/s will be enough to clear any gap—even a 360° gap. The ball would be in circular orbit.

Note that a satellite in circular orbit is always moving in a direction perpendicular to the force of gravity that acts upon it. The satellite does not move in the direction of the force, which would increase its speed, nor does it move in a direction against the force, which would decrease its speed. Instead, the satellite moves at right angles to the gravitational force that acts upon it. No change in speed occurs—only a change in direction. So we see why a satellite in circular orbit sails parallel to the surface of the Earth at constant speed—a very special form of free fall.

For a satellite close to Earth, the period (the time for a complete orbit about Earth) is about 90 minutes. For higher altitudes, the orbital speed is less, distance is more, and the period is longer. For example, communication satellites located in orbit 5.5 Earth radii above the surface of Earth have a period of 24 hours. This period matches the period of daily Earth rotation. For an orbit around the equator, these satellites always remain above the same point on the ground. The Moon is even farther away and has a period of 27.3 days. The higher the orbit of a satellite, the less its speed, the longer its path, and the longer its period.[1]

The initial vertical climb gets a rocket quickly through the denser part of the atmosphere. Eventually, the rocket must acquire enough tangential speed to remain in orbit without thrust, so it must tilt until its path is parallel to Earth's surface.

Putting a satellite into Earth orbit requires control over the speed and direction of the rocket that carries it above the atmosphere. A rocket initially fired vertically is intentionally tipped from the vertical course. Then, once above the resistance of the atmosphere, it is aimed horizontally, whereupon the satellite is given a final thrust to orbital speed. We see this in Figure 10.24, where, for the sake of simplicity, the

[1]The speed of a satellite in circular orbit is given by $v = \sqrt{\frac{GM}{d}}$ and the period of satellite motion is given by $T = 2\pi\sqrt{\frac{d^3}{GM}}$, where G is the universal gravitational constant (see previous Chapter 9), M is the mass of Earth (or whatever body the satellite orbits), and d is the distance of the satellite from the center of Earth or other parent body.

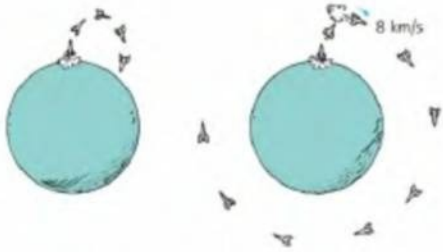


FIGURE 10.24
The initial thrust of the rocket pushes it up above the atmosphere. Another thrust to a tangential speed of at least 8 km/s is required if the rocket is to fall around rather than into Earth.

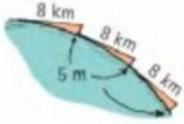
satellite is the entire single-stage rocket. With the proper tangential velocity, it falls around Earth, rather than into it, and becomes an Earth satellite.

CHECK POINT

1. True or false: The space shuttle orbits at altitudes in excess of 150 km to be above both gravity and Earth's atmosphere.
2. Satellites in close circular orbit fall about 5 m during each second of orbit. Why doesn't this distance accumulate and send satellites crashing into Earth's surface?

Check Your Answers

1. False. What satellites are above is the atmosphere and air resistance—*not* gravity! It's important to note that Earth's gravity extends throughout the universe in accord with the inverse-square law.
2. In each second, the satellite falls about 5 m below the straight-line tangent it would have followed if there were no gravity. Earth's surface also curves 5 m beneath a straight-line 8-km tangent. The process of falling with the curvature of Earth continues from tangent line to tangent line, so the curved path of the satellite and the curve of Earth's surface "match" all the way around the planet. Satellites do, in fact, crash to Earth's surface from time to time when they encounter air resistance in the upper atmosphere that decreases their orbital speed.



Elliptical Orbits

If a projectile just above the resistance of the atmosphere is given a horizontal speed somewhat greater than 8 km/s, it will overshoot a circular path and trace an oval path called an **ellipse.** An ellipse is a specific curve: the closed path taken by a point that moves in such a way that the sum of its distances from two fixed points (called *foci*) is constant. For a satellite orbiting a planet, one focus is at the center of the planet; the other focus could be internal or external to the planet. An ellipse can be easily constructed by using a pair of tacks (one at each focus), a loop of string, and a pencil (Figure 10.25). The closer the foci are to each other, the closer the ellipse is to a circle. When both foci are together, the ellipse *is* a circle. So we can see that a circle is a special case of an ellipse.

FIGURE 10.25
INTERACTIVE FIGURE
A simple method for constructing an ellipse.

FIGURE 10.26
The shadows cast by the ball from each lamp in the room are all ellipses. The point at which the ball makes contact with the table is the common focus of all three ellipses.

Whereas the speed of a satellite is constant in a circular orbit, speed varies in an elliptical orbit. For an initial speed greater than 8 km/s, the satellite overshoots a circular path and moves away from Earth, against the force of gravity. It therefore loses speed. The speed it loses in receding is regained as it falls back toward Earth, and it finally rejoins its original path with the same speed it had initially (Figure 10.27). The procedure repeats over and over, and an ellipse is traced each cycle.

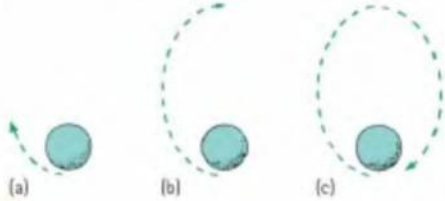


FIGURE 10.27

Elliptical orbit. An Earth satellite that has a speed somewhat greater than 8 km/s overshoots a circular orbit (a) and travels away from Earth. Gravitation slows it to a point where it no longer moves farther from Earth (b). It falls toward Earth, gaining the speed it lost in receding (c), and follows the same path as before in a repetitious cycle.

Interestingly enough, the parabolic path of a projectile, such as a tossed baseball or a cannonball, is actually a tiny segment of a skinny ellipse that extends within and just beyond the center of Earth (Figure 10.28a). In Figure 10.28b, we see several paths of cannonballs fired from Newton's mountain. All these ellipses have the center of Earth as one focus. As muzzle velocity is increased, the ellipses are less eccentric (more nearly circular); and, when muzzle velocity reaches 8 km/s, the ellipse rounds into a circle and does not intercept Earth's surface. The cannonball coasts in circular orbit. At greater muzzle velocities, orbiting cannonballs trace the familiar external ellipses.

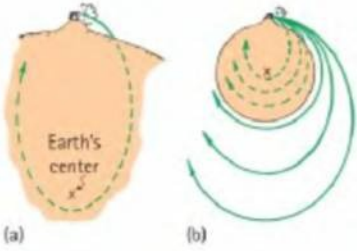
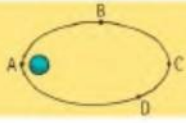


FIGURE 10.28

(a) The parabolic path of the cannonball is part of an ellipse that extends within Earth. Earth's center is the far focus.
(b) All paths of the cannonball are ellipses. For less than orbital speeds, the center of Earth is the far focus; for a circular orbit, both foci are Earth's center; for greater speeds, the near focus is Earth's center.

CHECK POINT

The orbital path of a satellite is shown in the sketch. In which of the marked positions A through D does the satellite have the greatest speed? The lowest speed?



Check Your Answer

The satellite has its greatest speed as it whips around position A and has its lowest speed at position C. After passing C, it gains speed as it falls back to A to repeat its cycle.

World Monitoring by Satellite

Satellites are useful in monitoring our planet. Figure A shows the path traced in one period by a satellite in circular orbit launched in a northeasterly direction from Cape Canaveral, Florida. The path is curved only because the map is flat. Note that the path crosses the equator twice in one period, for the path describes a circle whose plane passes through Earth's center. Note also that the path does not terminate where it begins. This is because Earth rotates beneath the satellite while it orbits. During the 90-minute period, Earth turns 22.5°, so, when the satellite makes a complete orbit it begins its new sweep many kilometers to the west (about 2500 km at the equator). This is quite advantageous for Earth-monitoring satellites. Figure B shows the area monitored over 10 days by successive sweeps for a typical satellite.

A dramatic but typical example of such monitoring is the 3-year worldwide watch of the distribution of ocean phytoplankton (Figure C). Such extensive information would have been impossible to acquire before the advent of satellites.

FIGURE A

The path of a typical satellite launched in a northeasterly direction from Cape Canaveral. Because Earth rotates while the satellite orbits, each sweep passes overhead some 2100 km farther west at the latitude of Cape Canaveral.

FIGURE B

Typical sweep pattern for a satellite over the period of a week.

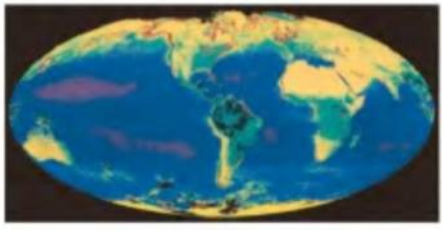


FIGURE C

Phytoplankton production in Earth's oceans over a 3-year period. Magenta and yellow show the highest concentrations, while blue shows moderately high concentrations.

Kepler's Laws of Planetary Motion

Newton's law of gravitation was preceded by three important discoveries about planetary motion by the German astronomer Johannes Kepler, who started as a junior assistant to the famed Danish astronomer Tycho Brahe. Brahe directed the world's first great observatory, in Denmark, just before the advent of the telescope. Using huge, brass, protractor-like instruments called *quadrants*, Brahe measured the positions of planets over 20 years so accurately that his measurements are still valid today. Brahe entrusted his data to Kepler. After Brahe's death, Kepler converted Brahe's measurements to values that would be obtained by a stationary observer outside the solar system. Kepler's expectation that the planets would move in perfect circles around the Sun was shattered after years of effort. He discovered the paths to be ellipses. This is Kepler's first law of planetary motion:

Tycho Brahe (1546–1601)

Johannes Kepler (1571–1630)

The path of each planet around the Sun is an ellipse with the Sun at one focus.

Kepler also found that the planets do not revolve around the Sun at a uniform speed but move faster when they are nearer the Sun and slower when they are farther from the Sun. They do this in such a way that an imaginary line or spoke joining the Sun and the planet sweeps out equal areas of space in equal times. The triangular-shaped area swept out during a month when a planet is orbiting far from the Sun (triangle ASB in Figure 10.29) is equal to the triangular area swept out during a month when the planet is orbiting closer to the Sun (triangle CSD in Figure 10.29). This is Kepler's second law:

The line from the Sun to any planet sweeps out equal areas of space in equal time intervals.

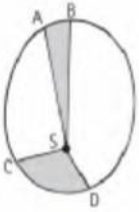


FIGURE 10.29

Equal areas are swept out in equal intervals of time.

Kepler was the first to coin the word *satellite.* He had no clear idea as to *why* the planets moved as he discovered. He lacked a conceptual model. Kepler didn't see that a satellite is simply a projectile under the influence of a gravitational force directed toward the body that the satellite orbits. You know that if you toss a rock upward, it goes slower the higher it rises because it's moving against gravity. And you know that when it returns, it's moving with gravity and its speed increases. Kepler didn't see that a satellite behaves in the same way. Going away from the Sun, it slows. Going toward the Sun, it speeds up. A satellite, whether a planet orbiting the Sun or one of today's satellites orbiting Earth, moves slower against the gravitational field and faster with the field. Kepler didn't see this simplicity and instead fabricated complex systems of geometrical figures to find sense in his discoveries. These systems proved to be futile.

After 10 years of searching by trial and error for a connection between the time it takes a planet to orbit the Sun and its distance from the Sun, Kepler discovered a third law. From Brahe's data, Kepler found that the square of any planet's period (T) is directly proportional to the cube of its average orbital radius (r). Law three is:

The square of the orbital period of a planet is directly proportional to the cube of the average distance of the planet from the Sun ($T^2 \sim r^3$ for all planets).

With Kepler's third law, you can calculate the radius of a planet's orbit from its orbital period.

This means that the ratio T^2/r^3 is the same for all planets. So, if a planet's period is known, its average orbital radial distance is easily calculated (or vice versa).

It is interesting to note that Kepler was familiar with Galileo's ideas about inertia and accelerated motion, but he failed to apply them to his own work. Like Aristotle, he thought that the force on a moving body would be in the same direction as the body's motion. Kepler never appreciated the concept of inertia. Galileo, on the other hand, never appreciated Kepler's work and held to his conviction that the planets move in circles.[2] Further understanding of planetary motion required someone who could integrate the findings of these two great scientists.[3] The rest is history, for this task fell to Isaac Newton.

fyi

- In 2009, 400 years after Galileo invented the telescope, the United States launched an orbiting telescope named Kepler, specifically to see Earth-like planets obscured by the light of their sun.

[2]It is not easy to look at familiar things through the new insights of others. We tend to see only what we have learned to see or wish to see. Galileo reported that many of his colleagues were unable or refused to see the moons of Jupiter when they peered skeptically through his telescopes. Galileo's telescopes were a boon to astronomy, but more important than an improved instrument to see things clearer was a new way of understanding what is seen. Is this still true today?

[3]Perhaps your instructor will show that Kepler's third law results when Newton's inverse-square formula for gravitational force is equated to centripetal force, and how T^2/r^3 equals a constant that depends only on G and M, the mass of the body about which orbiting occurs. Intriguing stuff!

Energy Conservation and Satellite Motion

Recall, from Chapter 7, that an object in motion possesses kinetic energy (KE) due to its motion. An object above Earth's surface possesses potential energy (PE) by virtue of its position. Everywhere in its orbit, a satellite has both KE and PE. The sum of the KE and PE is a constant all through the orbit. The simplest case occurs for a satellite in circular orbit.

In a circular orbit, the distance between the satellite and the center of the attracting body does not change, which means that the PE of the satellite is the same everywhere in its orbit. Then, by the conservation of energy, the KE must also be constant. So a satellite in circular orbit coasts at an unchanging PE, KE, and speed (Figure 10.30).

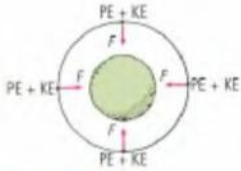


FIGURE 10.30
The force of gravity on the satellite is always toward the center of the body it orbits. For a satellite in circular orbit, no component of force acts along the direction of motion. The speed and thus the KE do not change.

In an elliptical orbit, the situation is different. Both speed and distance vary. PE is greatest when the satellite is farthest away (at the *apogee*) and least when the satellite is closest (at the *perigee*). Note that the KE will be least when the PE is most, and the KE will be most when the PE is least. At every point in the orbit, the sum of KE and PE is the same (Figure 10.31).

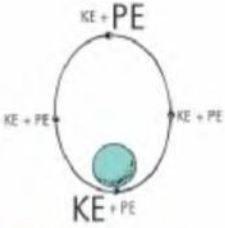


FIGURE 10.31
The sum of KE and PE for a satellite is a constant at all points along its orbit.

At all points along the elliptical orbit, except at the apogee and the perigee, there is a component of gravitational force parallel to the direction of motion of the satellite. This component of force changes the speed of the satellite. Or we can say that (this component of force) × (distance moved) = ΔKE. Either way, when the satellite gains altitude and moves against this component, its speed and KE decrease. The decrease continues to the apogee. Once past the apogee, the satellite moves in the same direction as the component, and the speed and KE increase. The increase continues until the satellite whips past the perigee and repeats the cycle.

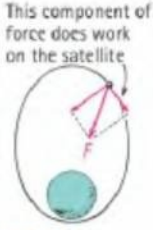
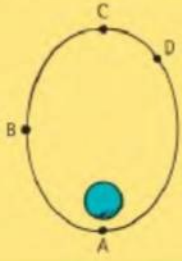


FIGURE 10.32
In elliptical orbit, a component of force exists along the direction of the satellite's motion. This component changes the speed and, thus, the KE. (The perpendicular component changes only the direction.)

CHECK POINT

1. The orbital path of a satellite is shown in the sketch. In which marked positions A through D does the satellite have the greatest KE? The greatest PE? The greatest total energy?
2. Why does the force of gravity change the speed of a satellite when it is in an elliptical orbit but not when it is in a circular orbit?



Check Your Answers

1. KE is maximum at the perigee A; PE is maximum at the apogee C; the total energy is the same everywhere in the orbit.
2. In circular orbit, the gravitational force is always perpendicular to the orbital path. With no component of gravitational force along the path, only the direction of motion changes—not the speed. In elliptical orbit, however, the satellite moves in directions that are not perpendicular to the force of gravity. Then components of force do exist along the path, which change the speed of the satellite. A component of force along (parallel to) the direction the satellite moves does work to change its KE.

Escape Speed

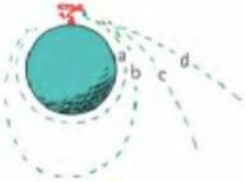


FIGURE 10.33
INTERACTIVE FIGURE

If Superman tosses a ball 8 km/s horizontally from the top of a mountain high enough to be just above air resistance (a), then about 90 minutes later he can turn around and catch it (neglecting Earth's rotation). Tossed slightly faster (b), it will take an elliptical orbit and return in a slightly longer time. Tossed at more than 11.2 km/s (c), it will escape Earth. Tossed at more than 42.5 km/s (d), it will escape the solar system.

We know that a cannonball fired horizontally at 8 km/s from Newton's mountain would find itself in orbit. But what would happen if the cannonball were instead fired at the same speed *vertically?* It would rise to some maximum height, reverse direction, and then fall back to Earth. Then the old saying "What goes up must come down" would hold true, just as surely as a stone tossed skyward will be returned by gravity (unless, as we shall see, its speed is great enough).

In today's spacefaring age, it is more accurate to say, "What goes up *may* come down," for there is a critical starting speed that permits a projectile to outrun gravity and to escape Earth. This critical speed is called the **escape speed** or, if direction is involved, the *escape velocity.* From the surface of Earth, escape speed is 11.2 km/s. If you launch a projectile at any speed greater than that, it will leave Earth, traveling slower and slower, never stopping due to Earth's gravity.[4] We can understand the magnitude of this speed from an energy point of view.

How much work would be required to lift a payload against the force of Earth's gravity to a distance very, very far ("infinitely far") away? We might think that the change of PE would be infinite because the distance is infinite. But gravity diminishes with distance by the inverse-square law. The force of gravity on the payload would be strong only near Earth. Most of the work done in launching a rocket occurs within 10,000 km or so of Earth. It turns out that the change of PE of a 1-kg body moved from the surface of Earth to an infinite distance is 62 million joules (62 MJ). So, to put a payload infinitely far from Earth's surface requires at least 62 MJ of energy per kilogram of load. We won't go through the calculation here, but 62 MJ per kilogram corresponds to a speed of 11.2 km/s, whatever the total mass involved. This is the escape speed from the surface of Earth.[5]

If we give a payload any more energy than 62 MJ per kilogram at the surface of Earth or, equivalently, any more speed than 11.2 km/s, then, neglecting air drag, the payload will escape from Earth, never to return. As it continues outward, its PE increases and its KE decreases. Its speed becomes less and less, though it is never reduced to zero. The payload outruns the gravity of Earth. It escapes.

Wouldn't Newton have relished seeing satellite motion in terms of *energy*—a concept that came much later?

The escape speeds from various bodies in the solar system are shown in Table 10.1. Note that the escape speed from the surface of the Sun is 620 km/s. Even at a 150,000,000-km distance from the Sun (Earth's distance), the escape speed to break free of the Sun's influence is 42.5 km/s—considerably more than the escape speed from Earth. An object projected from Earth at a speed greater than 11.2 km/s but less than 42.5 km/s will escape Earth but not the Sun. Rather than recede forever, it will occupy an orbit around the Sun.

The first probe to escape the solar system, *Pioneer 10,* was launched from Earth in 1972 with a speed of only 15 km/s. The escape was accomplished by directing the probe to pass just behind giant Jupiter. It was whipped about by Jupiter's great gravitational field, picking up speed in the process—similar to the increase in the speed of a baseball encountering an oncoming bat (but without physical contact). Its speed of departure from Jupiter was increased enough to exceed the escape speed from the Sun at the distance of Jupiter. *Pioneer 10* passed the orbit of Pluto in 1984. Unless it collides with another body, it will wander indefinitely through interstellar space. Like a bottle cast into the sea with a note inside, *Pioneer 10* contains information about

[4]Escape speed from any planet or any body is given by $v = \sqrt{\frac{2GM}{d}}$, where G is the universal gravitational constant, M is the mass of the attracting body, and d is the distance from its center. (At the surface of the body, d would simply be the radius of the body.) For a bit more mathematical insight, compare this formula with the one for orbital speed in footnote 1 a few pages back.

[5]Interestingly enough, this might well be called the *maximum falling speed.* Any object, however far from Earth, released from rest and allowed to fall to Earth only under the influence of Earth's gravity, would not exceed 11.2 km/s. (With air friction, it would be less.)

TABLE 10.1

Escape Speeds at the Surface of Bodies in the Solar System

Astronomical Body	Mass (Earth masses)	Radius (Earth radii)	Escape Speed (km/s)
Sun	333,000	109	620
Sun (at a distance of Earth's orbit)		23,500	42.2
Jupiter	318	11	60.2
Saturn	95.2	9.2	36.0
Neptune	17.3	3.47	24.9
Uranus	14.5	3.7	22.3
Earth	1.00	1.00	11.2
Venus	0.82	0.95	10.4
Mars	0.11	0.53	5.0
Mercury	0.055	0.38	4.3
Moon	0.0123	0.27	2.4

The mind that encompasses the universe is as marvelous as the universe that encompasses the mind.

Earth that might be of interest to extraterrestrials, in hopes that it will one day "wash up" and be found on some distant "seashore."

It is important to point out that the escape speed of a body is the initial speed given by a brief thrust, after which there is no force to assist motion. One could escape Earth at *any* sustained speed more than zero, given enough time. For example, suppose a rocket is launched to a destination such as the Moon. If the rocket engines burn out when still close to Earth, the rocket needs a minimum speed of 11.2 km/s. But if the rocket engines can be sustained for long periods of time, the rocket could reach the Moon without ever attaining 11.2 km/s.

FIGURE 10.34

Historic *Pioneer 10*, launched from Earth in 1972, passed the outermost planet in 1984 and is now wandering in our galaxy.

It is interesting to note that the accuracy with which an unmanned rocket reaches its destination is not accomplished by staying on a preplanned path or by getting back on that path if the rocket strays off course. No attempt is made to return the rocket to its original path. Instead, the control center in effect asks, "Where is it now and what is its velocity? What is the best way to reach its destination, given its present situation?" With the aid of high-speed computers, the answers to these questions are used in finding a new path. Corrective thrusters direct the rocket to this new path. This process is repeated over and over again all the way to the goal.[6]

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- Just as planets fall around the Sun, stars fall around the centers of galaxies. Those with insufficient tangential speeds are pulled into, and are gobbled up by, the galactic nucleus—usually a black hole.

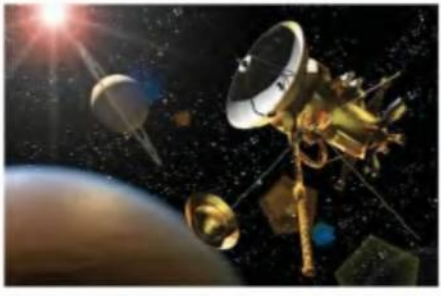


FIGURE 10.35

The European–U.S. spacecraft *Cassini* beams close-up images of Saturn and its giant moon Titan to Earth. It also measures surface temperatures, magnetic fields, and the size, speed, and trajectories of tiny surrounding space particles.

[6]Is there a lesson to be learned here? Suppose you find that you are off course. You may, like the rocket, find it more fruitful to follow a course that leads to your goal as best plotted from your present position and circumstances, rather than try to get back on the course you plotted from a previous position and under, perhaps, different circumstances.

SUMMARY OF TERMS

Projectile Any object that moves through the air or through space under the influence of gravity.

Parabola The curved path followed by a projectile under the influence only of constant gravity.

Satellite A projectile or small celestial body that orbits a larger celestial body.

Ellipse The oval path followed by a satellite. The sum of the distances from any point on the path to two points called foci is a constant. When the foci are together at one point, the ellipse is a circle. As the foci get farther apart, the ellipse becomes more "eccentric."

Kepler's laws Law 1: The path of each planet around the Sun is an ellipse with the Sun at one focus.
Law 2: The line from the Sun to any planet sweeps out equal areas of space in equal time intervals.
Law 3: The square of the orbital period of a planet is directly proportional to the cube of the average distance of the planet from the Sun ($T^2 \sim r^3$ for all planets).

Escape speed The speed that a projectile, space probe, or similar object must reach to escape the gravitational influence of Earth or of another celestial body to which it is attracted.

REVIEW QUESTIONS

1. Why must a horizontally moving projectile have a large speed to become an Earth satellite?

Projectile Motion

2. What exactly is a projectile?

Projectiles Launched Horizontally

3. Why does the vertical component of velocity for a projectile change with time, whereas the horizontal component of velocity doesn't?

Projectiles Launched at an Angle

4. A stone is thrown upward at an angle. What happens to the horizontal component of its velocity as it rises? As it falls?
5. A stone is thrown upward at an angle. What happens to the vertical component of its velocity as it rises? As it falls?
6. A projectile falls beneath the straight-line path it would follow if there were no gravity. How many meters does it fall below this line if it has been traveling for 1 s? For 2 s?
7. Do your answers to the previous question depend on the angle at which the projectile is launched?
8. A projectile is launched upward at an angle of 75° from the horizontal and strikes the ground a certain distance downrange. For what other angle of launch at the same speed would this projectile land just as far away?
9. A projectile is launched vertically at 100 m/s. If air resistance can be neglected, at what speed will it return to its initial level?

Fast-Moving Projectiles—Satellites

10. How can a projectile "fall around the Earth"?
11. Why will a projectile that moves horizontally at 8 km/s follow a curve that matches the curvature of the Earth?
12. Why is it important that the projectile in the previous question be above Earth's atmosphere?

Circular Satellite Orbits

13. Why doesn't the force of gravity change the speed of a satellite in circular orbit?
14. How much time is taken for a complete revolution of a satellite in close orbit about the Earth?
15. For orbits of greater altitude, is the period longer or shorter?

Elliptical Orbits

16. Why does the force of gravity change the speed of a satellite in an elliptical orbit?

Kepler's Laws of Planetary Motion

17. Who gathered the data that were used to show that the planets travel in elliptical paths around the Sun? Who discovered elliptical orbits? Who explained them?
18. What did Kepler discover about the periods of planets and their distances from the Sun? Was this discovery aided by thinking of satellites as projectiles moving under the influence of the Sun?
19. In Kepler's thinking, what was the direction of the force on a planet? In Newton's thinking, what was the direction of the force?

Energy Conservation and Satellite Motion

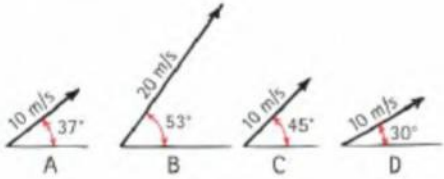
20. Why is kinetic energy a constant for a satellite in a circular orbit but not for a satellite in an elliptical orbit?
21. Is the sum of kinetic and potential energies a constant for satellites in circular orbits, in elliptical orbits, or in both?

Escape Speed

22. We talk of 11.2 km/s as the escape speed from Earth. Is it possible to escape from Earth at half this speed? At one-quarter this speed? If so, how?

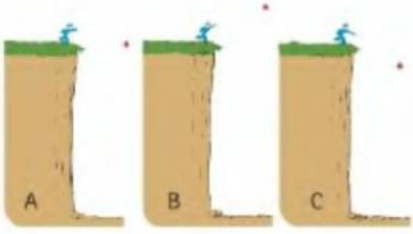
RANKING

1. A ball is thrown upward at velocities and angles shown. From greatest to least, rank them by their



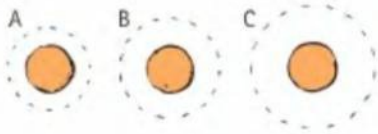
a. vertical components of velocity.
b. horizontal components of velocity.
c. accelerations when they reach the top of their paths.

2. A ball is tossed off the edge of a cliff with the same speed but at different angles, as shown. From greatest to least, rank the



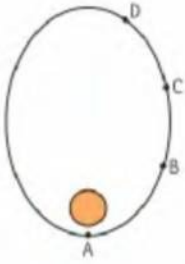
a. initial PEs of the balls relative to the ground below.
b. initial KEs of the balls when tossed.
c. KEs of the balls when hitting the ground below.
d. times of flight while airborne.

3. The dashed lines show three circular orbits about Earth. Rank the following quantities from greatest to least.



a. Their orbital speed
b. Their time to orbit Earth

4. The positions of a satellite in elliptical orbit are indicated. Rank these quantities from greatest to least.



a. Gravitational force
b. Speed
c. Momentum
d. KE
e. PE
f. Total energy (KE + PE)
g. Acceleration

EXERCISES

1. In synchronized diving, divers remain in the air for the same time. With no air drag, they would fall together. But air drag is appreciable, so how do they remain together in fall?

2. Suppose you roll a ball off a tabletop. Will the time to hit the floor depend on the speed of the ball? (Will a fast ball take a longer time to hit the floor?) Defend your answer.

3. Suppose you roll a ball off a tabletop. Compared with a slow roll, will a faster-moving ball hit the floor with a higher *speed*? Defend your answer.

4. If you toss a ball vertically upward in a uniformly moving train, it returns to its starting place. Will it do the same if the train is accelerating? Explain.

5. A heavy crate accidentally falls from a high-flying airplane just as it flies directly above a shiny red Porsche smartly parked in a car lot. Relative to the Porsche, where will the crate crash?

6. Suppose you drop an object from an airplane traveling at constant velocity, and further suppose that air resistance doesn't affect the falling object. What will be its falling path as observed by someone at rest on the ground, not directly below but off to the side where there's a clear view? What will be the falling path as observed by you looking downward from the airplane? Where will the object strike the ground, relative to you in the airplane? Where will it strike in the more realistic case in which air resistance does affect the fall?
7. Fragments of fireworks beautifully illuminate the night sky. (a) What specific path is ideally traced by each fragment? (b) What paths would the fragments trace in a gravity-free region?

8. In the absence of air resistance, why does the horizontal component of a projectile's motion not change, while the vertical component does?
9. At what point in its trajectory does a batted baseball have its minimum speed? If air drag can be neglected, how does this compare with the horizontal component of its velocity at other points?
10. A friend claims that bullets fired by some high-powered rifles travel for many meters in a straight-line path before they start to fall. Another friend disputes this claim and states that all bullets from any rifle drop beneath a straight-line path a vertical distance given by $\frac{1}{2}gt^2$ and that the curved path is apparent for low velocities and less apparent for high velocities. Now it's your turn: Will all fired bullets drop the same vertical distance in equal times? Explain.
11. For maximum range, a football should be punted at about 45° to the horizontal—somewhat less due to air drag. But punts are often kicked at angles greater than 45°. Can you think of a reason why?
12. When a rifle is being fired at a distant target, why isn't the barrel aligned so that it points exactly at the target?
13. Two golfers each hit a ball at the same speed, but one at 60° with the horizontal and the other at 30°. Which ball goes farther? Which hits the ground first? (Ignore air resistance.)
14. A park ranger shoots a monkey hanging from a branch of a tree with a tranquilizing dart. The ranger aims directly at the monkey, not realizing that the dart will follow a parabolic path and thus will fall below the monkey. The monkey, however, sees the dart leave the gun and lets go of the branch to avoid being hit. Will the monkey be hit anyway? Does the velocity of the dart affect your answer, assuming that it is great enough to travel the horizontal distance to the tree before hitting the ground? Defend your answer.

15. A projectile is fired straight upward at 141 m/s. How fast is it moving at the instant it reaches the top of its trajectory? Suppose that it were fired upward at 45° instead. Then its horizontal component of velocity is 100 m/s. What would be the speed of the projectile at the top of its trajectory?
16. When you jump upward, your hang time is the time your feet are off the ground. Does hang time depend on your vertical component of velocity when you jump, your horizontal component of velocity, or both? Defend your answer.
17. The hang time of a basketball player who jumps a vertical distance of 2 feet (0.6 m) is about $\frac{2}{3}$ second. What will be the hang time if the player reaches the same height while jumping 4 feet (1.2 m) horizontally?
18. Since the Moon is gravitationally attracted to Earth, why doesn't it simply crash into Earth?
19. Which planets have a more-than-one-Earth-year period, planets nearer than Earth to the Sun, or planets farther from the Sun than Earth?
20. When the space shuttle coasts in a circular orbit at constant speed about Earth, is it accelerating? If so, in what direction? If not, why not?
21. Does the speed of a falling object depend on its mass? Does the speed of a satellite in orbit depend on its mass? Defend your answers.
22. On which does the speed of a circling satellite *not* depend: the mass of the satellite, the mass of Earth, or the distance of the satellite from Earth.
23. A circularly moving object requires a centripetal force. What supplies this force for satellites that orbit Earth?
24. If you have ever watched the launching of an Earth satellite, you may have noticed that the rocket starts vertically upward, then departs from a vertical course and continues its climb at an angle. Why does it start vertically? Why does it not continue vertically?
25. Mars has about $\frac{1}{9}$ the mass of Earth. If Mars were somehow positioned into the same orbit as Earth's, how would its time to circle the Sun compare with Earth's? (Longer, shorter, or the same?)
26. If a cannonball is fired from a tall mountain, gravity changes its speed all along its trajectory. But if it is fired fast enough to go into circular orbit, gravity does not change its speed at all. Explain.
27. A satellite can orbit at 5 km above the Moon, but not at 5 km above Earth. Why?

28. In 2000–2001, NASA's Near Earth Asteroid Rendezvous (NEAR) spacecraft orbited around the 20-mile-long asteroid Eros. Was the orbital speed of this spacecraft greater or less than 8 km/s? Defend your answer.

29. Would the speed of a satellite in close circular orbit about Jupiter be greater than, equal to, or less than 8 km/s?

30. Why are satellites normally sent into orbit by firing them in an easterly direction, the direction in which Earth spins?

31. When a satellite in circular orbit slows, perhaps due to the firing of a "retro rocket," it ends up gaining more speed than it had initially. Why?

32. Earth is closer to the Sun in December than in June. In which of these two months is Earth moving faster around the Sun?

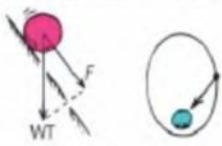
33. Of all the United States, why is Hawaii the most efficient launching site for nonpolar satellites? (*Hint:* Look at the spinning Earth from above either pole and compare it to a spinning turntable.)

34. Two planets are never seen at midnight. Which two, and why?

35. Why does a satellite burn up when it descends into the atmosphere when it doesn't burn up when it ascends through the atmosphere?

36. Neglecting air resistance, could a satellite be put into orbit in a circular tunnel beneath Earth's surface? Discuss.

37. In the sketch on the left, a ball gains KE when rolling down a hill because work is done by the component of weight (F) that acts in the direction of motion. Sketch in the similar component of gravitational force that does work to change the KE of the satellite on the right.



38. Why is work done by the force of gravity on a satellite when it moves from one part of an elliptical orbit to another, but not when it moves from one part of a circular orbit to another?

39. What is the shape of the orbit when the velocity of the satellite is everywhere perpendicular to the force of gravity?

40. If a space shuttle circled Earth at a distance equal to the Earth–Moon distance, how long would it take for it to make a complete orbit? In other words, what would be its period?

41. Can a satellite coast in a stable orbit in a plane that doesn't intersect the Earth's center? Defend your answer.

42. Can a satellite maintain an orbit in the plane of the Arctic Circle? Why or why not?

43. You read in an article about astronauts in a major magazine that "about 62 miles up, the atmosphere ends and gravity becomes very weak. . . ." What error is made here?

44. A "geosynchronous" Earth satellite can remain nearly directly overhead in Singapore, but not in San Francisco. Why?

45. When an Earth satellite is placed into a higher orbit, what happens to its period?

46. If a flight mechanic drops a box of tools from a high-flying jumbo jet, it crashes to Earth. In 2008 an astronaut on the orbiting space shuttle accidentally dropped a box of tools. Why did the tools not crash to Earth? Defend your answer.

47. How could an astronaut in a space shuttle "drop" an object vertically to Earth?

48. A high-orbiting spaceship travels at 7 km/s with respect to Earth. Suppose it projects a capsule rearward at 7 km/s with respect to the ship. Describe the path of the capsule with respect to Earth.

49. A satellite in circular orbit about the Moon fires a small probe in a direction opposite to the velocity of the satellite. If the speed of the probe relative to the satellite is the same as the satellite's speed relative to the Moon, describe the motion of the probe. If the probe's relative speed is twice the speed of the satellite, why would it pose a danger to the satellite?

50. The orbital velocity of Earth about the Sun is 30 km/s. If Earth were suddenly stopped in its tracks, it would simply fall radially into the Sun. Devise a plan whereby a rocket loaded with radioactive wastes could be fired into the Sun for permanent disposal. How fast and in what direction with respect to Earth's orbit should the rocket be fired?

51. If you stopped an Earth satellite dead in its tracks, it would simply crash into Earth. Why, then, don't the communications satellites that "hover motionless" above the same spot on Earth crash into Earth?

52. In an accidental explosion, a satellite breaks in half while in circular orbit about Earth. One half is brought momentarily to rest. What is the fate of the half brought to rest? What happens to the other half?

53. A giant rotating wheel in space provides artificial gravity for its occupants, as discussed in Chapter 8. Instead of a full wheel, discuss the idea of a pair of capsules joined by a tether line and rotating about each other. Can such an arrangement provide artificial gravity for the occupants?

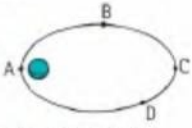
54. What is the advantage of launching space vehicles from high-flying aircraft instead of from the ground?

55. Which requires less fuel, launching a rocket to escape speed from the Moon or from Earth? Defend your answer.

56. What is the maximum possible speed of impact upon the surface of Earth for a faraway body initially at rest that falls to Earth by virtue of Earth's gravity only?

57. As part of their training before going into orbit, astronauts experience weightlessness when riding in an airplane that is flown along the same parabolic trajectory as a freely falling projectile. A classmate says that gravitational forces on everything inside the plane during this maneuver cancel to zero. Another classmate looks to you for confirmation. What is your response?

58. At which of the indicated positions does the satellite in elliptical orbit experience the greatest gravitational force? Have the greatest speed? The greatest velocity? The greatest momentum? The greatest kinetic energy? The greatest gravitational potential energy? The greatest total energy? The greatest angular momentum? The greatest acceleration?



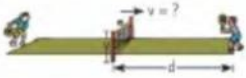
59. At what point in its elliptical orbit about the Sun is the acceleration of Earth toward the Sun at a maximum? At what point is it at a minimum? Defend your answers.

60. A rocket coasts in an elliptical orbit around Earth. To attain the greatest amount of KE for escape using a given amount of fuel, should it fire its engines to accelerate forward when it is at the apogee or at the perigee? (*Hint:* Let the formula $Fd = \Delta KE$be your guide to thinking. Suppose the thrust F is brief and of the same duration in either case. Then consider the distance d the rocket would travel during this brief burst at the apogee and at the perigee.)

PROBLEMS

1. A ball is thrown horizontally from a cliff at a speed of 10 m/s. You predict that its speed 1 s later will be slightly greater than 14 m/s. Your friend says it will be 10 m/s. Show who is correct.
2. You're in an airplane that flies horizontally with speed 1000 km/h (280 m/s) when an engine falls off. Neglecting air resistance, assume it takes 30 s for the engine to hit the ground.
   a. Show that the airplane is 4.5 km high.
   b. Show that the horizontal distance that the aircraft engine falls is 8400 m.
   c. If the airplane somehow continues to fly as if nothing had happened, where is the engine relative to the airplane at the moment the engine hits the ground?
3. A cannonball shot with an initial velocity of 141 m/s at an angle of 45° follows a parabolic path and hits a balloon at the top of its trajectory. Neglecting air resistance, show that the cannonball hits the balloon at a speed of 100 m/s.
4. Students in Chuck Stone's lab (Figure 10.5) measure the speed of a steel ball to be 8.0 m/s when launched horizontally from a 1.0-m high tabletop. Their objective is to place a 20-cm tall coffee can on the floor to catch the ball. Show that they score a bull's-eye when the can is placed 3.2 m from the base of the table.
5. At a particular point in orbit a satellite in an elliptical orbit has a gravitational potential energy of 5000 MJ with respect to Earth's surface and a kinetic energy of 4500 MJ. Later in its orbit, the satellite's potential energy is 6000 MJ. What is its kinetic energy at that point?
6. A certain satellite has a kinetic energy of 8 billion joules at perigee (the point at which it is closest to Earth) and 5 billion joules at apogee (the point at which it is farthest from Earth). As the satellite travels from apogee to perigee, how much work does the gravitational force do on it? Does its potential energy increase or decrease during this time, and by how much?
7. Calculate the hang time of a person who moves horizontally 3 m during a 1.25-m high jump. What is the hang time when moving 6 m horizontally during this jump?

• 8. A horizontally moving tennis ball barely clears the net, a distance y above the surface of the court. To land within the tennis court the ball must not be moving too fast.



   a. To remain within the court's border, a horizontal distance d from the bottom of the net, show that the ball's maximum speed over the net is

$$v = \frac{d}{\sqrt{\frac{2y}{g}}}$$

   b. Suppose the height of the net is 1.00 m, and the court's border is 12.0 m from the bottom of the net. Use $g = 10\ \text{m/s}^2$ and show that the maximum speed of the horizontally moving ball clearing the net is about 27 m/s (about 60 mi/h).
   c. Does the mass of the ball make a difference? Defend your answer.

CHAPTER 10 ONLINE RESOURCES

PhysicsPlace.com

Interactive Figures

- 10.3, 10.4, 10.9, 10.11, 10.13, 10.21, 10.25, 10.33

Tutorials

- Projective Motion
- Orbital Motion

Videos

- Projectile Motion
- More Projectile Motion
- Circular Orbits

Quizzes

Flashcards

Links

PART ONE MULTIPLE-CHOICE PRACTICE EXAM

Choose the BEST answer to the following:

1. The language of science is
   (a) mathematics.
   (b) Latin.
   (c) Chinese.
   (d) Arabic.
2. Somebody who says, "that's only a theory" likely doesn't know that a scientific theory is
   (a) an educated guess.
   (b) a hypothesis.
   (c) a vast synthesis of well-tested hypotheses and facts.
   (d) None of these.
3. The force needed to keep a ball rolling along a bowling alley is
   (a) due to gravity.
   (b) an inertial force.
   (c) a slight breeze.
   (d) None of these.
4. The equilibrium rule, $\Sigma F = 0$, applies to objects
   (a) at rest.
   (b) moving at constant velocity.
   (c) Both.
   (d) Neither.
5. If gravity between the Sun and Earth suddenly vanished, Earth would continue moving in
   (a) a curve.
   (b) a straight line.
   (c) an outward spiral.
   (d) an inward spiral.
6. The average speed of a gazelle traveling a distance of 2 km in a time of one-half hour is
   (a) 1 km/h.
   (b) 2 km/h.
   (c) 4 km/h.
   (d) more than 4 km/h.
7. An object in free fall undergoes an increase in
   (a) speed.
   (b) acceleration.
   (c) both speed and acceleration.
8. If a falling object gains 10 m/s each second it falls, its acceleration is
   (a) 10 m/s. (b) 10 m/s per second. (c) Both. (d) Neither.
9. An object with a huge mass also must have a huge
   (a) weight. (b) volume. (c) size. (d) surface area.
10. Why the acceleration of free fall is the same for all masses is explained by Newton's
    (a) first law. (b) second law. (c) third law. (d) law of gravity.
11. The amount of air drag on an 0.8-N flying squirrel dropping vertically at terminal velocity is
    (a) less than 0.8 N.
    (b) 0.8 N.
    (c) more than 0.8 N.
    (d) dependent on the orientation of its body.
12. When a cannonball is fired from a cannon, both the cannonball and the cannon experience equal
    (a) amounts of force. (b) accelerations. (c) Both. (d) Neither.
13. The team that wins in a tug-of-war is the team that
    (a) produces more tension in the rope than the opponent.
    (b) pushes hardest on the ground.
    (c) Both.
    (d) Neither.
14. An airplane with its nose pointing north with an airspeed of 40 km/h in a 30-km/h crosswind (at right angles) has a groundspeed of
    (a) 30 km/h. (b) 40 km/h. (c) 50 km/h. (d) 60 km/h.
15. The impulse-momentum relationship is a direct result of Newton's
    (a) first law. (b) second law. (c) third law. (d) law of gravity.
16. A big fish swims upon and swallows a small fish at rest. Right after lunch, the fattened big fish has a change in
    (a) speed. (b) momentum. (c) Both. (d) Neither.
17. The work done on a 100-kg crate that is hoisted 2 m in a time of 4 s is
    (a) 200 J. (b) 500 J. (c) 800 J. (d) 2000 J.
18. The power required to raise a 100-kg crate a vertical distance of 2 m in a time of 4 s is
    (a) 200 W. (b) 500 W. (c) 800 W. (d) 2000 W.
19. A model car with 3 times as much speed as another has a kinetic energy that is
    (a) the same. (b) twice. (c) 3 times. (d) None of these.
20. Lift a 100-N crate with an ideal pulley system by pulling a rope downward with 25 N of force. For every 1-m length of rope pulled down, the crate rises
    (a) 25 cm. (b) 25 m. (c) 50 cm. (d) None of these.
21. When 100 J are put into a device that puts out 40 J of useful work, the efficiency of the device is
    (a) 40%. (b) 50%. (c) 60%. (d) 140%.
22. A machine cannot multiply
    (a) forces. (b) distances. (c) energy. (d) None of these.
23. When a tin can is whirled in a horizontal circle, the net force on the can acts
    (a) inward. (b) outward. (c) upward. (d) None of these.
24. A torque is a force
    (a) like any other force.
    (b) multiplied by a lever arm.
    (c) that is fictitious.
    (d) that accelerates things.
25. The rotational inertial of an object is greater when most of the mass is located
    (a) near the rotational axis.
    (b) away from the axis.
    (c) on the rotational axis.
    (d) off center.
26. If the Sun were twice as massive, its pull on Mars would be
    (a) unchanged.
    (b) twice as much.
    (c) half as much.
    (d) 4 times as much.
27. The highest ocean tides occur when the Earth and Moon are
    (a) lined up with the Sun.
    (b) at right angles to the Sun.
    (c) at any angle to the Sun.
    (d) lined up during spring.
28. The component of velocity that can remain constant for a tossed baseball is
    (a) horizontal.
    (b) vertical.
    (c) Either of these.
    (d) None of these.
29. The magnitude of gravitational force on a satellite is constant if the orbit is
    (a) parabolic. (b) circular. (c) elliptical. (d) All of these.
30. A satellite in Earth orbit is above Earth's
    (a) atmosphere.
    (b) gravitational field.
    (c) Both.
    (d) Neither.

After you have made thoughtful choices, and discussed them with your friends, find the answers on page 681.

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Part Two
Properties of Matter

11 The Atomic Nature of Matter

1 An artist's rendition of the tip of a scanning probe microscope (SPM), which maps out the relative positions of atoms on the surface of a material. The tip can also be used to move individual atoms around as desired or to sketch patterns, such as those needed for ultra small integrated circuits. 2 Extraordinary 20th-century physicist Richard P. Feynman. 3 A depiction of a DNA molecule, the stuff of life.

Most people, when asked who was the most outstanding physicist of the 20th century, are likely to answer Albert Einstein. When physicists are asked who was the most playful and colorful physicist of the 20th century, if their answer isn't Einstein, it's likely to be Richard Feynman. This chapter is about atoms, the focus of Feynman's work and teaching that led to our further understanding of the atom, and a Nobel Prize in Physics for him. If you read his book *Surely You're Joking, Mr. Feynman,* you will see that in addition to his love of physics, he was very much interested in how physics is taught—particularly in high school. I was privileged to be on a panel of teachers with Feynman at a meeting of physics educators in 1987. The panel addressed the question of what kind of physics should be taught in high school. When I arrived at the school where the meeting was held, I spotted Feynman standing in the hall, alone. It was known that Feynman was often alone at such meetings, for teachers were uncomfortable in his presence. What do you talk about to someone like Feynman? I had something to talk about because he had been sent a copy of my brand-new high school version of *Conceptual Physics,* and I wanted his impression of it. To my delight, but not to my surprise, he had read it—all of it, judging by his recommended improvements for the next edition. As his own *Joking* book makes

clear, Feynman "did his homework" before giving his presentations. He had read my book and several other high school books in preparation for this panel, which, sadly, was his last public appearance. We all knew he was fighting cancer.

On the panel I was almost flabbergasted to realize he and I were debating not how physics should be taught in high schools but rather whether it should be taught at all. Feynman liked extreme points of view, and his position was that it shouldn't be taught in high school because most of the teachers lacked a passion for the subject. This lack of passion would be communicated to students, who would be better off arriving at college with a clean slate. My position was that physics should be taught conceptually, with any problem-solving course as a second course in physics—that the central concepts of physics should be familiar to all students—that physics, like math and English and history, should be in the educational mainstream. Feynman countered that a major problem with my position was the inadequate number of trained physics teachers. Where would they come from? My reply was that if we made the course delightful, more than the current percentage of students would like physics, then major in it, and in 10 years be in the ranks of needed teachers.

Ten years later at a physics meeting in Las Vegas, a young man stopped me in the hall to tell me how his encounter with my book steered him to majoring in physics and then becoming a physics teacher. He further expressed a passion for physics. I thought to myself, "Did you hear that, Richard?" For it was true, the conceptual orientation of physics helped increase the ranks of new physics teachers. My motto since has been that, if a learner's first course in physics is delightful, the rigor of a second course will be welcomed.

The Atomic Hypothesis

The idea that matter is composed of atoms goes back to the Greeks in the 5th century BC. Investigators of nature back then wondered whether matter was continuous or not. We can break a rock into pebbles, and the pebbles into fine gravel. The gravel can be broken into fine sand, which then can be pulverized into powder. To the 5th-century Greeks, there was a smallest bit of rock, an "atom," that could not be divided any further.

Aristotle, the most famous of the early Greek philosophers, didn't agree with the idea of atoms. In the 4th century BC, he taught that all matter is composed of various combinations of four elements—earth, air, fire, and water. This view seemed reasonable because, in the world around us, matter is seen in only four forms: solids (earth), gases (air), liquids (water), and the state of flames (fire). The Greeks viewed

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- If, in some cataclysm, all of scientific knowledge were to be destroyed, and only one sentence could be passed on to the next generation of creatures, Richard Feynman chose this: "All things are made of atoms—little particles that move around in perpetual motion, attracting each other when they are a little distance apart, but repelling upon being squeezed into one another." The idea that matter is composed of atoms is a central foundation of all of science.

Falling Alice

Imagine that you inhabit the world of Alice in Wonderland when she shrank in size. Pretend that you topple from a chair and fall in slow motion to the floor—and while falling, you continually shrink. You brace yourself for impact on the wood floor, and, as you get nearer and nearer, becoming smaller and smaller, you notice that the surface of the floor is not as smooth as it first looked. Great crevices appear that are the microscopic irregularities that are found in all wood. In falling into one of these canyon-sized crevices, you again brace yourself for impact, only to find that the bottom of the canyon consists of many other crevices. Falling farther while growing even smaller, you notice the solid walls throb and pucker. The throbbing surfaces consist of hazy blobs, mostly spherical, some egg-shaped, some larger than others, and all oozing into each other, forming long chains of complicated structures. Falling still farther, you brace for impact as you approach one of these cloudy spheres, closer and closer, smaller and smaller, and—Wow! You have entered what seems to be a new universe. You fall into a sea of emptiness, occupied by occasional specks whirling past at unbelievably high speeds. You are in an *atom*, as empty of matter as the solar system. The solid floor you have fallen into is, except for specks of matter here and there, mostly empty space. You have entered the world of the atom.

FIGURE 11.1
An early model of the atom, with a central nucleus and orbiting electrons, much like a solar system with orbiting planets.

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Video
Evidence for Atoms

We can't see atoms because they're too small. We can't see the farthest star either. There's much that we can't see with our eyes. But that doesn't prevent investigation of such things so that we can "see" them via our instruments.

fire as the element of change, since fire was observed to produce changes on substances that burned. Aristotle's ideas about the nature of matter persisted for more than 2000 years.

The atomic idea was revived in the early 1800s by an English meteorologist and school teacher, John Dalton. He successfully explained the nature of chemical reactions by proposing that all matter is made of atoms. He and others of the time, however, had no direct evidence for their existence. Then, in 1827, a Scottish botanist named Robert Brown noticed something very unusual in his microscope. He was studying grains of pollen suspended in water, and he saw that the grains were continually moving and jumping about. At first he thought the grains were some kind of moving life forms, but later he found that dust particles and grains of soot suspended in water moved in the same way. This perpetual and haphazard jiggling of tiny particles—now called **Brownian motion**—results from collisions between visible particles and invisible atoms. The atoms are invisible because they're so small. Although he couldn't see the atoms, Brown could see the effect they had on particles he *could* see. It's like a supergiant beach ball being bounced around by a crowd of people at a football game. From a high-flying airplane, you wouldn't see the people because they are small relative to the enormous ball, which you would be able to see. The pollen grains that Brown observed moved because they were constantly being jostled by the atoms (actually, by the atomic combinations referred to as molecules) that made up the water surrounding them.

Brownian motion was explained in 1905 by Albert Einstein, the same year that he announced the theory of special relativity. Until Einstein's explanation—which made it possible to find the masses of atoms—many prominent physicists remained skeptical about the existence of atoms. So we see that the reality of the atom was not firmly established until the early 20th century.

Characteristics of Atoms

Atoms Are Incredibly Tiny An atom is as many times smaller than you as an average star is larger than you. A nice way to say this is that we stand between the atoms and the stars. Or another way of stating the smallness of atoms is that the diameter of an atom is to the diameter of an apple as the diameter of an apple is to the diameter of Earth. So, to imagine an apple full of atoms, think of the Earth solid-packed with apples. Both have about the same number.

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- How long would it take you to count to 1 million? If each count takes 1 second, counting nonstop to a million would take 11.6 days. To count to a billion (10^9) would take 31.7 years. To count to a trillion (10^{12}) would take 31,700 years. Counting to 10^{22} would take more than 10,000 times the age of the universe!

Atoms Are Numerous There are about 100,000,000,000,000,000,000,000 atoms in a gram of water (a thimbleful). In scientific notation, that's 10^{23} atoms. The number 10^{23} is an enormous number, more than the number of drops of water in all the lakes and rivers of the world. So there are more atoms in a thimbleful of water than there are drops of water in the world's lakes and rivers. In the atmosphere, there are about 10^{22} atoms in a liter of air. Interestingly, the volume of the atmosphere contains about 10^{22} liters of air. That's an incredibly large number of atoms, and the same incredibly large number of liters of atmosphere. Atoms are so small and so numerous that there are about as many atoms in the air in your lungs at any moment as there are breathfuls of air in Earth's atmosphere.

Atoms Are Perpetually Moving In solids, they vibrate in place; in liquids, they migrate from one location to another; and in gases, the rate of migration is even greater. Drops of food coloring in a glass of water, for example, soon spread to color the entire glass of water. The same would be true of a cupful of food coloring

thrown into an ocean: It would spread around and later be found in every part of the world's oceans.

Atoms and molecules in the atmosphere zip around at speeds up to 10 times the speed of sound. They spread rapidly, so some of the oxygen molecules you breathe may have been halfway across the country a few days ago. Taking Figure 11.2 further, your exhaled breaths of air quite soon mix with other atoms in the atmosphere. After the few years it takes for your breath to mix uniformly in the atmosphere, anyone, anywhere on Earth, who inhales a breath of air will take in, on the average, one of the atoms in that exhaled breath of yours. But you exhale many, many breaths, so other people breathe in many, many atoms that were once in your lungs—that were once a part of you; and, of course, vice versa. Believe it or not, with each breath you take in, you breathe atoms that were once a part of everyone who ever lived! Considering that the atoms we exhale were part of our bodies (the nose of a dog has no trouble discerning this), it can be truly said that we are literally breathing one another.

Smell discrimination for salmon has been measured in parts per *trillion*—quite incredible. When the time comes to return from the ocean to their original habitat, salmon follow their noses. They swim in a direction where concentrations of familiar water become greater. In time, they encounter the source of that water where they spent the first 2 years of their lives.

Atoms Are Ageless Many atoms in your body are nearly as old as the universe itself. When you breathe, for example, only some of the atoms that you inhale are exhaled in your next breath. The remaining atoms are taken into your body to become part of you, and they later leave your body by various means. You don't "own" the atoms that make up your body; you borrow them. We all share from the same atom pool, as atoms forever migrate around, within, and among us. Atoms cycle from person to person as we breathe and as our perspiration is vaporized. We recycle atoms on a grand scale.

The origin of the lightest atoms goes back to the origin of the universe, and most heavier atoms are older than the Sun and Earth. There are atoms in your body that have existed since the first moments of time, recycling throughout the universe among innumerable forms, both nonliving and living. You're the present caretaker of the atoms in your body. There will be many who will follow you.

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Video
Atoms Are Recyclable

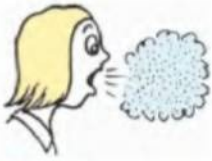


FIGURE 11.2
There are as many atoms in a normal breath of air as there are breathfuls of air in Earth's atmosphere.

CHECK POINT

1. Which are older, the atoms in the body of an elderly person or those in the body of a baby?
2. World population grows each year. Does this mean that the mass of Earth increases each year?
3. Are there really atoms that were once a part of Albert Einstein incorporated in the brains of all the members of your family?

Check Your Answers

1. The age of the atoms in both is the same. Most of the atoms were manufactured in stars that exploded before the solar system came into existence.
2. The greater number of people increases the mass of Earth by zero. The atoms that make up our bodies are the same atoms that were here before we were born—we are but dust, and unto dust we shall return. The materials that make up human cells are rearrangements of material already present. The atoms that make up a baby forming in its mother's womb are supplied by the food the mother eats. And those atoms originated in stars—some of them in far-away galaxies. (Interestingly, the mass of Earth *does* increase by the incidence of roughly 40,000 tons of interplanetary dust each year, but not by the birth and survival of more people.)
3. Quite so, and of Barack Obama too. However, these atoms are combined differently than they were previously. If you experience one of those days when you feel like you'll never amount to anything, take comfort in the thought that many of the atoms that now constitute your body will live forever in the bodies of all the people on Earth who are yet to be. Our atoms are immortal.

Life is not measured by the number of breaths we take, but by the moments that take our breath away.—*George Carlin*

FIGURE 11.3
Information about the ship is revealed by passing waves because the distance between wave crests is small compared with the size of the ship. The passing waves reveal nothing about the chain.

FIGURE 11.4
The strings of dots are chains of thorium atoms imaged with a scanning electron microscope. This historic photograph of individual atoms was taken in 1970 by researchers at the University of Chicago's Enrico Fermi Institute.

Sometimes a model is useful even when it's incorrect. Scotsman James Watt constructed a workable steam engine in the 18th century based on a model of heat that turned out to be quite incorrect.

Atomic Imagery

Atoms are too small to be seen with visible light. Because of diffraction, you can discern details no smaller than the wavelength of light you use to look with. This can be understood by an analogy with water waves. A ship is much larger than the water waves that roll on by it. As Figure 11.3 shows, water waves can reveal features of the ship. The waves *diffract* as they pass the ship. But diffraction is nil for waves that pass by the anchor chain, revealing little or nothing about it. Similarly, waves of visible light are too coarse compared with the size of an atom to show details of atomic size and shape.

Yet here in Figure 11.4 we see a picture of atoms—the historic 1970 image of chains of individual thorium atoms. The picture is not a photograph but an electron micrograph—it was not made with light but with a thin electron beam in a scanning electron microscope (SEM) developed by Albert Crewe at the University of Chicago's Enrico Fermi Institute. An electron beam, such as the one that sprays a picture on an early television screen, is a stream of particles that have wave properties. The wavelength of an electron beam is smaller than the wavelengths of visible light, and atoms are larger than the tiny wavelengths of an electron beam. Crewe's electron micrograph is the first high-resolution image of individual atoms.

In the mid-1980s, researchers developed a new kind of microscope—the scanning tunneling microscope (STM). It employs a sharp tip that is scanned over a surface at a distance of a few atomic diameters in a point-by-point and line-by-line fashion. At each point, a tiny electric current, called a tunneling current, is measured between the tip and the surface. Variations in the current reveal the surface topology. The image of Figure 11.5 beautifully shows the position of a ring of atoms. The ripples shown in the ring reveal the wave nature of matter. This image, among many others, underscores the delightful interplay of art and science.

Because we can't see inside an atom, we construct models. A model is an abstraction that helps us to visualize what we can't see, and, importantly, it enables us to make predictions about unseen portions of the natural world. An early model of the atom (and the one most familiar to the general public) is akin to that of the solar system. As with the solar system, most of an atom's volume is empty space. At the center is a tiny and very dense nucleus in which most of the mass is concentrated. Surrounding the nucleus are "shells" of orbiting particles. These are **electrons,** electrically charged basic units of matter (the same electrons that constitute the electric current in your iPhone). Although electrons electrically repel other electrons, they are electrically attracted to the nucleus, which has a positive charge. As the size and charge of the nuclei increase, electrons are pulled closer, and the shells become smaller. Interestingly, the uranium atom, with its 92 electrons, is not appreciably larger in diameter than the lightest atom, hydrogen. This model was first proposed in the early 20th century, and it reflects a rather simplified understanding of the atom. It was soon discovered, for example, that electrons don't orbit the atom's

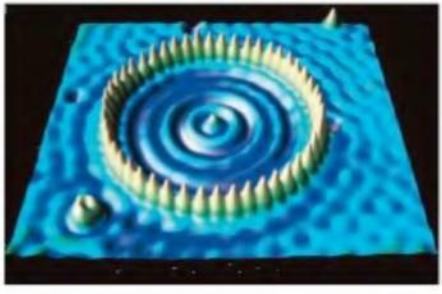


FIGURE 11.5
An image of 48 iron atoms positioned into a circular ring that "corrals" electrons on a copper crystal surface, taken with a scanning tunneling microscope at the IBM Almaden Laboratory in San Jose, California.

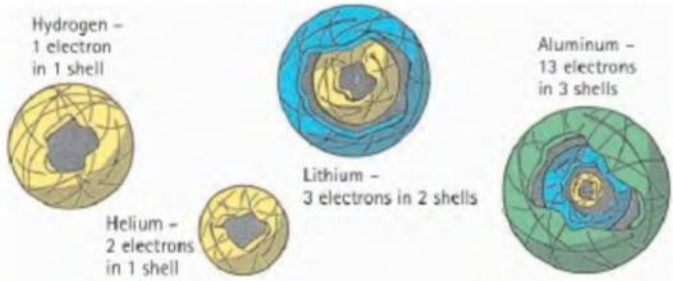


FIGURE 11.6
A simplified model of the atom consists of a tiny nucleus surrounded by electrons that orbit in shells. As the charges of nuclei increase, electrons are pulled closer, and the shells become smaller.

center like planets orbit the Sun. Like most early models, however, the planetary atomic model served as a useful stepping stone to further understanding and more accurate models. Any atomic model, no matter how refined, is nothing more than a symbolic representation of the atom and not a physical picture of the actual atom.

Artists and scientists both look for patterns in nature, finding connections that have always been there yet have missed the eye.

Atomic Structure

Nearly all the mass of an atom is concentrated in the **atomic nucleus,** which occupies only a few quadrillionths of its volume. The nucleus, therefore, is extremely dense. If bare atomic nuclei could be packed against each other into a lump 1 centimeter in diameter (about the size of a large pea), the lump would weigh 133,000,000 tons! Huge electrical forces of repulsion prevent such close packing of atomic nuclei because each nucleus is electrically charged and repels all other nuclei. Only under special circumstances are the nuclei of two or more atoms squashed into contact. It can happen when nuclei in a laboratory are slammed into a target, or when matter is heated to millions of degrees. A nuclear reaction resulting from high temperature is called a *thermonuclear fusion reaction.* It occurs in the centers of stars and ultimately makes them shine. (We'll discuss these nuclear reactions in Chapter 34.)

The principal building block of the nucleus is the *nucleon,* which is in turn composed of fundamental particles called *quarks.* When a nucleon is in an electrically neutral state, it is a *neutron;* when it is in a positively charged state, it is a **proton.** All protons are identical; they are copies of one another. Likewise with neutrons: Each neutron is like every other neutron. The lighter nuclei have roughly equal numbers of protons and neutrons; more massive nuclei have more neutrons than protons. Protons have a positive electric charge that repels other positive charges but attracts negative charges. So like kinds of electrical charges repel one another, and unlike charges attract one another. It is the positive protons in the nucleus that attract a surrounding cloud of negatively charged electrons to constitute an atom. (The strong nuclear force, which binds the protons to neutrons and to each other within the nucleus, is described in Chapter 33.)

The Elements

When a substance is composed of only one kind of atom, we call that substance an **element.** The words *element* and *atom* are often used in a similar context, the distinction being that elements are made of atoms and not the other way around. A pure 24-carat gold ring, for example, is composed only of gold atoms. A gold ring with a lower carat value is composed of gold and other elements, such as nickel. The silvery liquid in a barometer or thermometer is the element mercury. The entire liquid consists of only mercury atoms. An atom of a particular element is the smallest sample of that element. Although atom and element are often used interchangeably,

fyi

- A combination of 26 letters makes up every word in the English language. Similarly, all material things in the world are composed of different combinations of about 100 different elements.

element refers to a type of substance (one containing only one type of atom), whereas atom refers to the individual particles that make up that substance. For example, we speak of isolating a mercury *atom* from a flask of the *element* mercury.

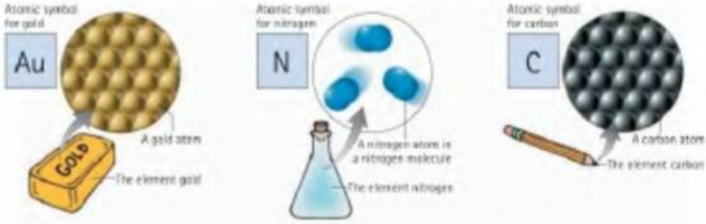


FIGURE 11.7
Any element consists only of one kind of atom. Gold consists only of gold atoms, a flask of gaseous nitrogen consists only of nitrogen atoms, and the carbon of a graphite pencil is composed only of carbon atoms.

FIGURE 11.8
Both you and Leslie are made of stardust—in the sense that the carbon, oxygen, nitrogen, and other atoms that make up your body originated in the deep interiors of ancient stars that have long since exploded.

The lightest atom of all is that of hydrogen. In the universe at large, hydrogen is the most abundant element—more than 90% of the atoms are hydrogen atoms. Helium, the second-lightest element, provides most of the remaining atoms in the universe. Heavier atoms in our surroundings were manufactured by the fusion of light elements in the hot, high-pressure cauldrons deep within the interiors of stars. The heaviest elements form when huge stars implode and then explode—supernovas. Nearly all the elements on Earth are remnants of stars that exploded long before the solar system came into existence.

To date, more than 115 elements have been identified. Of these, about 90 occur in nature. The others are produced in the laboratory with high-energy atomic accelerators and nuclear reactors. These laboratory-produced elements are too unstable (radioactive) to occur naturally in appreciable quantities. From a pantry containing less than 100 elements, we have the atoms that constitute almost every simple, complex, living, or nonliving substance in the known universe. More than 99% of the material on Earth is formed from only about a dozen of the elements. The other elements are relatively rare. Living things are composed primarily of five elements: oxygen (O), carbon (C), hydrogen (H), nitrogen (N), and calcium (Ca). The letters in parentheses represent the chemical symbols for these elements.

The Periodic Table of the Elements

Elements are classified by the number of protons in their nucleus—their **atomic number.** Hydrogen, containing one proton per atom, has atomic number 1; helium, containing two protons per atom, has atomic number 2; and so on in sequence to the heaviest naturally occurring element, uranium, with atomic number 92. The numbers continue beyond atomic number 92 through the artificially produced transuranic (beyond uranium) elements. The arrangement of elements by their atomic numbers makes up the **periodic table of the elements** (Figure 11.9).

The periodic table is a chart that lists atoms by their atomic number and also by their electrical arrangements. It bears some resemblance to a calendar with its weeks in rows and its days in columns. From left to right, each element has atoms with one more proton and electron than the preceding element. Reading down the table, each element has atoms with one more shell than the one above. The inner shells are filled to their capacities, and the outer shell may or may not be, depending on the element. Only the elements at the far right of the table, where Saturdays would be on a calendar, have their outer shells filled to capacity. These are the *noble gases*—helium, neon,

fyi

- Mercury, element number 80, is commonly found in rocks and minerals such as cinnabar ore and fossil fuels. Mercury on its own, undisturbed, is not harmful. But when ore is smashed or coal is burned, mercury is released into the air, where it can waft over hundreds of kilometers, depositing itself on trees and land or streams, lakes, and oceans. That is where it becomes a danger. When it combines with carbon it becomes methyl mercury, a deadly neurotoxin. Each year about 75 tons of mercury are in coal delivered to U.S. power plants and about $\frac{2}{3}$ of this is emitted to the air. China has now joined in this practice.

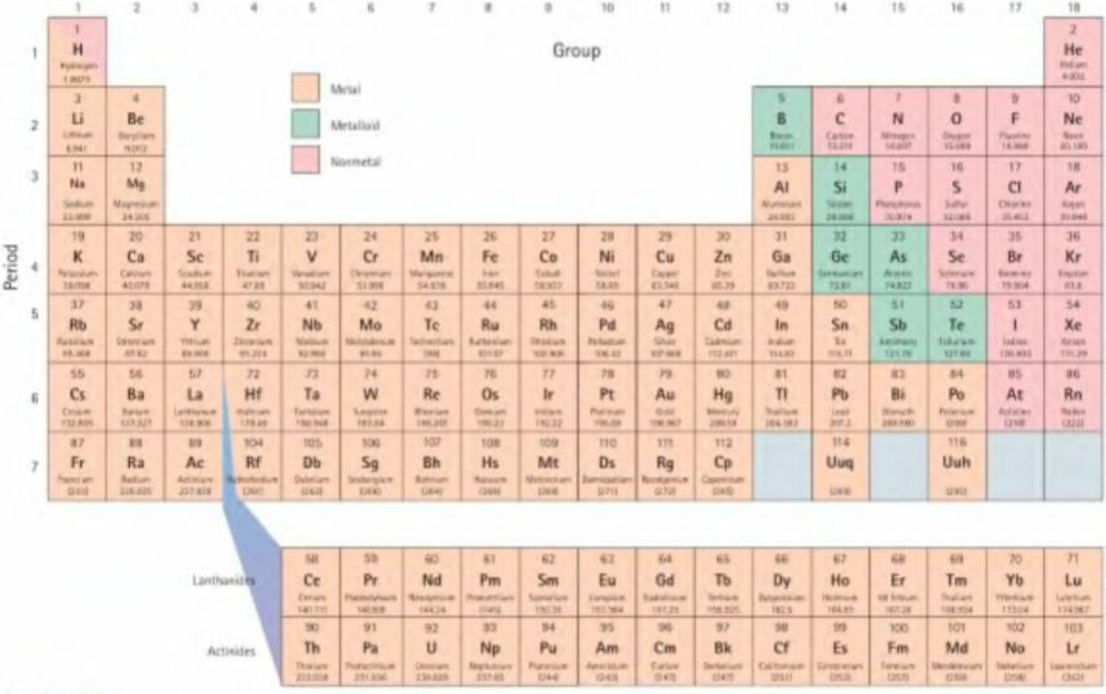


FIGURE 11.9

The periodic table of the elements. The number above the chemical symbol is the *atomic number*, and the number below is the *atomic mass* averaged by isotopic abundance in Earth's surface and expressed in atomic mass units (amu). Atomic masses for radioactive elements shown in parentheses are the whole number nearest the most stable isotope of that element.

Most of the elements of the periodic table are found in interstellar gases.

argon, krypton, xenon, and radon. The periodic table is the chemist's road map—and much more. Most scientists consider the periodic table to be the most elegant organizational chart ever devised. The enormous human effort and ingenuity that went into finding its regularities makes a fascinating atomic detective story.[1]

Elements may have up to seven shells, and each shell can hold some maximum number of electrons. The first and innermost shell has a capacity for two electrons and the second shell has a capacity for eight electrons. The arrangement of electrons in the shells dictates such properties as the melting and freezing temperatures, electrical conductivity, and the taste, texture, appearance, and color of substances. The arrangements of electrons quite literally give life and color to the world.

Models of the atom evolve with new findings. The old orbital model of the atom has given way to a model that views the electron as a standing wave—altogether different from the idea of an orbiting particle. This is the quantum mechanical model, introduced in the 1920s, which is a theory of the small-scale world that includes predicted wave properties of matter. It deals with "lumps" occurring at the subatomic level—lumps of matter or lumps of such things as energy and angular momentum. (More about the quantum in Chapter 31.)

Relative Sizes of Atoms

The diameters of the electron shells of atoms are determined by the amount of electrical charge in the nucleus. For example, the positive proton in the hydrogen atom holds one electron in an orbit at a certain radius. If we double the positive charge in the nucleus, the orbiting electron will be pulled into a tighter orbit with half its former radius, since the electrical attraction is doubled. This occurs for helium, which has a doubly charged nucleus when it attracts a single electron. Interestingly, an added second electron isn't pulled in as far because the first electron partially offsets the attraction of the doubly charged nucleus. This is a neutral helium atom, which is somewhat smaller than a hydrogen atom.

An atom with unbalanced electrical charge, for example a nucleus with more positive charge than the surrounding negative charges, is called an **ion.** An ion is a charged atom. A helium atom that holds only one electron, for example, is a helium ion. We say it is a positive ion because it has more positive charge than negative charge.

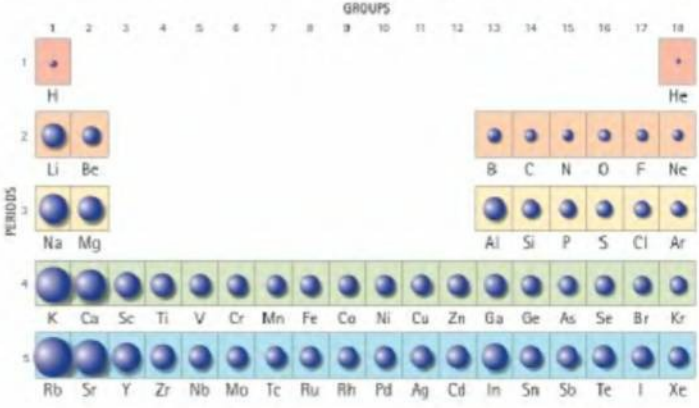


FIGURE 11.10

The sizes of atoms gradually decrease from left to right across the periodic table (only the first five periods are shown here).

[1] The periodic table is credited to Russian chemistry professor Dmitri Mendeleev (1834–1907), who, most importantly, predicted with his table the existence of elements not then known. Mendeleev was a much loved and devoted teacher whose lecture halls were filled by students wanting to hear him speak. He was both a great teacher and a great scientist. Element 101 is named in his honor.

So two electrons around a doubly charged nucleus assume a configuration characteristic of helium. Two electrons surrounding a helium nucleus constitute a neutral atom. A third proton in an atomic nucleus can pull two electrons into an even closer orbit and, furthermore, hold a third electron in a somewhat larger orbit. This is the lithium atom, atomic number 3. We can continue with this process, increasing the positive charge of the nucleus and adding successively more electrons and more orbits all the way up to atomic numbers above 100, to the "synthetic" radioactive elements.[2]

We find that as the nuclear charge increases and additional electrons are added in outer orbits, the inner orbits shrink in size because of the stronger nuclear attraction. This means that the heavier elements are not much larger in diameter than the lighter elements. The diameter of the xenon atom, for example, is only about four helium diameters, even though it is nearly 33 times as massive. The relative sizes of atoms in Figure 11.10 are approximately to the same scale.

CHECK POINT

What fundamental force dictates the size of an atom?

Check Your Answer

The electrical force.

Isotopes

Whereas the number of protons in a nucleus exactly matches the number of electrons around the nucleus in a neutral atom, the number of protons in the nucleus need not match the number of neutrons there. For example, most iron nuclei with 26 protons contain 30 neutrons, while a small percentage contains 29 neutrons. Atoms of the same element that contain different numbers of neutrons are **isotopes** of the element. The various isotopes of an element all have the same number of electrons, and so, for the most part, they behave identically. We shall return to isotopes in Chapter 33.

We identify isotopes by their *mass number*, which is the total number of protons and neutrons (in other words, the number of nucleons) in the nucleus. A hydrogen isotope with one proton and no neutrons, for example, has a mass number of 1 and is referred to as hydrogen-1. Likewise, an iron atom with 26 protons and 30 neutrons has a mass number of 56 and is referred to as iron-56. An iron atom with 26 protons and only 29 neutrons is designated as iron-55.

The total mass of an atom is called its *atomic mass*. This is the sum of the masses of all the atom's components (electrons, protons, and neutrons). Because electrons are so much less massive than protons and neutrons, their contribution to atomic mass is negligible. Atoms are so small that expressing their masses in units of grams or kilograms is not practical. Instead, scientists use a specially defined unit of mass known as the **atomic mass unit** or **amu.** A nucleon has a mass of about 1 amu. The amu is defined as exactly 1/12 of the mass of a carbon-12 atom. The periodic table lists atomic masses in units of amu.

Don't confuse an isotope with an *ion*, which is an atom that is electrically charged owing to an excess or a deficiency of electrons.

Most elements have a variety of isotopes. The atomic mass for each element listed in the periodic table is the weighted average of the masses of these isotopes based on the occurrence of each isotope on Earth. For example, although the predominant isotope of carbon contains six protons and six neutrons, about 1% of all carbon atoms contain seven neutrons. The heavier isotope raises the average atomic mass of carbon from 12.000 amu to 12.011 amu.

[2]Each orbit will hold only so many electrons. The numbers for the first four shells, for example, are 2, 8, 8, 18.

Don't confuse mass number with the atomic mass. *Mass number* is an integer that specifies an isotope and has no units—it's simply equal to the number of nucleons in a nucleus. *Atomic mass* is an average of the masses of isotopes of a given element, expressed in *atomic mass units* (amu).

CHECK POINT

1. Which contributes more to an atom's mass, electrons or protons? Which contributes more to an atom's volume (its size)?
2. Which is represented by a whole number—the mass number or the atomic mass?
3. Do two isotopes of iron have the same *atomic number?* The same *atomic mass number?*

Check Your Answers

1. Protons contribute more to an atom's mass; electrons contribute more to its size.
2. The mass number is always given as a whole number, such as hydrogen-1 or carbon-12. Atomic mass, by contrast, is the average mass of the various isotopes of an element and is thus represented by a fractional number.
3. The two isotopes of iron have the same atomic number 26, because they each have 26 protons in the nucleus. They have different atomic mass numbers if they have different numbers of neutrons in the nucleus.

Compounds and Mixtures

When atoms of different elements bond to one another, they make a **compound.** Examples of simple compounds include water, ammonia, and methane. A compound is uniquely different from the elements from which it is made, and it can only be separated into its constituent elements by chemical means. Sodium, for example, is a metal that reacts violently with water. Chlorine is a poisonous yellow-green gas. Yet the compound of these two elements is the harmless white crystal (NaCl) that you sprinkle on your potatoes. Consider also that, at ordinary temperatures, the elements hydrogen and oxygen are both gases. When combined, they form the compound water (H_2O), a liquid—quite different.

Not all substances react with one another chemically when they are brought close together. A substance that is mixed together without chemically bonding is called a **mixture.** Sand combined with salt is a mixture. Hydrogen and oxygen gas form a mixture until ignited, whereupon they form the compound water. A common mixture that we all depend on is nitrogen and oxygen together with a little argon and small amounts of carbon dioxide and other gases. It is the air that we breathe.

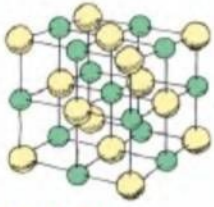


FIGURE 11.11

Table salt (NaCl) is a crystalline compound that is not made of molecules. The sodium (green) and chlorine (yellow) atoms comprise a crystal.

CHECK POINT

Is common table salt an element, a compound, or a mixture?

Check Your Answer

Salt is not an element, for if it were you'd see it listed in the periodic table. Pure table salt is a compound of the elements sodium and chlorine, represented in Figure 11.11. Notice that the sodium atoms (green) and the chlorine atoms (yellow) are arranged in a three-dimensional repeating pattern—a crystal. Each sodium atom is surrounded by six chlorine atoms, and each chlorine atom is surrounded by six sodium atoms. Interestingly, there are no separate sodium–chlorine groups that can be labeled molecules.[3]

[3]In a strict sense, common table salt *is* a mixture—often with small amounts of potassium iodide and sugar. The iodine in the potassium iodide has virtually eliminated a common affliction of earlier times, a swelling of the thyroid gland known as endemic goiter. Tiny amounts of sugar prevent oxidation of the salt, which otherwise would turn yellow.

Molecules

A **molecule** consists of two or more atoms that bond together by sharing electrons. (We say such atoms are *covalently bonded.*) A molecule may be as simple as the two-atom combination of oxygen, O_2, or the two-atom combination of nitrogen, N_2, which are the elements that comprise most of the air we breathe. Two atoms of hydrogen combine with a single atom of oxygen to form a water molecule, H_2O. Changing a molecule by one atom can make a big difference. Replacing the oxygen atom with a sulfur atom produces hydrogen sulfide, H_2S, a strong-smelling, toxic gas.

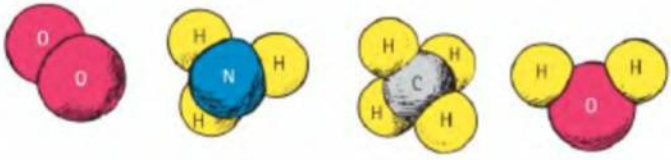


FIGURE 11.12
Models of simple molecules: O_2, NH_3, CH_4, and H_2O. The atoms in a molecule are not just mixed together, but are joined in a well-defined way.

CHECK POINT

How many atomic nuclei are in a single oxygen atom? In a single oxygen molecule?

Check Your Answer

There is one nucleus in an oxygen atom, O, and two in the combination of two oxygen atoms—an oxygen molecule, O_2.

Energy is required to pull molecules apart. We can understand this by considering a pair of magnets stuck together. Just as some "muscle energy" is required to pull the magnets apart, the breaking apart of molecules requires energy. During photosynthesis, plants use the energy of sunlight to break apart the bonds within atmospheric carbon dioxide and water to produce oxygen gas and carbohydrate molecules. These carbohydrate molecules retain this solar energy until the process is reversed—the plant is oxidized, either slowly by rotting or quickly by burning. Then the energy that came from the sunlight is released back into the environment. So the slow warmth of decaying compost or the quick warmth of a campfire is really the warmth of stored sunlight!

More things can burn besides those that contain carbon and hydrogen. Iron "burns" (oxidizes) too. That's what rusting is—the slow combination of oxygen atoms with iron atoms, releasing energy. When the rusting of iron is speeded up, it makes nice hand-warmer packs for skiers and winter hikers. Any process in which atoms rearrange to form different molecules is called a *chemical reaction*.

Our sense of smell is sensitive to exceedingly small quantities of molecules. Our olfactory organs easily detect small concentrations of such noxious gases as hydrogen sulfide (the stuff that smells like rotten eggs), ammonia, and ether. The smell of perfume is the result of molecules that rapidly evaporate and diffuse haphazardly in the air until some of them get close enough to your nose to be inhaled. They are just a few of the billions of jostling molecules that, in their aimless wanderings, happen to end up in the nose. You can get an idea of the speed of molecular diffusion in the air when you are in your bedroom and smell food very soon after the oven door has been opened in the kitchen.

Although H_2O is the major greenhouse gas in the atmosphere, CO_2, the second most abundant greenhouse gas, is notorious because its growth is attributable to human activity. Since further warming by CO_2 can trigger more H_2O, a present concern is the growing amounts of both gases in the atmosphere.

Antimatter

Whereas matter is composed of atoms with positively charged nuclei and negatively charged electrons, **antimatter** is composed of atoms with negative nuclei and positive electrons, or *positrons*.

FIGURE 11.13
An atom of antimatter has a negatively charged nucleus surrounded by positrons.

Positrons were first discovered in 1932, in cosmic rays bombarding Earth's atmosphere. Today, antiparticles of all types are regularly produced in laboratories using large nuclear accelerators. A positron has the same mass as an electron and the same magnitude of charge, but the opposite sign. Antiprotons have the same mass as protons but are negatively charged. The first complete artificial anti-atom, a positron orbiting an antiproton, was constructed in 1995. Every charged particle has an antiparticle of the same mass and opposite charge. Neutral particles (such as the neutron) also have antiparticles, which are alike in mass and in some other properties but opposite in certain other properties. Every particle has an antiparticle. There are even antiquarks.

Gravitational force does not distinguish between matter and antimatter—each attracts the other. Also, there is no way to indicate whether something is made of matter or antimatter by the light it emits. Only through much subtler, hard-to-measure nuclear effects could we determine whether a distant galaxy is made of matter or antimatter. But, if an antistar were to meet a star, it would be a different story. They would mutually annihilate each other, with most of the matter converting to radiant energy (this is what happened to the anti-atom created in 1995, when it encountered normal matter and rapidly annihilated in a puff of energy). This process, more so than any other known, results in the maximum energy output per gram of substance—$E = mc^2$, with a 100% mass conversion.[4] (Nuclear fission and fusion, by contrast, convert less than 1% of the matter involved.)

There cannot be both matter and antimatter in our immediate environment, at least not in appreciable amounts or for appreciable times. That's because something made of antimatter would be completely transformed to radiant energy as soon as it touched matter, consuming an equal amount of normal matter in the process. If the Moon were made of antimatter, for example, a flash of energetic radiation would result as soon as one of our spaceships touched it. Both the spaceship and an equal amount of the antimatter Moon would disappear in a burst of radiant energy. We know the Moon is not antimatter because this didn't happen during the Moon missions. (Actually, astronauts weren't in this kind of danger, for previous evidence showed that the Moon is made of ordinary matter.) But what about other galaxies? There is strong reason to believe that in the part of the universe we know (the "observable universe"), galaxies are made only of normal matter—apart from the occasional transitory antiparticle. But what of the universe beyond? Or other universes? We don't know.

"Science is a way to teach how something gets to be known, what is not known, to what extent things are known (for nothing is known absolutely), how to handle doubt and uncertainty, what the rules of evidence are, how to think about things so that judgments can be made, and how to distinguish truth from fraud and from show."—*Richard Feynman*

CHECK POINT

If a 1-gram body of antimatter meets a 10-gram body of matter, what mass survives?

Check Your Answer

Nine grams of matter survive (the other 2 grams are transformed into radiant energy).

[4]Some physicists speculate that right after the Big Bang, the early universe had billions of times more particles than it has now, and that a near total extinction of matter and antimatter caused by their mutual annihilation left only the relatively small amount of matter now present in the universe.

Dark Matter

We know that the elements in the periodic table are not confined to our planet. From studies of radiation coming from other parts of the universe, we find that stars and other objects "out there" are composed of the same particles we have on Earth. Stars emit light with the same "fingerprints" (*atomic spectra*, Chapter 30) as the elements in the periodic table. How wonderful to find that the laws that govern matter on Earth extend throughout the observable universe. Yet there remains one troubling detail. Gravitational forces within galaxies are measured to be far greater than visible matter can account for.

Astrophysicists talk of the **dark matter**—matter we can't see that tugs on stars and galaxies that we *can* see. In the closing years of the 20th century, astrophysicists confirmed that some 23% of matter in the universe is composed of the unseen dark matter. Whatever dark matter is, most or all of it is likely to be "exotic" matter—very different from the elements that make up the periodic table, and different from any extension of the present list of elements. Much of the rest of the universe is *dark energy*, which pushes outward on the expanding universe. Both dark matter and dark energy make up some 90% of the universe. Only in this 21st century has this type of energy been apparent. At this writing, neither has been identified. Speculations abound about dark matter and dark energy, but we don't know what they are.

Richard Feynman often used to shake his head and say he didn't know anything. When he and other top physicists say they don't know anything, they mean that what they *do* know is closer to nothing than to what they *can* know. Scientists know enough to realize that they have a relatively small handle on an enormous universe still full of mysteries. From a looking-backward point of view, today's scientists know enormously more than their forebears a century ago, and scientists then knew much more than *their* forebears. But, from our present vantage point, looking forward, there is so much yet to be learned. Physicist John A. Wheeler, Feynman's graduate-school advisor, envisioned the next level of physics going beyond *how* to *why*—to meaning. We have scarcely scratched the surface.

Finding the nature of the dark matter and the nature of the energy of empty space are high-priority quests in these times. What we will have learned by 2050 will likely dwarf all that we have ever known.

"I can live with doubt and uncertainty and not knowing. I think it is much more interesting to live not knowing than to have answers that might be wrong." — *Richard Feynman*

SUMMARY OF TERMS

Atom The smallest particle of an element that has all of the element's chemical properties.

Brownian motion The haphazard movement of tiny particles suspended in a gas or liquid resulting from their bombardment by the fast-moving atoms or molecules of the gas or liquid.

Electron Negatively charged particle that whizzes about within an atom.

Atomic nucleus The core of an atom, consisting of two basic subatomic particles—protons and neutrons.

Proton Positively charged particle in the nucleus of an atom.

Element A pure substance consisting of only one kind of atom.

Atomic number The number that designates the identity of an element, which is the number of protons in the nucleus of an atom; in a neutral atom, the atomic number is also the number of electrons in the atom.

Periodic table of the elements A chart that lists the elements in horizontal rows by their atomic number and in vertical columns by their similar electron arrangements and chemical properties. (See Figure 11.9.)

Ion An electrically charged atom; an atom with an excess or deficiency of electrons.

Isotope An atom of the same element that contains a different number of neutrons.

Atomic mass unit (amu) The standard unit of atomic mass, which is equal to 1/12 the mass of the most common atom of carbon. One amu has a mass of 1.661×10^{-27} kg.

Compound A material in which atoms of different elements are chemically bonded to one another.

Mixture A substance whose components are mixed together without combining chemically.

Molecule Two or more atoms that bond together by a sharing of electrons. Atoms combine to become molecules.

Antimatter A "complementary" form of matter composed of atoms with negative nuclei and positive electrons.

Dark matter Unseen and unidentified matter that is evident by its gravitational pull on stars in the galaxies. Dark matter, along with dark energy, constitutes perhaps 90% of the stuff of the universe.

REVIEW QUESTIONS

The Atomic Hypothesis

1. What causes dust particles and tiny grains of soot to move with Brownian motion?
2. Who first explained Brownian motion and made a convincing case for the existence of atoms?
3. According to Richard Feynman, when do atoms attract each other, and when do they repel?

Characteristics of Atoms

4. How does the approximate number of atoms in the air in your lungs compare with the number of breaths of air in Earth's atmosphere?
5. Are most of the atoms around us younger or older than the Sun?

Atomic Imagery

6. Why can atoms not be seen with a powerful optical microscope?
7. Why can atoms be seen with an electron beam?
8. What is the purpose of a model in science?

Atomic Structure

9. How does the mass of an atomic nucleus compare with the mass of an atom as a whole?
10. What is a nucleon?
11. How does the mass and electric charge of a proton compare with the mass and charge of an electron?
12. Since atoms are mostly empty space, why don't we fall through a floor we stand on?

The Elements

13. What element has the lightest atoms?
14. What is the most abundant element in the known universe?
15. How were elements heavier than hydrogen formed?
16. Where did the heaviest elements originate?
17. What are the five most common elements in living things?

The Periodic Table of the Elements

18. What does the atomic number of an element tell you about the element?
19. What is characteristic of the columns in the periodic table?

Relative Sizes of Atoms

20. What kind of basic force pulls electrons close to the atomic nucleus?
21. Why are heavier elements not much larger than lighter elements?

Isotopes

22. How does one isotope differ from another?
23. Distinguish between *mass number* and *atomic mass*.

Compounds and Mixtures

24. What is a compound? Cite three examples.
25. What is a mixture? Cite three examples.

Molecules

26. How does a molecule differ from an atom?
27. Compared with the energy it takes to separate oxygen and hydrogen from water, how much energy is released when they recombine? (In Chapter 5 you studied the conservation of energy.)

Antimatter

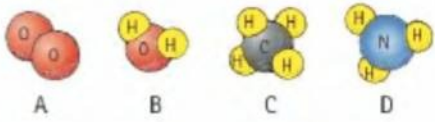
28. How do matter and antimatter differ?
29. What occurs when a particle of matter and a particle of antimatter meet?

Dark Matter

30. What is the evidence that dark matter exists?

RANKING

1. Consider the following atoms: A. Gold, B. Copper, C. Carbon, D. Silver.
   Consult the periodic table and rank these atoms, from most to least, by their
   a. mass.
   b. number of electrons.
   c. number of protons.
2. Rank the number of shells in these noble-gas atoms from most to least:
   a. Argon. b. Radon. c. Helium. d. Neon.
3. Rank the mass of these molecules from most to least.



PROJECTS

1. A candle will burn only if oxygen is present. Will a candle burn twice as long in an inverted liter jar as it will in an inverted half-liter jar? Try it and see.
2. Write a letter to Grandma or Grandpa and describe how long the atoms that make up their bodies have been around. And how long they will continue to be around.

EXERCISES

1. How many types of atoms can you expect to find in a pure sample of any element?
2. How many individual atoms are in a water molecule?
3. When a container of gas is heated, what happens to the average speed of its molecules?
4. The average speed of a perfume-vapor molecule at room temperature may be about 300 m/s, but you'll find the speed at which the scent travels across the room is much less. Why?
5. A cat strolls across your backyard. An hour later, a dog with his nose to the ground follows the trail of the cat. Explain this occurrence from a molecular point of view.
6. If no molecules in a body could escape, would the body have any odor?
7. Where were the atoms that make up a newborn infant "manufactured"?
8. Which of the following is not an element: hydrogen, carbon, oxygen, water?
9. Which of the following are pure elements: H_2, H_2O, He, Na, NaCl, H_2SO_4, U?
10. Your friend says that what makes one element distinct from another is the number of electrons about the atomic nucleus. Do you agree wholeheartedly, partially, or not at all? Explain.
11. What is the cause of the Brownian motion of dust particles? Why aren't larger objects, such as baseballs, similarly affected?
12. Why don't equal masses of golf balls and Ping-Pong balls contain the same number of balls?
13. Why don't equal masses of carbon atoms and oxygen atoms contain the same number of particles?
14. Which contains more atoms: 1 kg of lead or 1 kg of aluminum?
15. How many atoms are in a molecule of ethanol, C_2H_6O?
16. The atomic masses of two isotopes of cobalt are 59 and 60. (a) What is the number of protons and neutrons in each? (b) What is the number of orbiting electrons in each when the isotopes are electrically neutral?
17. A particular atom contains 29 electrons, 34 neutrons, and 29 protons. What is the identity of this element and its atomic number?
18. If two protons and two neutrons are removed from the nucleus of an oxygen atom, what nucleus remains?
19. What element results if you add a pair of protons to the nucleus of mercury? (See the periodic table.)
20. What element results if two protons and two neutrons are ejected from a radium nucleus?
21. To become a negative ion, does an atom lose or gain an electron?
22. To become a positive ion, does an atom lose or gain an electron?
23. You could swallow a capsule of germanium without ill effects. But, if a proton were added to each of the germanium nuclei, you would not want to swallow the capsule. Why? (Consult the periodic table.)
24. Helium is an inert gas, meaning that it doesn't readily combine with other elements. What five other elements would you also expect to be inert gases? (See the periodic table.)
25. Which of the following elements would you predict to have properties most like those of silicon (Si): aluminum (Al), phosphorus (P), or germanium (Ge)? (Consult the periodic table.)
26. A carbon atom, with a half-full outer shell of electrons—four in a shell that can hold eight—readily shares its electrons with other atoms and forms a vast number of molecules, many of which are the organic molecules that form the bulk of living matter. Looking at the periodic table, what other element do you think might play a role like carbon in life forms on some other planet?
27. Which contributes more to an atom's mass—electrons or protons? Which contributes more to an atom's size?
28. A hydrogen atom and a carbon atom move at the same speed. Which has the greater kinetic energy?
29. In a gaseous mixture of hydrogen and oxygen gas, both with the same average kinetic energy, which molecules move faster on average?
30. The atoms that constitute your body are mostly empty space, and structures such as the chair you're sitting on are composed of atoms that are also mostly empty space. So why don't you fall through the chair?
31. In what sense can you truthfully say that you are a part of every person in history? In what sense can you say that you will tangibly contribute to every person on Earth who will follow?
32. What are the chances that at least one of the atoms exhaled by your very first breath will be in your next breath?
33. Hydrogen and oxygen always react in a 1:8 ratio by mass to form water. Early investigators thought this meant that oxygen was 8 times more massive than hydrogen. What chemical formula did these investigators assume for water?
34. Somebody told your friend that if an antimatter alien ever set foot upon Earth, the whole world would explode into pure radiant energy. Your friend looks to you for verification or refutation of this claim. What do you say?
35. Make up a multiple-choice question that will test your classmates on the distinction between any two terms in the Summary of Terms list.

CHAPTER 11 ONLINE RESOURCES

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- Evidence for Atoms
- Atoms Are Recyclable

Quizzes

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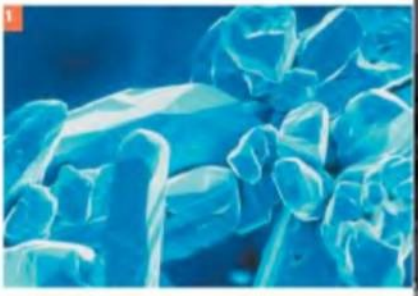
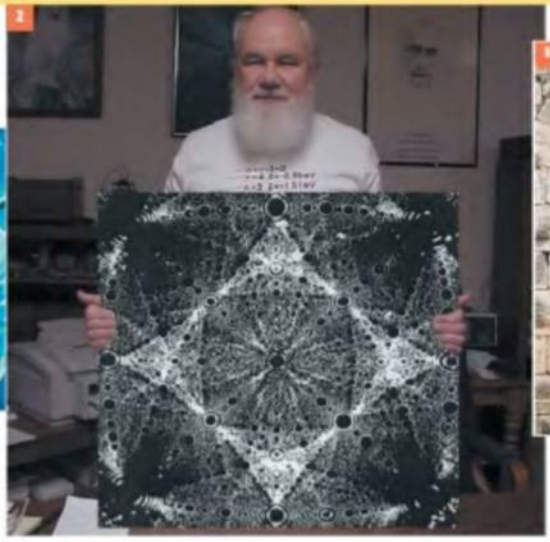
12 Solids





1 Silver crystals, close up. 2 John Hubisz displays an enlarged image of one of Erie Müller's famous micrographs. 3 Compression between adjacent stones accounts for the strength of semicircular arches, which for centuries have been used in the construction of doorways, bridges, and many structures.

Over two nights in February 1945, late in World War II, the German city of Dresden was firebombed, leveling the city and killing tens of thousands of its inhabitants. Beneath those bombs, and surviving, was the German physicist Erwin Wilhelm Müller.

Before the war, Müller invented the field emission microscope and later was the first person to experimentally observe atoms. After the war, in 1951, he invented the field ion microscope, which provided a sharper and clearer view of atoms in a crystal lattice. A sample of this is shown in the striking photograph above held by physicist John Hubisz. The photograph is a *micrograph*, produced in 1958 by Müller after he joined the faculty at Pennsylvania State University.

Müller used an extremely fine platinum needle with an incredibly tiny hemisphere-shaped tip. The needle was enclosed in a tube of rarefied helium and subjected to a very high positive voltage relative to its surroundings. This voltage created such an intense electric force that any helium atoms "settling" on the atoms of the needle tip were stripped of electrons to become *ions*. Positively charged helium ions streamed away from the platinum needle tip in a direction almost perpendicular to its surface at every point. They then struck a fluorescent screen, producing this picture of the needle tip, which magnifies the spacing of the atoms by approximately 750,000 times. Clearly, the platinum is crystalline, with the atoms arranged like oranges in a grocer's display. Although the photograph is not of the atoms themselves, it shows the positions of the atoms and reveals the microarchitecture of one of the solids that make up our world.

Crystal Structure

Metals, salts, and most minerals—the materials of Earth—are made up of crystals. People have known for centuries about crystals such as salt and quartz, but it wasn't until the 20th century that crystals were interpreted as regular arrays of atoms. In 1912, physicists used X-rays to confirm that each crystal is a three-dimensional orderly arrangement—a crystalline latticework of atoms. The atoms in a crystal were measured to be very close together, about the same distance apart as the wavelength of X-rays.

The German physicist Max von Laue discovered that a beam of X-rays directed upon a crystal is diffracted, or separated, into a characteristic pattern (Figure 12.1). X-ray *diffraction patterns* on photographic film show crystals to be neat mosaics of atoms sited on regular lattices, like three-dimensional chessboards or children's jungle gyms. Such metals as iron, copper, and gold have relatively simple crystal structures. Tin and cobalt are a little more complex. All metals contain a jumble of many crystals, each almost perfect, with the same regular lattice but at some inclination to the crystal nearby. These metal crystals can be seen when a metal surface is *etched*, or cleaned, with acid. You can see the crystal structures on the surface of galvanized iron exposed to the weather, or on brass doorknobs etched by the perspiration of many hands.

Von Laue's photographs of the X-ray diffraction patterns fascinated English scientists William Henry Bragg and his son William Lawrence Bragg. They developed a mathematical formula that showed just how X-rays should scatter from the various regularly spaced atomic layers in a crystal. With this formula and an analysis of the pattern of spots in a diffraction pattern, they could determine distances between the atoms in a crystal. X-ray diffraction is a vital tool today in the biological and physical sciences.

Noncrystalline solids are said to be *amorphous*. In the amorphous state, atoms and molecules in a solid are distributed randomly. Rubber, glass, and plastic are among the materials that lack an orderly, repetitive arrangement of their basic particles. In many amorphous solids, the particles have some freedom to wander. This is evident in the elasticity of rubber and the tendency of glass to flow when subjected to stress over long periods of time.

Whether atoms are in a crystalline state or in an amorphous state, each atom or ion vibrates about its own position. Atoms are tied together by electrical bonding forces. We'll not discuss **atomic bonding** now, except to mention the four principal types of bonding in solids: ionic, covalent, metallic, and Van der Waals', the last being the weakest. Some properties of a solid are determined by the types of bonds it has. More information about these bonds can be found in almost any chemistry text.

fyi

- Humans have been using solid materials for many thousands of years. The names of the time periods Stone Age, Bronze Age, and Iron Age tell us the importance of solid materials in the development of civilization. The numbers and uses of materials multiplied over the centuries, yet there was little progress in understanding the nature of solids. This understanding had to await discoveries about atoms that occurred in the 20th century. With that knowledge, investigators now invent new materials daily, meeting the demands of today's information age.

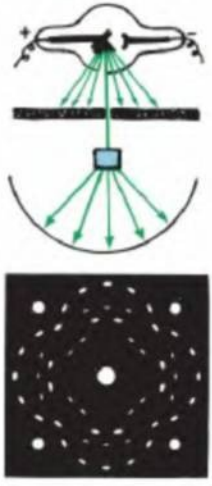


FIGURE 12.1
X-ray determination of crystal structure. The photograph of common table salt (sodium chloride) is a product of X-ray diffraction. Rays from the X-ray tube are blocked by a lead screen except for a narrow beam that hits the salt crystal. The radiation that penetrates the crystal and reaches the photographic film makes the pattern shown. The white spot in the center is due to the main unscattered beam of X-rays. The size and arrangement of the other spots result from the latticework structure of sodium and chlorine ions in the crystal. A crystal of sodium chloride always produces this same design. Every crystalline structure has its own unique X-ray diffraction picture.

Diffraction patterns of DNA (similar to the one of salt shown here), made by Maurice Wilkins and Rosalind Franklin in 1953, provided the data from which James D. Watson and Francis Crick discovered the double helix of DNA.

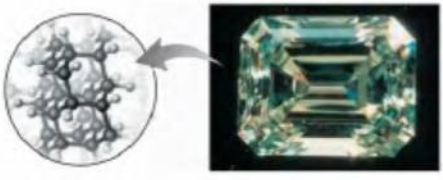


FIGURE 12.2
The crystalline structure of diamond is illustrated with sticks to represent the covalent bonds responsible for its extreme hardness.

The Van der Waals force is the mechanism that provides adhesion of the many ridges in the feet of a gecko.

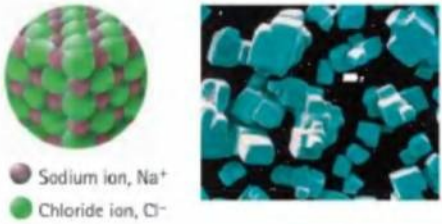


FIGURE 12.3
The cubic crystalline structure of common salt as seen through a microscope. The cubic shape is a consequence of the cubic arrangement of sodium and chloride ions.

Density

FIGURE 12.4
When the volume of the bread is reduced, its density increases.

Is iron heavier than wood? The question is ambiguous, for it depends on the amounts of iron and wood. A large log is clearly heavier than an iron nail. A better question to ask is if iron is *denser* than wood, in which case the answer is *yes*, iron is denser than wood. The masses of the atoms and the spacing between them determine the **density** of materials. We think of density as the "lightness" or "heaviness" of materials of the same size. It's a measure of the compactness of matter, of how much mass occupies a given space; it is the amount of mass per unit volume:

$$\text{Density} = \frac{\text{mass}}{\text{volume}}$$

Density is a property of a material; it doesn't matter how much of the material you actually have. The densities of a few materials are shown in Table 12.1. Density

Crystal Power

The regularly repeating internal structure of atoms in crystals gives them aesthetic properties that have long made them attractive in jewelry. Crystals also have properties that are very important to the electronics and optical industries, and they are used in just about every type of modern technology. In times past, crystals were valued for their alleged healing powers. This belief continues today, particularly among occultists and New Age healers. Crystals are said to channel "good energy" and ward off "bad energy." They carry "vibrations" that resonate with healing "frequencies" that help maintain a beneficial body balance. When properly arranged, crystals are said to provide protection against harmful electromagnetic forces emitted by power lines, cellular phones, computer monitors, microwave ovens, and other people. We are told that crystals are "medically proven" to heal and to protect and that such claims are "based on Nobel Prize–winning physics."

Crystals *do* give off energy—as every other object does. We'll learn in Chapter 16 that all things radiate energy—and also that all things absorb energy. If a crystal or any substance radiates more energy than it receives, its temperature drops. Atoms in crystals *do* vibrate and *do* resonate with matching frequencies of external vibrations—just as molecules in all gases and in all liquids do. If purveyors of crystal power are talking about some kind of energy special to crystals, or to life, no scientific evidence supports this (the discoverer of such a special kind of energy would quickly become world-famous). Of course, evidence for a new kind of energy, such as the dark energy discussed in the previous chapter, could one day be found, but this is not what is claimed by purveyors of crystal power, who assert that modern scientific evidence supports their claims.

The evidence for crystal power is not experimental; rather, it is confined to *testimonials*. As advertising illustrates, people are generally more persuaded by testimonials than by confirmed facts. Testimonials by people who are convinced of the personal benefits of crystals are common. Being convinced by scientific evidence is one thing; being convinced by wishful thinking, communal reinforcement, or by a placebo effect is quite another. None of the claims for the special powers of crystals have ever been backed up by scientific evidence.

Claims aside, wearing crystal pendants seems to give some people a good *feeling*, and even a feeling of protection. These feelings, and the aesthetic qualities of crystals, are their virtues. Some people feel that crystals bring good luck, just as carrying a rabbit's foot in your pocket is supposed to do. The difference between crystal power and rabbit's feet, however, is that the benefits of crystals are couched in scientific terms, whereas claims for the benefits of carrying a rabbit's foot are not. Hence, the purveyors of crystal power are into full-fledged pseudoscience.

is usually expressed with metric units, generally kilograms per cubic meter, kilograms per liter, or grams per cubic centimeter. Water, for example, has a mass density of 1000 kg/m^3, or, equivalently, 1 g/cm^3. So the mass of a cubic meter of fresh water is 1000 kg, and, equivalently, the mass of a cubic centimeter (about the size of a sugar cube) of fresh water is 1 g.

Density may be expressed in terms of weight rather than mass. This is *weight density*, which is defined as weight per unit volume:

$$\text{Weight density} = \frac{\text{weight}}{\text{volume}}$$

Weight density is measured in N/m^3. Because a 1-kg body has a weight of 9.8 N, weight density is numerically 9.8 × mass density. For example, the weight density of water is 9800 N/m^3. In the British system, 1 cubic foot (ft^3) of fresh water (almost 7.5 gallons) weighs 62.4 pounds. Thus, in the British system, fresh water has a weight density of 62.4 lb/ft^3.

The density of a material depends upon the masses of the individual atoms that make it up and the spacing between those atoms. Iridium, a hard, brittle, silvery-white metal in the platinum family, is the densest substance on Earth. Although the individual iridium atom is less massive than individual atoms of platinum, gold, lead, or uranium, the close spacing of iridium atoms in the crystalline form contributes to its greater density. More iridium atoms fit into a cubic centimeter than other, more massive but more widely spaced atoms. Hence iridium has a whopping density of 22,650 kg/m^3.

TABLE 12.1

Densities of Common Substances (kg/m^3) (for density in g/cm^3, divide by 1000)

Solids	Density
Iridium	22,650
Osmium	22,610
Platinum	21,090
Gold	19,300
Uranium	19,050
Lead	11,340
Silver	10,490
Copper	8,920
Brass	8,600
Iron	7,870
Tin	7,310
Aluminum	2,700
Concrete	2,300
Ice	919
Liquids	
Mercury	13,600
Glycerin	1,260
Seawater	1,025
Water at 4°C	1,000
Ethyl alcohol	785
Gasoline	680

CHECK POINT

1. *Here's an easy one:* When water freezes, it expands. What does this say about the density of ice compared with the density of water?
2. *Here's a slightly tricky one:* Which weighs more, a liter of ice or a liter of water?
3. Which has the greater density—100 kg of lead or 1000 kg of aluminum?
4. What is the density of 1000 kg of water?
5. What is the volume of 1000 kg of water?

Check Your Answers

1. Ice is less dense than water (because it has more volume for the same mass), which is why ice floats on water.
2. Don't say that they weigh the same! A liter of water weighs more. If it is frozen, then its volume will be more than a liter. If you shave that part off so that the chunk of ice is the same size as the original liter of water, it will certainly weigh less.
3. Density is a *ratio* of mass and volume (or weight and volume), and this ratio is greater for any amount of lead than for any amount of aluminum—see Table 12.1.
4. The density of *any* amount of water is 1000 kg/m^3 (or 1 g/cm^3).
5. The volume of 1000 kg of water is 1 m^3.

Elasticity

When an object is subjected to external forces, it undergoes changes in size, or in shape, or in both. The changes depend on the arrangement and bonding of the atoms in the material. A spring, for example, can be stretched or compressed by external forces.

A weight hanging on a spring stretches the spring. Additional weight stretches it further. If the weights are removed, the spring returns to its original length. We say

FIGURE 12.5

Both Stephanie and the tree are composed mainly of hydrogen, oxygen, and carbon. Food ingestion supplies these to Stephanie, whereas the tree gets most of its oxygen and carbon from the air. In this sense, a tree can be thought of as "solid air."

A cubic meter is a sizable volume and contains a million cubic centimeters, so there are a million grams of water in a cubic meter (or, equivalently, a thousand kilograms of water in a cubic meter). Hence, $1\ g/cm^3 = 1000\ kg/m^3$.

that the spring is *elastic*. When a batter hits a baseball, the bat temporarily changes the ball's shape. An archer, about to shoot an arrow, first bends the bow, which springs back to its original shape when the arrow is released. The spring, the baseball, and the bow are examples of elastic objects. A body's **elasticity** describes how much it changes shape when a deforming force acts upon it, and how well it returns to its original shape when the force is removed. Clay, putty, and dough do *not* return to their original shape when a deforming force is applied and then removed. Materials such as these, which do not resume their original shape after being deformed, are said to be *inelastic*. Lead is also inelastic, since it's easy to distort lead's shape permanently.

When you hang a weight on a spring, the weight applies a force to the spring and this stretches the spring. Twice the weight causes twice as much stretch; triple the force causes triple the stretch. We can say,

$$F \sim \Delta x$$

That is, the stretch is directly proportional to the applied force (Figure 12.7). This relationship, noted in the mid-17th century by the British physicist Robert Hooke, a contemporary of Isaac Newton, is called **Hooke's law.**

If an elastic material is stretched or compressed beyond a certain amount, it will not return to its original state and will remain distorted. The distance beyond which permanent distortion occurs is called the *elastic limit*. Hooke's law holds only as long as the force does not stretch or compress the material beyond its elastic limit.

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- The enamel in your teeth is the hardest substance in your body.

FIGURE 12.6
A baseball is elastic.

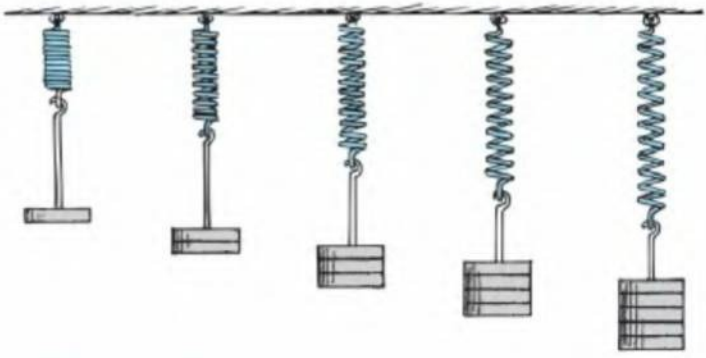

FIGURE 12.7
The stretch of the spring is directly proportional to the applied force. If the weight is doubled, the spring stretches twice as much.

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- Robert Hooke, one of England's greatest scientists, was the first to propose a wave theory of light and the first to describe the cell (for which he became known as the father of microscopy). As an artist and surveyor, he helped Christopher Wren rebuild London after the great fire in 1766. As a physicist, he collaborated with Robert Boyle and other physicists of his time and was chosen to head the Royal Society. Upon Hooke's death, Isaac Newton became president of the Royal Society, and he jealously destroyed everything he could of Hooke's work. No paintings or likenesses of Robert Hooke survive today.

CHECK POINT

1. A 2-kg antique painting is hung from the end of a spring. The spring then stretches a distance of 10 cm. If, instead, a 4-kg painting is hung from the same spring, how much will the spring stretch? What if a 6-kg painting were hung from the same spring? (Assume that none of these loads stretches the spring beyond its elastic limit.)
2. If a force of 10 N stretches a certain spring 4 cm, how much stretch will occur for an applied force of 15 N?

Check Your Answers

1. A 4-kg load (painting in this case) has twice the weight of a 2-kg load. In accord with Hooke's law, $F \sim \Delta x$, 2 times the applied force results in 2 times the stretch, so the spring should stretch 20 cm. The weight of the 6-kg load makes the spring stretch 3 times as far, 30 cm. (If the elastic limit were exceeded, the amount of stretch could not be predicted with the information given.)

2. The spring will stretch 6 cm. By ratio and proportion, (10 N)/(4 cm) = (15 N)/(x cm), which is read: 10 newtons is to 4 centimeters as 15 newtons is to x centimeters. $x = 6$ cm. If taking a lab, you'll learn that the ratio of force to stretch is called the *spring constant*, k (in this case $k = 2.5$ N/cm), and Hooke's law is expressed as the equation $F = k\Delta x$.

Tension and Compression

When something is pulled on (stretched), it is said to be in *tension*. When it is pushed in (squashed), it is in *compression*. If you bend a ruler (or any stick), the part bent on the outside of the curve is in tension. The inner curved part, which is pushed in, is in compression. Compression causes things to get shorter and wider, whereas tension causes them to get longer and thinner. This is not obvious for most rigid materials, however, because the shortening or lengthening is very small.

Steel is an excellent elastic material, because it can withstand large forces and then return to its original size and shape. Because of its strength and elastic properties, it is used to make not only springs but construction girders as well. Vertical girders of steel used in the construction of tall buildings undergo only slight compression. A typical 25-meter-long vertical steel girder (column) used in high-rise construction is compressed about a millimeter when it carries a 10-ton load. This can add up. A 70- to 80-story building can compress the huge steel columns at its base by some 2.5 centimeters (a full inch) when construction is completed.

More deformation occurs when girders are used horizontally, where their tendency is to sag under heavy loads. When a horizontal beam is supported at one or both ends, it is under both tension and compression from its weight and the load it supports. Consider the horizontal beam supported at one end (known as a cantilever beam) in Figure 12.8. It sags because of its own weight and because of the load it supports at its end. A little thought will show that the top part of the beam tends to be stretched. Atoms tend to be pulled apart. The top part is slightly longer

A diving board with a diver standing at one end is a cantilever.

FIGURE 12.8
The top part of the beam is stretched and the bottom part is compressed. What happens in the middle portion, between top and bottom?

and is under tension. More thought shows that the bottom part of the beam is squashed. It is compressed as atoms there are squeezed together. The bottom part is slightly shorter because of the way it is bent. Can you see that, somewhere between the top and bottom, there is a region in which nothing happens, in which there is neither tension nor compression? This is the *neutral layer*.

The horizontal beam shown in Figure 12.9, known as a simple beam, is supported at both ends and carries a load in the middle. Here there is compression in the top of the beam and tension in the bottom part. Again, there is a neutral layer along the middle portion of the thickness of the beam all along its length.

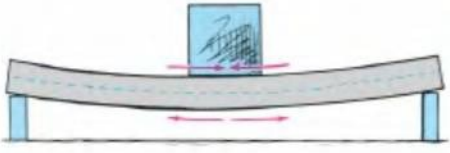

FIGURE 12.9
The top part of the beam is compressed and the bottom part is stretched. Where is the neutral layer (the part that is not under stress due to tension or compression)?

Practicing Physics

If you nail four sticks together to form a rectangle, they can be deformed into a parallelogram without too much effort. But, if three sticks are nailed together to form a triangle, the shape cannot be changed without actually breaking the sticks or dislodging the nails. The triangle is the strongest of all the geometrical figures, which is why you see triangular shapes in bridges. Go ahead and nail three sticks together and try this out, and then look at the triangles used in strengthening structures of many kinds.

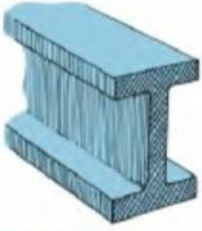

FIGURE 12.10

An I-beam is like a solid bar with some of the steel scooped from its middle where it is needed least. The beam is therefore lighter, but it has nearly the same strength.

With the neutral layer in mind, we can see why the cross section of steel girders has the form of the letter I (Figure 12.10). Most of the material in these I-beams is concentrated in the top and bottom *flanges*. When the beam is used horizontally in construction, the stress is predominantly in the top and bottom flanges. One flange is squeezed while the other is stretched, the two flanges supporting virtually all stresses in the beam. Between the flanges is a relatively stress-free region, the *web*, that acts principally to hold the top and bottom flanges well apart. Because of the web, comparatively little material is needed. An I-beam is nearly as strong as a solid rectangular bar of the same overall dimensions, with considerably less weight. A large rectangular steel beam on a certain span might fail under its own weight, whereas an I-beam of the same depth could support much added load.

FIGURE 12.11

The upper half of each horizontal branch is under tension because of the branch's weight, while the lower half is under compression. In what location is the wood neither stretched nor compressed?

CHECK POINT

1. When you walk on floorboards in an old house that sag due to your weight, where is the neutral layer?
2. Suppose you drill a hole horizontally through a tree branch as shown. Where will the hole weaken the branch the least—through the upper portion, the middle portion, or the lower portion of the branch?

Check Your Answers

1. The neutral layer is midway between the top and bottom surfaces of the floorboards.
2. Drill the hole horizontally through the middle of the branch, through the neutral layer—a hole at that location will hardly affect the branch's strength because fibers there are neither stretched nor compressed. Wood fibers in the top part are being stretched, so a hole there may result in fibers pulling apart. Fibers in the lower part are compressed, so a hole there might crush under compression.

Arches

Stone breaks more easily under tension than compression. The roofs of stone structures built by the Egyptians during the time of the pyramids were constructed with many horizontal stone slabs. Because of the weakness of these slabs under the forces produced by gravity, many vertical columns had to be erected to support the roofs. Likewise for the temples in ancient Greece. Then came arches—and fewer vertical columns.

FIGURE 12.12
The horizontal slabs of stone of the roof cannot be too long because stone easily breaks under tension. That is why many vertical columns are needed to support the roof.

FIGURE 12.13
Common semicircular stone arches, which have stood for centuries.

Look at the tops of the windows in old brick buildings. Chances are the tops are arched. Likewise for the shapes of old stone bridges. When a load is placed on a properly arched structure, the compression strengthens rather than weakens the structure. The stones are pushed together more firmly and are held together by compressive forces. With just the right shape of the arch, the stones do not even need cement to hold them together.

When the load being supported is uniform and extends horizontally, as with a bridge, the proper shape is a parabola, the same curve followed by a thrown ball. The cables of a suspension bridge provide an example of an "upside-down" parabolic arch. If, on the other hand, the arch is supporting only its own weight, the curve that gives it maximum strength is called a *catenary*. A catenary is the curve formed by a rope or chain hung between two points of support. Tension along every part of the rope or chain is parallel to the curve. So, when a free-standing arch takes the shape of an inverted catenary, compression within it is everywhere parallel to the arch, just as tension between adjacent links of a hanging chain is everywhere parallel to the chain. The Gateway Arch, which graces the waterfront of St. Louis, Missouri, is a catenary (Figure 12.14).

If you rotate an arch through a complete circle, you have a dome. The weight of the dome, like that of an arch, produces compression. Modern domes, such as the Astrodome in Houston, are inspired by three-dimensional catenaries, and they cover vast areas without the interruption of columns. There are shallow domes (the Jefferson Monument) and tall ones (the U.S. Capitol). And long before these, there were the igloos in the Arctic.

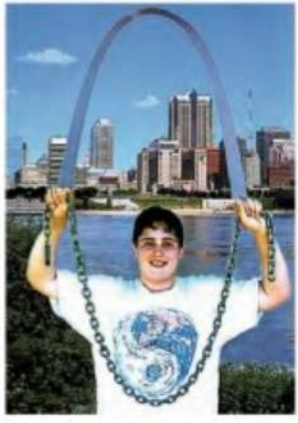

FIGURE 12.14
Both the curve of a sagging chain held by Manuel and the Gateway Arch in St. Louis are catenaries.

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- A catenary arch could even be made with slippery blocks of ice! Provided that the compressive forces between blocks are parallel to the arch and that temperature doesn't rise enough to cause melting, the arch will remain stable.

FIGURE 12.15

The weight of the dome produces compression, not tension, so no support columns are needed in the middle.

CHECK POINT

Why is it easier for a chicken inside an eggshell to poke its way out than it is for a chicken on the outside to poke its way in?

Check Your Answer

To poke its way into a shell, a chicken on the outside must contend with compression, which greatly resists shell breakage. But, when poking from the inside, only the weaker shell tension must be overcome. To see that the compression of the shell requires greater force, try crushing an egg along its long axis by squeezing it between your thumb and fingers. Surprised? Try it along its shorter diameter. Surprised? (Do this over a sink with some protection, such as gloves, for possible shell splinters.)

Scaling[1]

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Video
Scaling

Have you ever noticed how strong an ant is for its size? An ant can carry the weight of several ants on its back, whereas a strong elephant would have great difficulty carrying even a single elephant. How strong would an ant be if it were scaled up to the size of an elephant? Would this "super ant" be several times stronger than an elephant? Surprisingly, the answer is *no*. Such an ant would be unable to lift its own weight off the ground. Its legs would be too thin for its greater weight, and they would likely break.

Scaling was studied by Galileo, who differentiated the bone sizes of various creatures.

There is a reason for the thin legs of the ant and the thick legs of an elephant. As the size of a thing increases, it grows heavier much faster than it grows stronger. You can support a toothpick horizontally at its ends and notice no sag. But support an entire tree trunk of the same kind of wood horizontally at its ends and you'll notice an appreciable sag. Relative to its weight, the toothpick is much stronger than the tree. **Scaling** is the study of how the volume and shape (size) of any object affect the relationship of its strength, weight, and surface area.

Strength is related to the area of the cross section (which is two-dimensional and is measured in *square* centimeters), whereas *weight* relates to volume (which is three-

[1]Material in this section is based on two delightful and informative essays: "On Being the Right Size," by J. B. S. Haldane, and "On Magnitude," by Sir D'Arcy Wentworth Thompson, both in James R. Newman (ed.), *The World of Mathematics*, vol. II. (New York: Simon & Schuster, 1956).

dimensional and is measured in *cubic* centimeters). To understand this square–cube relationship, consider the simplest case of a solid cube of matter, 1 centimeter on a side—say, a sugar cube. Any 1-cubic-centimeter cube has a cross section of 1 square centimeter. That is, if we sliced through the cube parallel to one of its faces, the sliced area would be 1 square centimeter. Compare this with a cube made of the same material that has double the linear dimensions—a cube 2 centimeters on each side. As shown in Figure 12.16, its cross-sectional area will be 2×2, or 4 square centimeters, and its volume will be $2 \times 2 \times 2$, or 8 cubic centimeters. Therefore, the larger cube will be 4 times as strong but 8 times as heavy. Careful investigation of Figure 12.16 shows that, for increases of linear dimensions, the cross-sectional area and the total area grow as the square of the increase, whereas volume and weight grow as the cube of the increase.

A sphere has the least area per volume. Now you know why elevated water reservoirs are often spherical in shape.

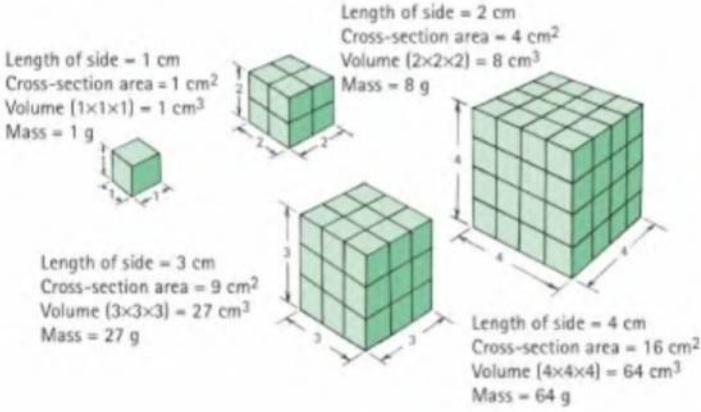

FIGURE 12.16

INTERACTIVE FIGURE

As the linear dimensions of an object change by some factor, the cross-sectional area changes as the square of this factor, and the volume (and hence the weight) changes as the cube of this factor. We see that, when the linear dimensions are doubled (factor 2), the area grows by $2^2 = 4$, and the volume grows by $2^3 = 8$.

Volume (and thus weight) increases much faster than the corresponding increase of cross-sectional area. Although Figure 12.16 demonstrates the simple example of a cube, the principle applies to an object of any shape. Consider a football player who can do many pushups. Suppose he could somehow be scaled up to twice his size—that is, twice as tall and twice as broad, with his bones twice as thick and every linear dimension increased by a factor of 2. Would he be twice as strong and be able to lift himself with twice the ease? The answer is *no*. Although his twice-as-thick arms would have four times the cross-sectional area and be four times as strong, he would be eight times as heavy. For comparable effort, he would be able to lift only half his weight. Relative to his new weight, he would be weaker than before.

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Surface Area vs. Volume

We find in nature that large animals have disproportionately thick legs compared with those of small animals. This is because of the relationship between volume and area—the fact that volume (and weight) grows as the cube of the factor by which the linear dimension increases, while strength (and area) grows as the square of the increase factor. So we see that there is a reason for the thin legs of a deer or an antelope, as well as for the thick legs of a rhinoceros, a hippopotamus, or an elephant. So the great strengths attributed to King Kong and other fictional giants cannot be taken seriously. The fact that the consequences of scaling are conveniently omitted is one of the differences between science and science fiction.

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- Leonardo da Vinci was the first to report that the cross-sectional area of a tree trunk is equal to the combined surface areas produced by making a horizontal slice through all of the branches farther up on the tree (but perpendicular to each branch). Likewise for the cross-sectional areas of capillaries with the cross section of the vein that supplies blood to them.

Important also is the comparison of total surface area to volume (Figure 12.17). Total surface area, just like cross-sectional area, grows in proportion to the square of

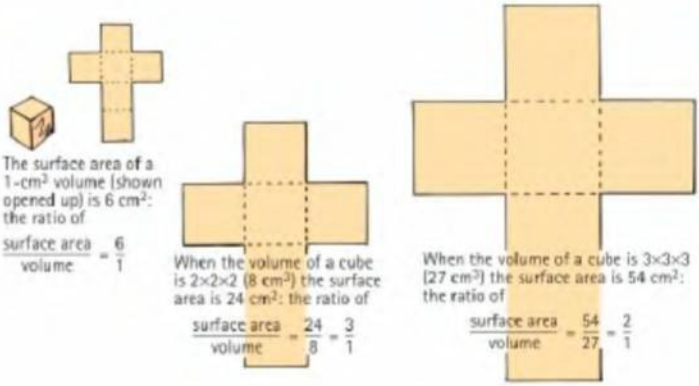


FIGURE 12.17
As the size of an object increases, there is a greater increase in its volume than in its surface area; as a result, the ratio of surface area to volume decreases.

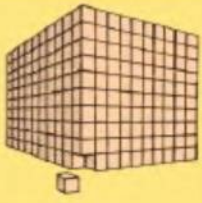
an object's linear size, whereas volume grows in proportion to the cube of the linear size. So, as an object grows, its surface area and volume grow at different rates, with the result that the ratio of surface area to volume *decreases*. In other words, both the surface area and the volume of a growing object increase, but the growth of surface area *relative to* the growth of volume decreases. Not many people really understand this concept. The following examples may be helpful.

A chef knows that more potato peelings result from peeling 5 kg of small potatoes than from peeling 5 kg of large potatoes. Smaller objects have more surface area per kilogram. Thin french fries cook faster in oil than thicker french fries. Flattened hamburgers cook faster than meatballs of the same mass. Crushed ice will cool a drink much faster than a single ice cube of the same mass, because crushed ice presents more surface area to the beverage. Steel wool rusts away at the sink while steel knives rust more slowly. Iron rusts when exposed to air, but it rusts much faster, and is soon eaten away, if it is in the form of small strands or filings.

Burning is an interaction between oxygen molecules in the air and molecules on the surface of the fuel. That's why chunks of coal burn, while coal dust explodes when ignited, and why we light fires with several thin pieces of wood instead of the same mass of wood as a single log. These are all consequences of the fact that volume and area are not in direct proportion to each other.

CHECK POINT

1. Consider a 1-cm³ cube scaled up to a cube 10 cm long on each edge.
   a. What would be the volume of the scaled-up cube?
   b. What would be its cross-sectional surface area?
   c. What would be its total surface area?
2. If you were somehow scaled up to twice your size while retaining your present proportions, would you be stronger or weaker? Explain your reasoning.



Check Your Answers

1. a. The volume of the scaled-up cube would be (length of side)³ = (10 cm)³, or 1000 cm³.
   b. Its cross-sectional surface area would be (length of side)² = (10 cm)², or 100 cm².
   c. Its total surface area = 6 sides × area of a side = 6 × (10 cm)² = 600 cm².

2. Your scaled-up self would be four times as strong, because the cross-sectional area of your twice-as-thick bones and muscles increase by four. You could lift a load four times as heavy. But your weight would be eight times greater than before, so you would not be stronger relative to your greater weight. You have four times the strength but carry eight times the weight, which gives you a strength-to-weight ratio of only half its former value. So, if you can barely lift your own weight now, when scaled up you could lift only half your new weight. Your strength would increase, but your strength-to-weight ratio would decrease. Stay as you are!

FIGURE 12.18

The African elephant has less surface area relative to its weight than many other animals. It compensates for this with its large ears, which significantly increase its radiating surface area and promote cooling of the body.

The large ears of African elephants are nature's way of compensating for the small ratio of surface area to volume for these large creatures. The large ears may enhance hearing, but better, they enhance cooling. The rate at which a creature generates heat is proportional to its mass (or volume), but the heat that it can dissipate is proportional to its surface area. If an African elephant didn't have large ears, it would not have enough surface area to cool its huge mass. The large ears greatly increase its overall surface area, which facilitates cooling in hot climates.

At the microscopic level, living cells must contend with the fact that the growth of volume is faster than the growth of surface area. Cells obtain nourishment by diffusion through their surfaces. As cells grow, their surface area increases, but not fast enough to keep up with their increasing volume. For example, if the surface area increases by four, the corresponding volume increases by eight. Eight times as much mass must be sustained by only four times as much nourishment. At some size, the surface area isn't large enough to allow sufficient nutrients to pass into the cell, placing a limit on how large cells can grow. So cells divide, and there is life as we know it. That's nice.

Not so nice is the fate of large animals when they fall. The saying "The bigger they are, the harder they fall" holds true and is a consequence of the small ratio of surface area to weight. Air resistance to movement through the air depends on the surface area of the moving object. If you fell off a cliff, even with air resistance, your speed would increase at the rate of very nearly 1 *g*. Your terminal speed (the speed at which the force of air resistance on you equals your weight) would be large unless you wore a parachute to increase your surface area. Small animals need no parachute.

Scaling works for shrinking things too. If your linear dimensions got smaller by a factor of 10, your area would decrease by a factor of 100, but your weight would decrease by 1000. Being this small means that you'd have 10 times as much surface area relative to your weight, so you would have a much lower terminal speed. This is why an insect can fall from the top of a tree to the ground below without harm. The ratio of surface area per weight is in the insect's favor—in a sense, the insect is its own parachute.

FIGURE 12.19

The long tail of the monkey not only helps the monkey to maintain its balance but also effectively radiates excess heat.

The dissimilar consequences of a fall are just one illustration of the different relationships that large organisms and small organisms have with the physical environment. The force of gravity is tiny for insects compared with cohesion forces (stickiness) between their feet and the surfaces they walk on. That's why a fly can crawl up a wall or along the ceiling completely ignoring gravity. Humans and elephants can't do that. The lives of small creatures are ruled not by gravity but by such forces as surface tension, cohesion, and capillarity, which we'll treat in the next chapter.

It is interesting to note that the heartbeat rate of a mammal is related to the size of the mammal. The heart of a tiny shrew beats about 20 times faster than the heart of an elephant. In general, small mammals live fast and die young; larger animals live at a leisurely pace and live longer. Don't feel bad about a pet hamster that doesn't live as long as a dog. All warm-blooded animals have about the same life span—not in terms of years, but in the average number of heartbeats (about 800 million). Humans are the exception: we live two to three times longer than other mammals of our size.

Large raindrops fall faster than small raindrops, and large fish swim faster than small fish.

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- Raindrops can get as large as 8 mm in diameter. Drops about 1 mm in diameter are spherical; at 2 mm, they flatten like a hamburger bun; and at 5 mm, air resistance distorts them to parachute shapes. When circulation tosses raindrops back up into the air, often repeatedly, they may freeze and form hail. Hailstones have been recorded that are as large as 178 mm in diameter.

Researchers are finding that, when something shrinks enough—whether it's an electronic circuit, a motor, a 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.[2] Scaling is enormously important as more devices are being miniaturized.

[2]A nanometer is one-billionth of a meter, so 1000 nanometers is one-millionth of a meter, or one-thousandth of a millimeter. Small indeed!

SUMMARY OF TERMS

Atomic bonding The linking together of atoms to form larger structures, including solids.

Density The mass of a substance per unit volume:

$$\text{Density} = \frac{\text{mass}}{\text{volume}}$$

Weight density is weight per unit volume:

$$\text{Weight density} = \frac{\text{weight}}{\text{volume}}$$

Elasticity The property of a material wherein it changes shape when a deforming force acts upon it and returns to its original shape when the force is removed.

Hooke's law The amount of stretch or compression of an elastic material is directly proportional to the applied force:

$$F \sim \Delta x$$

When the spring constant k is introduced, $F = k\Delta x$.

Scaling The study of how size affects the relationships among weight, strength, and surface.

SUMMARY OF EQUATIONS

$$\text{Density} = \frac{\text{mass}}{\text{volume}}$$

$$\text{Weight density} = \frac{\text{weight}}{\text{volume}}$$

$$F \sim \Delta x$$

REVIEW QUESTIONS

Crystal Structure

1. How does the arrangement of atoms in a crystalline substance differ from that in a noncrystalline substance?
2. What evidence can you cite for the microscopic crystal nature of certain solids? For macroscopic crystal nature?

Density

3. What happens to the volume of a loaf of bread that is squeezed? The mass? The density?
4. Which is denser, something having a density of 1000 kg/m^3 or something having a density of 1 g/cm^3? Defend your answer.
5. Iridium is not the heaviest atom found in nature. What, then, accounts for a chunk of pure iridium being the densest *substance* on Earth?
6. How does mass density differ from weight density?

Elasticity

7. Why do we say that a spring is elastic?
8. Why do we say a blob of putty is inelastic?
9. What is Hooke's law? Does it apply to elastic materials or to inelastic materials?
10. What is meant by the elastic limit for a particular object?
11. If a 1-kg object stretches a spring by 2 cm, how much will the spring be stretched when it supports a 3-kg object? (Assume the spring does not reach its elastic limit.)

Tension and Compression

12. Distinguish between *tension* and *compression*.
13. What and where is the neutral layer in a beam that supports a load?
14. Why are the cross sections of metal beams in the shape of the letter I instead of solid rectangles?

Arches

15. Why were so many vertical columns needed to support the roofs of stone buildings in ancient Egypt and Greece?
16. Is it *tension* or *compression* that strengthens an arch that supports a load?
17. Why is cement not needed between the stone blocks of an arch that has the shape of an inverted catenary?

18. Why are vertical columns not needed to support the middle of domed stadiums, such as the Houston Astrodome?

Scaling

19. Does the strength of a person's arm usually depend on the length of the arm or on its cross-sectional area?
20. What is the volume of a sugar cube that measures 1 cm on each side? What is the cross-sectional area of the cube? The total surface area?
21. If the linear dimensions of an object are doubled, by how much does the surface area increase? By how much does the volume increase?
22. As the volume of an object is increased, its surface area also increases. During this increase, does the *ratio* of square meters to cubic meters increase or does it decrease?
23. Which has more skin, an elephant or a mouse? Which has more skin *per unit of body weight*, an elephant or a mouse?
24. Why can small creatures fall considerable distances without injury, while people need parachutes to do the same?

RANKING

1. Consult Table 12.1 and rank the density of the following materials from greatest to least:
   a. concrete,
   b. liquid water,
   c. ice,
   d. aluminum.
2. Consider these three animals: A. dog, B. horse, C. elephant. Rank them, from highest to lowest, for their
   a. surface areas,
   b. masses,
   c. weights,
   d. volumes,
   e. surface area per weight.

PROJECTS

1. If you live in a region where snow falls, collect some snowflakes on black cloth and examine them with a magnifying glass. You'll see many hexagonal crystalline structures, among the most beautiful sights in nature.
2. Simulate atomic close packing with a couple of dozen or so pennies. Arrange them in a square pattern so each penny inside the perimeter makes contact with four others. Then arrange them hexagonally, so contact with six others occurs. Compare the areas occupied by the same number of pennies close packed both ways.
3. Are you slightly longer while lying down than you are tall when standing up? Make measurements and see.
4. Hold an egg vertically and dangle a small chain beside it. Can you see that the chain follows the contour of the egg—shallow sag for the more rounded end, and deeper sag for the more pointed end? Nature has not overlooked the catenary!

EXERCISES

1. You take 1000 mg of a vitamin and your friend takes 1 g of the same vitamin. Who takes more vitamins?
2. Your friend says that the primary difference between a solid and a liquid is the kind of atoms in the material. Do you agree or disagree, and why?
3. In what sense can it be said that a tree is solidified air?
4. Silicon is the chief ingredient of both glass and semiconductor devices, yet the physical properties of glass are different from those of semiconductor devices. Explain.
5. What evidence can you cite to support the claim that crystals are composed of atoms that are arranged in specific patterns?
6. What happens to the density of air in a common rubber balloon when it is heated?
7. Is iron necessarily heavier than cork? Explain.
8. How does the density of a 100-kg iron block compare with the density of an iron filing?
9. What happens to the density of water when it freezes to become ice?
10. In a deep dive, a whale is appreciably compressed by the pressure of the surrounding water. What happens to the whale's density during the dive?
11. The uranium atom is the heaviest and most massive atom among the naturally occurring elements. Why, then, isn't a solid bar of uranium the densest metal?
12. Which has more volume, a kilogram of gold or a kilogram of aluminum?
13. Which has more mass, a liter of ice or a liter of water?
14. How would you test the notion that a steel ball is elastic?
15. Why does the suspended spring stretch more at the top than at the bottom?

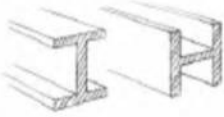
16. If the spring in the sketch above were supporting a heavy weight, how would the sketch be changed?
17. A thick rope is stronger than a thin rope of the same material. Is a long rope stronger than a short rope?

18. When you bend a meterstick, one side is under tension and the other is under compression. Which side is which?

19. Tension and compression occur in a partially supported horizontal beam when it sags due to gravity or when it supports a load. Make a simple sketch to show a means of supporting the beam so that tension occurs at the top part and compression at the bottom. Sketch another case in which compression is at the top and tension occurs at the bottom.

20. Suppose you're constructing a balcony that extends beyond the main frame of your house. In a concrete overhanging slab, should steel reinforcing rods be embedded in the top, middle, or bottom of the slab?

21. Can a horizontal I-beam support a greater load when the web is horizontal or when the web is vertical? Explain.



22. The sketches are of top views of a dam to hold back a lake. Which of the two designs is preferable? Why?

23. Consider a very large wooden barrel for storing wine. Should the "flat" ends be concave (bending inward) or convex (bending outward)? Why?

24. Why do you suppose that girders are so often arranged to form triangles in the construction of bridges and other structures? (Compare the stability of three sticks nailed together to form a triangle with four sticks nailed to form a rectangle, or any number of sticks to form multilegged geometric figures. Try it and see!)

25. Consider two bridges that are exact replicas of each other except that every dimension of the larger bridge is exactly twice that of the other—that is, twice as long, structural elements twice as thick, etc. Which bridge is more likely to collapse under its own weight?

26. Only with great difficulty can you crush an egg when squeezing it along its long axis, but it breaks easily if you squeeze it sideways. Why?

27. Archie designs an arch of a certain width and height to serve as an outdoor sculpture in a park. To achieve the size and shape for the strongest possible arch, he suspends a chain from two equally elevated supports as far apart as the arch is wide and allows the chain to hang as low as the arch is high. He then designs the arch to have exactly the inverted shape of the hanging chain. Explain why.

28. The photo shows a semicircular arch of stone. Note that it must be held together with steel rods to prevent outward movement. If the shape of the arch were not a semicircle but the shape used by Archie in the previous exercise, would the steel rods be necessary? Explain.

29. A candymaker making taffy apples decides to use 100 kg of large apples rather than 100 kg of small apples. Will the candymaker need to make more or less taffy to cover the apples?

30. Why is it easier to start a fire with kindling rather than with large sticks and logs of the same kind of wood?

31. Why does a chunk of coal burn when ignited, whereas coal dust explodes?

32. Why does a two-story house that is roughly a cube suffer less heat loss than a rambling one-story house of the same volume?

33. Why is heating more efficient in large apartment buildings than in single-family dwellings?

34. Some environmentally conscious people build their homes in the shape of a dome. Why is less heat lost in a dome-shaped dwelling than in a conventional dwelling with the same volume?

35. Why does crushed ice melt faster than the same mass of ice cubes?

36. Why do some animals curl up into a ball when they are cold?

37. Why is rust a greater problem for thin iron rods than for thick iron piles?

38. Why do thin french fries cook faster than thick fries?

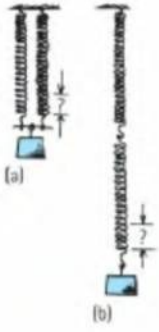
39. If you are grilling hamburgers and getting impatient, why is it a good idea to flatten the burgers to make them wider and thinner?

40. If you use a batch of cake batter for cupcakes and bake them for the time suggested for baking a cake, what will be the result?

41. Why are mittens warmer than gloves on a cold day? And which parts of the body are most susceptible to frostbite? Why?
42. What is the advantage to a gymnast of being short in stature?
43. How does scaling relate to the fact that the heartbeat of large creatures is generally slower than the heartbeat of smaller creatures?
44. Nourishment is obtained from food through the inner surface area of the intestines. Why is it that a small organism, such as a worm, has a simple and relatively straight intestinal tract, while a large organism, such as a human being, has a complex and extensively folded intestinal tract?
45. The human lungs have a volume of only about 4 L, yet an internal surface area of nearly 100 m^2. Why is this important, and how is this possible?
46. What does the concept of scaling have to do with the fact that living cells in a whale are about the same size as those in a mouse?
47. Which fall faster, large or small raindrops?
48. Who has more need for drink in a dry desert climate, a child or an adult?
49. Why doesn't a hummingbird soar like an eagle and an eagle flap its wings like a hummingbird?
50. Can you relate the idea of scaling to the governance of small versus large groups of citizens? Explain.

PROBLEMS

1. Show that the density of a 5-kg solid cylinder that is 10 cm tall with a radius of 3 cm is 17.7 g/cm^3.
2. What is the weight of a cubic meter of cork? Could you lift it? (For the density of cork, use 400 kg/m^3.)
3. A certain spring stretches 6 cm when a load of 30 N is suspended from it. How much will the spring stretch if 50 N is suspended from it (and it doesn't reach its elastic limit)?
4. Consider a spring that stretches 4 cm when a load of 10 N is suspended from it. How much will the spring stretch if an identical spring also supports the load as shown in (a) and (b)? (Neglect the weights of the springs.)



5. A cube 2 cm on a side is cut into cubes 1 cm on a side.
   a. How many cubes result?
   b. What was the surface area of the original cube and what is the total surface area of the eight smaller cubes? What is the ratio of surface areas?
   c. Show that the surface-to-volume ratio of the smaller cube is twice as great as for the single larger cube.
6. A 19.3-g mass of gold in the form of a cube is 1 cm long on each side (somewhat smaller than a sugar cube). What would be the length of the sides of a cube having twice this mass of gold?
7. In 2009, one of the U.S government's bailout packages was $700 billion when gold was worth $800 per ounce ($28.20 per gram). Calculate the mass in grams of $700 billion worth of gold. If this amount of gold were in the shape of a cube, how long would each of its sides be?

CHAPTER 12 ONLINE RESOURCES

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- 12.16

Videos

- Scaling
- Surface Area vs. Volume

Quizzes

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13 Liquids

1 The depth of water above ground level in the tower ensures substantial and reliable water pressure to the many homes it serves. 2 When Tsing Bardin shows her class Pascal's vases, she asks how the same levels of colored water relate to the saying that "water seeks its own level." 3 The Falkirk Wheel in Scotland lifts boats 18 m from a lower body of water to a higher one with ease. While one water-filled caisson rotates upward, the other rotates downward, always balanced regardless of the weights of boats it may or may not carry.

Blaise Pascal was an outstanding 17th-century scientist, writer, and theologian. In investigating the physics of fluids he invented the hydraulic press that uses hydraulic pressure to multiply force. He also invented the syringe. Pascal's notoriety was prompted by his commentary on Evangelista Torricelli's experimentation with barometers. Pascal questioned what force kept some mercury in the tube and what filled the space above the mercury in the tube. Most scientists at the time, in the spirit of Aristotle, didn't believe a vacuum was possible and thought some invisible matter was present in the "empty space." Pascal produced new experiments and contended that, indeed, a near-vacuum occupies the space above the column of liquid in a barometer tube.

Pascal, in poor health all his life, enlisted his brother-in-law to carry a barometer up the slope of a high mountain to investigate the effect on the mercury level in the tube. As Pascal hypothesized, the level of mercury dropped with increased altitude. Pascal conducted a more modest version of the experiment by carrying a barometer up to the top of a church bell tower, a height of about 50 meters. Again the mercury level dropped, but not as much. These, and other experiments of Pascal, were hailed throughout Europe as establishing the principle and value of the barometer.

To answer the criticism that some invisible matter must exist in the empty space, Pascal called on the scientific method and replied: "In order to show that a hypothesis is evident, it does not suffice that all the phenomena follow from it; instead, if it leads to something contrary to a single one of the phenomena, that suffices to establish its falsity." His insistence on the existence of the vacuum also led to conflict with other prominent scientists, including Descartes.

Pascal's work with hydraulics led him to what is now called Pascal's Principle: "A change in pressure at any point in an enclosed fluid at rest is transmitted undiminished to all points in the fluid." Ropes and pulleys have given way to this principle, as hydraulic devices multiply forces unimagined before the time of Pascal.

Although a devout theologian, Pascal took issue with some of the dogmas of the time. Some of his writings on religion were banned by the Church. As a scientist, he is remembered for the hydraulics that subsequently changed the technological landscape; as a theologian, he is remembered for his many assertions, one of which relates to centuries of human landscape: "Men never do evil so cheerfully and completely as when they do so from religious convictions."

Today, in honor of his scientific contributions, the name Pascal has been given to the SI unit of pressure and to a computer programming language. In literature, Pascal is regarded as one of the most important authors of the mid-17th century. His use of satire and wit influenced writers around the world.

Pressure

A liquid contained in a vessel exerts forces against the walls of the vessel. To discuss the interaction between the liquid and the walls, it is convenient to introduce the concept of **pressure.** Pressure is a force divided by the area over which the force is exerted.[1]

$$\text{Pressure} = \frac{\text{force}}{\text{area}}$$

As an illustration of the distinction between pressure and force, consider the two blocks in Figure 13.1. The blocks are identical, but one stands on its end and the other rests on its side. Both blocks are of equal weight and therefore exert the same force on the surface (if you were to put them on a bathroom scale, each would register the same), but the upright block exerts a greater *pressure* against the surface. If the block were tipped up so that its contact with the table were on a single corner, the pressure would be greater still.

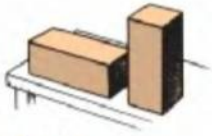


FIGURE 13.1
Although the weight of both blocks is the same, the upright block exerts greater pressure against the table.

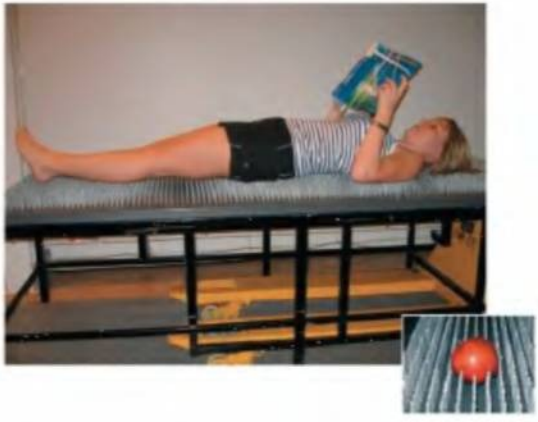


FIGURE 13.2
Physicist Sarah Blomberg lies without harm on the bed of nails because her weight is distributed over hundreds of nails, which makes the pressure at the point of each nail safely small. The inset photo of the dropped apple attests to the sharpness of the nails.

[1]Pressure may be measured in any unit of force divided by any unit of area. The standard international (SI) unit of pressure, the newton per square meter, is called the *pascal* (Pa). A pressure of 1 Pa is very small and approximately equals the pressure exerted by a dollar bill resting flat on a table. Science types more often use kilopascals (1 kPa = 1000 Pa).

fyi

- Molecules that make up a liquid can flow by sliding over one another. A liquid takes the shape of its container. Its molecules are close together and greatly resist compressive forces, so liquids, like solids, are difficult to compress.

Pressure in a Liquid

When you swim under water, you can feel the water pressure acting against your eardrums. The deeper you swim, the greater the pressure. The pressure you feel is due to the weight of water above you. As you swim deeper, there is more water above you and therefore greater pressure. The pressure a liquid exerts depends on its depth.

Liquid pressure also depends on the density of the liquid. If you were submerged in a liquid more dense than water, the pressure would be correspondingly greater. The pressure due to a liquid is precisely equal to the product of weight density and depth:[2]

$$\text{Liquid pressure} = \text{weight density} \times \text{depth}$$

FIGURE 13.3

The dependence of liquid pressure on depth is not a problem for the giraffe because of its large heart and its intricate system of valves and elastic, absorbent blood vessels in the brain. Without these structures, the giraffe would faint when suddenly raising its head, and it would be subject to brain hemorrhaging when lowering it.

Simply put, the pressure a liquid exerts against the sides and bottom of a container depends on the density and the depth of the liquid. If we neglect atmospheric pressure, at twice the depth, the liquid pressure against the bottom is twice as great; at three times the depth, the liquid pressure is threefold; and so on. Or, if the liquid is two or three times as dense, the liquid pressure is correspondingly two or three times as great for any given depth. Liquids are practically incompressible—that is, their volume can hardly be changed by pressure (water volume decreases by only 50 millionths of its original volume for each atmosphere increase in pressure). So, except for small changes produced by temperature, the density of a particular liquid is practically the same at all depths.[3]

If you press your hand against a surface, and somebody else presses against your hand in the same direction, then the pressure against the surface is greater than if you pressed alone. Likewise with the atmospheric pressure that presses on the sur-

[2]This is derived from the definitions of pressure and weight density. Consider an area at the bottom of a vessel of liquid. The weight of the column of liquid directly above this area produces pressure. From the definition

$$\text{Weight density} = \frac{\text{weight}}{\text{volume}}$$

we can express this weight of liquid as

$$\text{Weight} = \text{weight density} \times \text{volume}$$

where the volume of the column is simply the area multiplied by the depth. Then we get

$$\text{Pressure} = \frac{\text{force}}{\text{area}} = \frac{\text{weight}}{\text{area}} = \frac{\text{weight density} \times \text{volume}}{\text{area}} = \frac{\text{weight density} \times (\text{area} \times \text{depth})}{\text{area}}$$
$$= \text{weight density} \times \text{depth}$$

For total pressure, we add to this equation the pressure due to the atmosphere on the surface of the liquid.

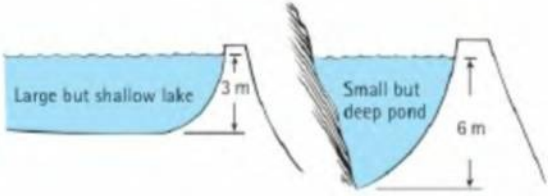
[3]The density of freshwater is 1000 kg/m^3. Since the weight (mg) of 1000 kg is 1000 × 10 N/kg = 10,000 N, the weight density of water is 10,000 newtons per cubic meter (or more precisely, 9800 N/m^3, using g = 9.8 N/kg). The water pressure beneath the surface of a lake is simply equal to this density multiplied by the depth in meters. For example, water pressure is 10,000 N/m^2 at a depth of 1 m and 100,000 N/m^2 at a depth of 10 m. In SI units, pressure is measured in pascals, so this would be 10,000 Pa and 100,000 Pa, respectively; or, in kilopascals, 10 kPa and 100 kPa, respectively. For the *total pressure* in these cases, add the pressure of the atmosphere, 101.3 kPa.

face of a liquid. The total pressure of a liquid, then, is weight density × depth *plus* the pressure of the atmosphere. When this distinction is important, we will use the term *total pressure*. Otherwise, our discussions of liquid pressure refer to pressure without regard to the normally ever-present atmospheric pressure. (You will learn more about atmospheric pressure in the next chapter.)

It is important to recognize that the pressure does not depend on the *amount* of liquid present. Volume is not the key—depth is. The average water pressure acting against a dam depends on the average *depth* of the water and not on the volume of water held back, as shown in Figure 13.4.

fyi

- Earth is the only planet in the solar system with a mostly liquid surface—its oceans. If Earth were a little closer to the Sun, the oceans would turn to vapor. If Earth were a little farther away, most of its surface, not just the polar regions, would be solid ice. It's nice that Earth is located where it is.



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Dam

FIGURE 13.4
The large, shallow lake exerts only one-half the average pressure that the small, deep pond exerts.

You'll feel the same pressure whether you dunk your head a meter beneath the surface of the water in a small pool or to the same depth in the middle of a large lake. The same is true for a fish. Refer to the connecting vases in Figure 13.5. If we hold a goldfish by its tail and dunk its head a couple of centimeters under the surface, the water pressure on the fish's head will be the same in any of the vases. If we release the fish and it swims a few centimeters deeper, the pressure on the fish will increase with depth and be the same no matter which vase the fish is in. If the fish swims to the bottom, the pressure will be greater, but it makes no difference what vase it swims in. All vases are filled to equal depths, so the water pressure is the same at the bottom of each vase, regardless of its shape or volume. If water pressure at the bottom of a vase were greater than water pressure at the bottom of a neighboring narrower vase, the greater pressure would force water sideways and then up the narrower vase to a higher level until the pressures at the bottom were equalized. But this doesn't happen. Pressure is depth dependent, not volume dependent, so we see that there is a reason why water seeks its own level.

FIGURE 13.5
Liquid pressure is the same for any given depth below the surface, regardless of the shape of the containing vessel. Liquid pressure = weight density × depth (for total pressure add the air pressure at the top).

The fact that water seeks its own level can be demonstrated by filling a garden hose with water and holding the two ends at the same height. The water levels will be equal. If one end is raised higher than the other, water will flow out of the lower end, even if it has to flow "uphill" part of the way. This fact was not fully understood by some of the early Romans, who built elaborate aqueducts with tall arches and roundabout routes to ensure that water would always flow slightly downward every place along its route from the reservoir to the city. If pipes were laid in the ground and followed the natural contour of the land, in some places the water

fyi

- Not all Romans in ancient times believed that water couldn't flow uphill, as evidenced by some pipe systems back then that ran upward as well as downward.

FIGURE 13.6
Roman aqueducts assured that water flowed slightly downhill from reservoir to city.

FIGURE 13.7
The forces of a liquid pressing against a surface add up to a net force that is perpendicular to the surface.

would have to flow uphill, and the Romans were skeptical of this. Careful experimentation was not yet the mode, so, with plentiful slave labor, the Romans built unnecessarily elaborate aqueducts.

An experimentally determined fact about liquid pressure is that it is exerted equally in all directions. For example, if we are submerged in water, no matter which way we tilt our heads we feel the same amount of water pressure on our ears. Because a liquid can flow, the pressure isn't only downward. We know pressure acts sideways when we see water spurting sideways from a leak in the side of an upright can. We know pressure also acts upward when we try to push a beach ball beneath the surface of the water. The bottom of a boat is certainly pushed upward by water pressure.

When liquid presses against a surface, there is a net *force* that is *perpendicular* to the surface. Although pressure doesn't have a specific direction, force does. Consider the triangular block in Figure 13.7. Focus your attention only at the three points midway along each surface. Water is forced against each point from many directions, only a few of which are indicated. Components of the forces that are not perpendicular to the surface cancel each other out, leaving only a net perpendicular force at each point.

That's why water spurting from a hole in a bucket initially exits the bucket in a direction at right angles to the surface of the bucket in which the hole is located. Then it curves downward due to gravity. The force exerted by a fluid on a smooth surface is always at right angles to the surface.[4]

FIGURE 13.8
The force vectors act perpendicularly to the inner container surface and increase with increasing depth.

CHECK POINT

Suppose that when standing on a bathroom scale you raise one foot. Does the pressure you exert on the scale change? Is there a difference in the scale reading?

Check Your Answers

When you shift your weight by standing on one foot, pressure on the scale doubles. But the scale doesn't measure pressure—it measures weight. Except for some jiggling as you shift your weight, the scale reading stays the same.

[4]The speed of liquid out of the hole is $\sqrt{2gh}$, where h is the depth below the free surface. Interestingly, this is the same speed the water (or anything else) would acquire if freely falling the same vertical distance h.

Buoyancy

Anyone who has ever lifted a heavy submerged object out of water is familiar with *buoyancy*, the apparent loss of weight experienced by objects submerged in a liquid. For example, lifting a large boulder off the bottom of a riverbed is a relatively easy task as long as the boulder is below the surface. When it is lifted above the surface, however, the force required to lift it is increased considerably. This is because, when the boulder is submerged, the water exerts an upward force on it that is exactly opposite to the direction of gravity's pull. This upward force is called the **buoyant force,** and it is a consequence of pressure increasing with depth. Figure 13.9 shows why the buoyant force acts upward. Forces due to water pressures are exerted everywhere against the boulder in a direction perpendicular to its surface, as shown by the vectors. Force vectors against the sides at equal depths cancel one another, so there is no horizontal buoyant force. Force vectors in the vertical direction, however, don't cancel. Pressure is greater against the bottom of the boulder because the bottom is deeper. So upward forces against the bottom are greater than downward forces against the top, producing a net force upward—the buoyant force.

FIGURE 13.9

INTERACTIVE FIGURE

The greater pressure against the bottom of a submerged object produces an upward buoyant force.

Understanding buoyancy requires understanding the expression "volume of water displaced." If a stone is placed in a container that is brimful of water, some water will overflow (Figure 13.10). Water is *displaced* by the stone. A little thought will tell us that the *volume of the stone*—that is, the amount of space it takes up—is equal to the *volume of the water displaced.* If you place any object in a container partly filled with water, the level of the surface rises (Figure 13.11). By how much? By exactly the same amount as if a volume of water were poured in that equals the volume of the submerged object. This is a good method for determining the volume of irregularly shaped objects: *A completely submerged object always displaces a volume of liquid equal to its own volume.*

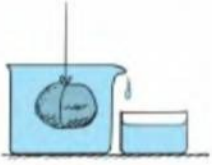

FIGURE 13.10

When a stone is submerged, it displaces water that has a volume equal to the volume of the stone.

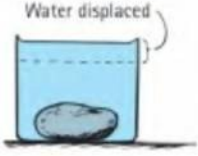

FIGURE 13.11

The increase in water level is the same as if you poured in a volume of water equal to the stone's volume.

CHECK POINT

A recipe calls for a specific amount of butter. How does the displacement method relate to the use of a kitchen measuring cup?

Check Your Answer

Put some water in the cup before you add the butter. Note the water-level reading on the side of the cup. Then add the butter and you'll note the water level rise. Because butter floats, poke it beneath the surface. When you subtract the lower-level reading from the higher-level reading, you know not only the volume of water displaced, but the volume of the butter.

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Buoyancy

Archimedes' Principle

The relationship between buoyancy and displaced liquid was first discovered in the 3rd century BC by the Greek scientist Archimedes. It is stated as follows:

An immersed object is buoyed up by a force equal to the weight of the fluid it displaces.

This relationship is called **Archimedes' principle.** It is true of liquids and gases, both of which are fluids. If an immersed object **displaces** 1 kg of fluid, the buoyant force acting on it is equal to the weight of 1 kg.[5] By *immersed,* we mean either *completely* or

If you stick your foot in water, it's immersed. If you jump in and sink and immersion is total, you're submerged.

[5]In lab, you may find it convenient to express buoyant force in kilograms, even though a kilogram is a unit of mass and not a unit of force. So, strictly speaking, the buoyant force is the *weight* of 1 kg, which is 10 N (or precisely, 9.8 N). Or we could as well say that the buoyant force is 1 *kilogram weight,* not simply 1 kg.

FIGURE 13.12

A liter of water occupies a volume of 1000 cm^3, has a mass of 1 kg, and weighs 9.8 N. Its density may therefore be expressed as 1 kg/L and its weight density as 9.8 N/L. (Seawater is slightly denser, about 10.0 N/L).

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Archimedes' Principle

partially submerged. If we immerse a sealed 1-L container halfway into the water, it will displace a half-liter of water and be buoyed up by a force equal to the weight of a half-liter of water—no matter what is in the container. If we immerse it completely (submerge it), it will be buoyed up by a force equal to the weight of a full liter of water (1 kg of mass). If the container is fully submerged and doesn't compress, the buoyant force will equal the weight of 1 kg of water at *any* depth. This is because, at any depth, the container can displace no greater volume of water than its own volume. And the weight of this displaced water (not the weight of the submerged object!) is equal to the buoyant force.

If a 30-kg object displaces 20 kg of fluid upon immersion, its apparent weight will be equal to the weight of 10 kg (100 N). Note that, in Figure 13.13, the 3-kg block has an apparent weight equal to the weight of a 1-kg block when submerged. The apparent weight of a submerged object is its usual weight in air minus the buoyant force.

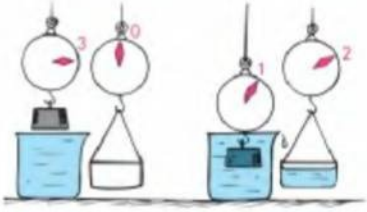

FIGURE 13.13

Objects weigh more in air than in water. When a 3-kg block is submerged, the scale reading reduces to 1 kg. The "missing" weight is equal to the weight of the 2 kg of water displaced, which equals the buoyant force.

FIGURE 13.14

INTERACTIVE FIGURE

The difference in the upward and downward force acting on the submerged block is the same at any depth.

Perhaps your instructor will summarize Archimedes' principle by way of a numerical example to show that the difference between the upward-acting and the downward-acting forces due to the similar pressure differences on a submerged cube is numerically identical to the weight of fluid displaced. If the density is nearly constant, as it is for most liquids, it makes no difference how deep the cube is placed. Although the pressures are greater with increasing depths, the *difference* between the pressure up against the bottom of the cube and the pressure down against the top of the cube is the same at any depth (Figure 13.14). Whatever the shape of the submerged body, the buoyant force is equal to the weight of fluid displaced.

CHECK POINT

1. True or false? Archimedes' principle tells us that any object that displaces 10 N of liquid will be buoyed up with 10 N.
2. A 1-L container completely filled with lead has a mass of 11.3 kg and is submerged in water. What is the buoyant force acting on it?
3. As a boulder thrown into a deep lake sinks deeper and deeper into the water, does the buoyant force upon it increase or decrease?

Check Your Answers

1. True. It's only the weight of the displaced liquid that counts. (Also look at it in a Newton's third law way: If the immersed object pushes 10 N of fluid aside, the displaced fluid reacts by pushing back on the immersed object with 10 N.)
2. The buoyant force equals the weight of the liter of water displaced—not the weight of the lead! One L of water has a mass of 1 kg and weighs 10 N. So the buoyant force on it is 10 N.
3. Buoyant force remains unchanged as the boulder sinks, because the boulder displaces the same volume and same weight of water at any depth.

What Makes an Object Sink or Float?

It's important to remember that the buoyant force acting on a submerged object depends on the *volume* of the object. Small objects displace small amounts of water and are acted on by small buoyant forces. Large objects displace large amounts of water and are acted on by larger buoyant forces. It is the *volume* of the submerged object—not its *weight*—that determines the buoyant force. The buoyant force is equal to the weight of the *volume of fluid* displaced. (Misunderstanding this idea is the root of much confusion that people have about buoyancy.)

The weight of an object does play a role, however, in floating. Whether an object will sink or float in a liquid depends on how the buoyant force *compares with the object's weight*. This, in turn, depends on the object's density. Consider these three simple rules:

1. **An object more dense than the fluid in which it is immersed will sink.**
2. **An object less dense than the fluid in which it is immersed will float.**
3. **An object having a density equal to the density of the fluid in which it is immersed will neither sink nor float.**

Rule 1 seems reasonable enough, for objects denser than water sink to the bottom, regardless of the water's depth. Scuba divers near the bottoms of deep bodies of water may sometimes encounter a waterlogged piece of wood hovering above the ocean floor (with a density equal to that of water at that depth), but never do they encounter hovering rocks!

From Rules 1 and 2, what can you say about people who, try as they may, cannot float? They're simply too dense! To float more easily, you must reduce your density. The formula *weight density = weight/volume* says you must either reduce your weight or increase your volume. Wearing a life jacket increases volume while correspondingly adding very little to your weight. It reduces your overall density.

Rule 3 applies to fish, which neither sink nor float. A fish normally has the same density as water. A fish can regulate its density by expanding and contracting an air sac in its body that changes its volume. The fish can move upward by increasing its volume (which decreases its density) and downward by contracting its volume (which increases its density).

For a submarine, weight, not volume, is varied to achieve the desired density. Water is taken into or blown out of its ballast tanks. Similarly, the overall density of a crocodile increases when it swallows stones. From 4 to 5 kg of stones have been found in the stomachs of large crocodiles. Because of this increased density, the crocodile swims lower in the water, thus exposing itself less to its prey (Figure 13.15).

fyi

- People who can't float are, 9 times out of 10, males. Most males are more muscular and slightly denser than females. Also, cans of diet soda float, whereas cans of regular soda sink in water. What does this tell you about their relative densities?

FIGURE 13.15

(Left) A crocodile coming toward you in the water. (Right) A stoned crocodile coming toward you in the water.

CHECK POINT

1. 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?
2. If a fish makes itself denser, it will sink; if it makes itself less dense, it will rise. In terms of buoyant force, why is this so?

Check Your Answers

1. The buoyant force is the same on each block because they displace the same volume of water. For submerged objects, buoyant force is determined only by the volume of water displaced, not the object's weight.
2. When the fish decreases its volume, it displaces less water, so the buoyant force decreases. When the fish expands its volume, the buoyant force increases.

Flotation

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Flotation

Primitive peoples made their boats of wood. Could they have conceived of an iron ship? We don't know. The idea of floating iron might have seemed strange. Today it is easy for us to understand how a ship made of iron can float.

Consider a 1-ton block of solid iron. Because iron is nearly 8 times denser than water, it displaces only 1/8 ton of water when submerged, which is not enough to keep it afloat. Suppose we reshape the same iron block into a bowl (Figure 13.16). It still weighs 1 ton. But when we put it in water, it displaces a greater volume of water than when it was a block. The deeper the iron bowl is immersed, the more water it displaces and the greater the buoyant force acting on it. When the buoyant force equals 1 ton, it will sink no farther.

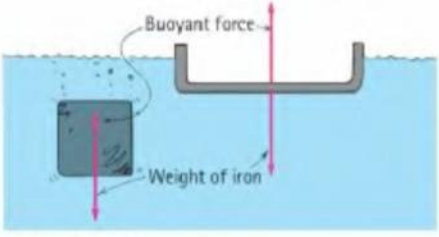


FIGURE 13.16
An iron block sinks, while the same quantity of iron shaped like a bowl floats.

When any boat displaces a weight of water equal to its own weight, it floats. This is sometimes called the **principle of flotation:**

A floating object displaces a weight of fluid equal to its own weight.

Every ship, every submarine, and every blimp must be designed to displace a weight of fluid equal to its own weight. Thus, a 10,000-ton ship must be built wide enough to displace 10,000 tons of water before it sinks too deep in the water. The same holds true for vessels in air. A blimp that weighs 100 tons displaces at least 100 tons of air. If it displaces more, it rises; if it displaces less, it falls. If it displaces exactly its weight, it hovers at constant altitude.

FIGURE 13.17
The weight of a floating object equals the weight of the water displaced by the submerged part.

For a given volume of displaced fluid, a denser fluid exerts a greater buoyant force than a less dense fluid. A ship, therefore, floats higher in saltwater than in freshwater because saltwater is slightly denser. Similarly, a solid chunk of iron will float in mercury, even though it will sink in water.

The physics of Figure 13.18 is nicely employed by the Falkirk Wheel, a unique rotating boat lift that replaced a series of 11 locks in Scotland. Connected to its 35-m tall wheel are two caissons brimful of water. When one or more boats enters a caisson, the amount of water that overflows weighs exactly as much as the boat(s). So the water-filled caissons always weigh the same whether or not they carry boats and the wheel always remains balanced. Therefore, in spite of its enormous mass, the wheel rotates each half revolution with very little power input.

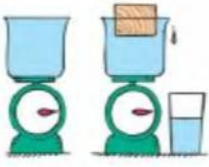


FIGURE 13.18
A floating object displaces a weight of fluid equal to its own weight.

FIGURE 13.19

The Falkirk Wheel has two balanced water-filled caissons, one going up and one going down. The caissons rotate as the wheel turns so the water and boats don't tip out.

CHECK POINT

1. Why is it easier for you to float in saltwater than in freshwater?
2. On a boat ride, the skipper gives you a life preserver filled with lead pellets. When he sees the skeptical look on your face, he says that you'll experience a greater buoyant force if you fall overboard than your friends who wear Styrofoam-filled life preservers. Is he being truthful?

Only in the special case of floating does the buoyant force acting on an object equal the object's weight.

Check Your Answers

1. 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).
2. 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.

Floating Mountains

The tip of a floating iceberg above the ocean's surface is approximately 10% of the whole iceberg. That's because ice is 0.9 times the density of water, so 90% of it submerges in water. Similarly, a mountain floats on the Earth's semiliquid mantle with only its tip showing. That's because Earth's continental crust is about 0.85 times the density of the mantle it floats upon; thus, about 85% of a mountain extends beneath the Earth's surface. So, like floating icebergs, mountains are appreciably deeper than they are high.

There is an interesting gravitational sidelight to this: Recall, from Chapter 9, that the gravitational field at the Earth's surface varies slightly with varying densities of underlying rock (which is valuable information to geologists and oil prospectors), and that gravitation is less at the top of a mountain because of the greater distance to Earth's center. Combining these ideas, we see that because the bottom of a mountain extends deep into the Earth's mantle, there is increased distance between a mountaintop and the denser mantle. This increased "gap" further reduces gravitation at the top of a mountain.

Another interesting fact about mountains: If you could shave off the top of an iceberg, the iceberg would be lighter and would be buoyed up to nearly its original height before being shaved. Similarly, when mountains erode, they are lighter, and they are pushed up from below to float to nearly their original heights. So, when a kilometer of mountain erodes away, some 85% of a kilometer of mountain thrusts up from below. That's why it takes so long for mountains to weather away.

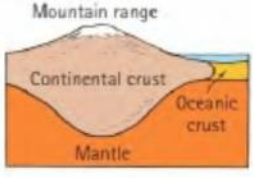


FIGURE 13.20

The continental crust is deeper beneath mountains.

CHECK POINT

A river barge loaded with gravel approaches a low bridge that it cannot quite pass under. Should gravel be removed *from* or added *to* the barge?

Check Your Answer

Ho, ho, ho! Do you think ol' Hewitt is going to give *all* the answers to Check Point questions? Good teaching is asking good questions, not providing all answers. You're on your own with this one!

Pascal's Principle

One of the most important facts about fluid pressure is that a change in pressure at one part of the fluid will be transmitted undiminished to other parts. For example, if the pressure of city water is increased at the pumping station by 10 units of pressure, the pressure everywhere in the pipes of the connected system will be increased by 10 units of pressure (provided that the water is at rest). This rule, discovered in the 17th century by Blaise Pascal, is called **Pascal's principle:**

A change in pressure at any point in an enclosed fluid at rest is transmitted undiminished to all points in the fluid.

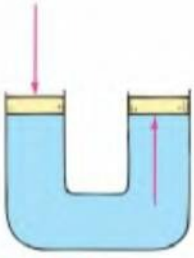


FIGURE 13.21
The force exerted on the left piston increases the pressure in the liquid and is transmitted to the right piston.

Fill a U-tube with water and place pistons at each end, as shown in Figure 13.21. Pressure exerted against the left piston will be transmitted throughout the liquid and against the bottom of the right piston. (The pistons are simply "plugs" that can slide freely but snugly inside the tube.) The pressure that the left piston exerts against the water will be exactly equal to the pressure the water exerts against the right piston. This is nothing to write home about. But suppose you make the tube on the right side wider and use a piston of larger area: Then the result will be impressive. In Figure 13.22 the piston on the right has 50 times the area of the piston

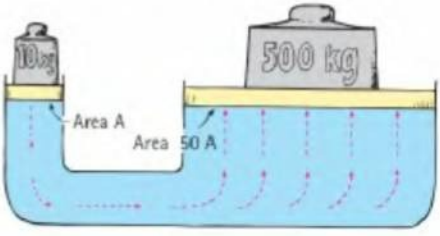


FIGURE 13.22
A 10-kg load on the left piston will support 500 kg on the right piston.

on the left (let's say that the left piston has a cross-sectional area of 100 square centimeters and that the right piston has a cross-sectional area of 5000 square centimeters). Suppose a 10-kg load is placed on the left piston. Then an additional pressure (nearly 1 N/cm^2) due to the weight of the load is transmitted throughout the liquid and up against the larger piston. Here is where the difference between force and pressure comes in. The additional pressure is exerted against every square centimeter of the larger piston. Since there is 50 times the area, 50 times as much force is exerted on the larger piston. Thus, the larger piston will support a 500-kg load—50 times the load on the smaller piston!

This *is* something to write home about, for we can multiply forces using such a device. One newton input produces 50 newtons output. By further increasing the area of the larger piston (or reducing the area of the smaller piston), we can multiply force, in principle, by any amount. Pascal's principle underlies the operation of the hydraulic press.

The hydraulic press does not violate energy conservation, because a decrease in distance moved compensates for the increase in force. When the small piston in Figure 13.22 is moved downward 10 centimeters, the large piston will be raised only one-fiftieth of this, or 0.2 centimeter. The input force multiplied by the distance moved by the smaller piston is equal to the output force multiplied by the distance moved by the larger piston; this is one more example of a simple machine operating on the same principle as a mechanical lever.

Pascal's principle applies to all fluids, whether gases or liquids. A typical application of Pascal's principle for gases and liquids is the automobile lift seen in many service stations (Figure 13.23). Increased air pressure produced by an air compressor

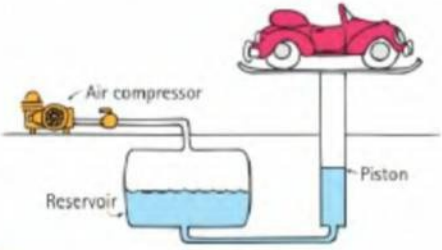


FIGURE 13.23
Pascal's principle in a service station.

is transmitted through the air to the surface of oil in an underground reservoir. The oil, in turn, transmits the pressure to a piston, which lifts the automobile. The relatively low pressure that exerts the lifting force against the piston is about the same as the air pressure in automobile tires.

Hydraulics is employed by modern devices ranging from very small to enormous. Note the hydraulic pistons in almost all construction machines where heavy loads are involved. The many applications of Pascal's principle have truly changed the landscape of our world.

FIGURE 13.24
Pascal's principle at work in the hydraulic devices on these incredible machines. We can only wonder whether Pascal envisioned the extent to which his principle would lead to the lifting of huge loads so easily.

CHECK POINT

1. As the automobile in Figure 13.23 is being lifted, how does the change in oil level in the reservoir compare with the distance the automobile moves?
2. If a friend commented that a hydraulic device is a common way of multiplying energy, what would you say?

Check Your Answers

1. The car moves up a greater distance than the oil level drops, since the area of the piston is smaller than the surface area of the oil in the reservoir.
2. No, no, no! Although a hydraulic device, like a mechanical lever, can multiply *force*, it always does so at the expense of distance. Energy is the product of force and distance. If you increase one, you decrease the other. No device has ever been found that can multiply energy!

Surface Tension

Suppose that you suspend a bent piece of clean wire from a sensitive spiral spring (Figure 13.25), lower the wire into water, and then raise it. As you attempt to free the wire from the water surface, you see from the stretched spring

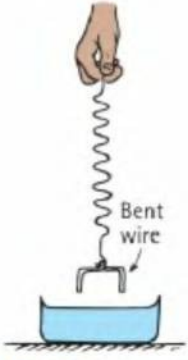


FIGURE 13.25
When the bent wire is lowered into the water and then raised, the spring will stretch because of surface tension.

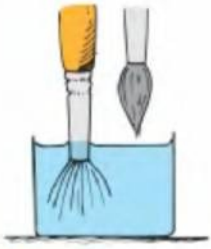


FIGURE 13.26
When the brush is taken out of the water, the hairs are held together by surface tension.

that the water surface exerts an appreciable force on the wire. The water surface resists being stretched, for it has a tendency to contract. You can also see this when a fine-haired paintbrush is wet. When the brush is under water, the hairs are fluffed pretty much as they are when the brush is dry, but when the brush is lifted out, the surface film of water contracts and pulls the hairs together (Figure 13.26). This contractive tendency of the surface of liquids is called **surface tension.**

Surface tension accounts for the spherical shape of liquid drops. Raindrops, oil drops, and falling drops of molten metal are all spherical because their surfaces tend to contract and force each drop into the shape having the least surface area. This is a sphere, the geometrical figure that has the least surface area for a given volume. For this reason, the mist and dewdrops on spider webs or on the downy leaves of plants are nearly spherical blobs. (The larger they are, the more gravity will flatten them.)

FIGURE 13.27
Small blobs of water are drawn by surface tension into spherelike shapes.

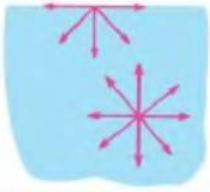


FIGURE 13.28
A molecule at the surface is pulled only sideways and downward by neighboring molecules. A molecule beneath the surface is pulled equally in all directions.

Surface tension is caused by molecular attractions. Beneath the surface, each molecule is attracted in every direction by neighboring molecules, resulting in no tendency to be pulled in any specific direction. A molecule on the surface of a liquid, however, is pulled only by neighbors on each side and downward from below; there is no pull upward (Figure 13.28). These molecular attractions thus tend to pull the molecule from the surface into the liquid, and this tendency minimizes the surface area. The surface behaves as if it were tightened into an elastic film. This is evident when dry steel needles or razor blades seem to float on water. They don't float in the usual sense, but they are supported by the surface molecules opposing an increase in surface area. The water surface sags like a piece of plastic wrap, which allows certain insects, such as water striders, to run across the surface of a pond.

The surface tension of water is greater than that of other common liquids, and pure water has a stronger surface tension than soapy water. We can see this when a little soap film on the surface of water is effectively pulled out over the entire surface. This minimizes the surface area of the water. The same thing happens for oil or grease floating on water. Oil has less surface tension than cold water, and it is drawn out into a film covering the whole surface. But hot water has less surface tension than cold water because the faster-moving molecules are not bonded as tightly. This allows the grease or oil in hot soups to float in little bubbles on the surface of the soup. When the soup cools and the surface tension of the water increases, the grease or oil is dragged out over the surface of the soup. The soup becomes "greasy." Hot soup tastes different from cold soup primarily because the surface tension of water in the soup changes with temperature.

Capillarity

When the end of a thoroughly clean glass tube with a small inside diameter is dipped into water, the water wets the inside of the tube and rises in it. In a tube with a bore of about 1/2 millimeter in diameter, for example, the water rises

FIGURE 13.29
Bubble Master Tom Noddy blows bubbles within bubbles. The large bubble is elongated due to blowing, but it will quickly settle to a spherical shape due to surface tension.

slightly higher than 5 centimeters. With a still smaller bore, the water rises much higher (Figure 13.30). This rise of a liquid in a fine, hollow tube or in a narrow space is **capillarity.**

When thinking of capillarity, think of molecules as sticky balls. Water molecules stick to glass more than to each other. The attraction between unlike substances such as water and glass is called *adhesion.* The attraction between like substances, molecular stickiness, is called *cohesion.* When a glass tube is dipped into water, the adhesion between the glass and water causes a thin film of water to be drawn up over the inner and outer surfaces of the tube (Figure 13.31a). Surface tension causes this film to contract (Figure 13.31b). The film on the outer surface contracts enough to make a rounded edge. The film on the inner surface contracts more and raises water with it until the adhesive force is balanced by the weight of the water lifted (Figure 13.31c). In a narrower tube, the weight of the water in the tube is small and the water is lifted higher than it would be if the tube were wider.

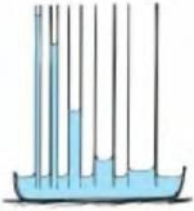


FIGURE 13.30
Capillary tubes.

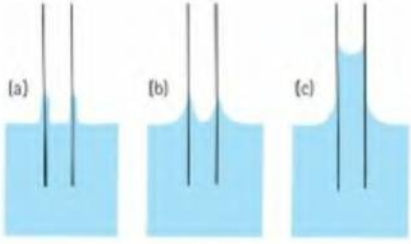


FIGURE 13.31
Hypothetical stages of capillary action, as seen in a cross-sectional view of a capillary tube.

If a paintbrush is dipped partway into water, the water will rise up into the narrow spaces between the bristles by capillary action. If your hair is long, let it hang into the sink or bathtub, and water will seep up to your scalp in the same way. This is how oil soaks upward in a lamp wick and water soaks into a bath towel when one end hangs in water. Dip one end of a lump of sugar in coffee, and the entire lump is quickly wet. Capillary action is essential for plant growth. It brings water to the roots of plants and transports sap and nourishment to high branches of trees. Just about everywhere we look, we can see capillary action at work. That's nice.

But from the point of view of an insect, capillarity is not so nice. Recall from the previous chapter that, because of an insect's relatively large surface area, it falls slowly in air. Gravity poses almost no risk at all—but not so with capillarity. Being in the grip of water may be fatal to an insect—unless it is equipped for water like a water strider.

SUMMARY OF TERMS

Pressure The ratio of force to the area over which that force is distributed:

$$\text{Pressure} = \frac{\text{force}}{\text{area}}$$

$$\text{Liquid pressure} = \text{weight density} \times \text{depth}$$

Buoyant force The net upward force that a fluid exerts on an immersed object.

Archimedes' principle An immersed body is buoyed up by a force equal to the weight of the fluid it displaces.

Principle of flotation A floating object displaces a weight of fluid equal to its own weight.

Pascal's principle The pressure applied to a motionless fluid confined in a container is transmitted undiminished throughout the fluid.

Surface tension The tendency of the surface of a liquid to contract in area and thus to behave like a stretched elastic membrane.

Capillarity The rise of a liquid in a fine, hollow tube or in a narrow space.

SUMMARY OF EQUATIONS

$$\text{Pressure} = \frac{\text{force}}{\text{area}}$$

$$\text{Liquid pressure} = \text{weight density} \times \text{depth}$$

REVIEW QUESTIONS

1. Give two examples of a fluid.

Pressure

2. Distinguish between *force* and *pressure*.

Pressure in a Liquid

3. What is the relationship between liquid pressure and the depth of a liquid? Between liquid pressure and density?
4. If you swim beneath the surface in saltwater, will the pressure be greater than in freshwater at the same depth? Why or why not?
5. How does water pressure 1 m below the surface of a small pond compare with water pressure 1 m below the surface of a huge lake?
6. If you punch a hole in a container filled with water, in what direction does the water initially flow outward from the container?

Buoyancy

7. Why does buoyant force act upward on an object submerged in water?
8. Why is there no horizontal buoyant force on a submerged object?
9. How does the volume of a completely submerged object compare with the volume of water displaced?

Archimedes' Principle

10. How does the buoyant force on a submerged object compare with the weight of water displaced?
11. Distinguish between a *submerged* body and an *immersed* body.
12. What is the mass of 1 L of water? What is its weight in newtons?
13. If a 1-L container is immersed halfway into water, what is the volume of water displaced? What is the buoyant force on the container?

What Makes an Object Sink or Float?

14. Is the buoyant force on a submerged object equal to the weight of the object itself or equal to the weight of the fluid displaced by the object?
15. There is a condition in which the buoyant force on an object does equal the weight of the object. What is this condition?
16. Does the buoyant force on a submerged object depend on the volume of the object or the weight of the object?
17. Fill in the blanks: An object denser than water will _____ in water. An object less dense than water will _____ in water. An object with the same density as water will _____ in water.
18. How is the density of a fish controlled? How is the density of a submarine controlled?

Flotation

19. It was emphasized earlier that buoyant force does not equal an object's weight but does equal the weight of displaced water. Now we say buoyant force equals the object's weight. Isn't this a grand contradiction? Explain.
20. Why do the caissons of the Falkirk Wheel (Figure 13.19) have the same weight whether or not they carry boats?

Pascal's Principle

21. What happens to the pressure in all parts of a confined fluid if the pressure in one part is increased?
22. If the pressure in a hydraulic press is increased by an additional 10 N/cm^2, how much extra load will the output piston support if its cross-sectional area is 50 cm^2?

Surface Tension

23. What geometrical shape has the least surface area for a given volume?
24. What is the cause of surface tension?

Capillarity

25. Distinguish between *adhesive* and *cohesive* forces.
26. What determines how high water will climb in a capillary tube?

PROJECTS

1. Place an egg in a pan of tap water. Then dissolve salt in the water until the egg floats. How does the density of an egg compare to that of tap water? To that of saltwater?
2. If you punch a couple of holes in the bottom of a water-filled container, water will spurt out because of water pressure. Now drop the container, and, as it freely falls, note that the water no longer spurts out! If your friends don't understand this, could you figure it out and then explain it to them?

3. Float a water-soaked Ping-Pong ball in a can of water held more than a meter above a rigid floor. Then drop the can. Careful inspection will show the ball was pulled beneath the surface as both the ball and the can drop. (What does this say about surface tension?) More dramatically, when the can makes impact with the floor, what happens to the ball, and why? Try it and you'll be astonished! (*Caution:* Unless you're wearing safety goggles, keep your head away from above the can when it makes impact.)
4. Soap greatly weakens the cohesive forces between water molecules. You can see this by adding some oil to a bottle of water and shaking it so that the oil and water mix. Notice that the oil and water quickly separate as soon as you stop shaking the bottle. Now add some liquid soap to the mixture. Shake the bottle again and you will see that the soap makes a fine film around each little oil bead and that a longer time is required for the oil to coalesce after you stop shaking the bottle. This is how soap works in cleaning. It breaks the surface tension around each particle of dirt so that the water can reach the particles and surround them. The dirt is carried away in rinsing. Soap is a good cleaner only in the presence of water.
5. Sprinkle some black pepper on the surface of some pure water in a saucer. The pepper floats. Add a drop of liquid dish soap to the surface and the pepper grains repel from the soap droplet. Stir gently once or twice and watch the pepper sink.

PLUG AND CHUG

Pressure = weight density * depth

(Neglect the pressure due to the atmosphere in the following calculations.)

1. Calculate the water pressure at the bottom of the 100-m-high water tower shown in the photo that opens this chapter.
2. Calculate the water pressure at the base of the Hoover Dam. The depth of water behind the dam is 220 m.
3. The top floor of a building is 50 m above the basement. Calculate how much greater the water pressure is in the basement than on the top floor.
4. A 1-m-tall barrel is closed on top except for a thin pipe extending 5 m up from the top. When the barrel is filled with water up to the base of the pipe (1 m deep) the water pressure on the bottom of the barrel is 10 kPa. What is the pressure on the bottom when water is added to fill the pipe to its top?

RANKING

1. Rank the pressures from most to least for the following:
   a. Bottom of a 20-cm-tall container of saltwater.
   b. Bottom of a 20-cm-tall container of freshwater.
   c. Bottom of a 5-cm-tall container of mercury.
2. Rank the following from most to least for the percentage of its volume above the water line:
   a. Basketball floating in freshwater
   b. Basketball floating in saltwater
   c. Basketball floating in mercury
3. Think about what happens to the volume of an air-filled balloon on top of water, and beneath. Then rank the buoyant force on a weighted balloon in water, from most to least, when it is
   a. barely floating with its top at the surface.
   b. pushed 1 m beneath the surface.
   c. pushed 2 m beneath the surface.

EXERCISES

1. What common liquid covers more than two-thirds of our planet, makes up 60% of our bodies, and sustains our lives and lifestyles in countless ways?
2. You know that a sharp knife cuts better than a dull knife. Do you know why this is so? Defend your answer.
3. Which is more likely to hurt—being stepped on by a 200-lb man wearing loafers or being stepped on by a 100-lb woman wearing high heels?
4. Which do you suppose exerts more pressure on the ground—a 5000-kg elephant or a 50-kg lady standing on spike heels? (Which will be more likely to make dents in a linoleum floor?) Approximate a rough calculation for each.
5. Why are persons who are confined to bed less likely to develop bedsores on their bodies if they rest on a waterbed rather than an ordinary mattress?
6. The photo shows physics instructor Marshall Ellenstein walking barefoot on broken glass bottles in his class. What physics concept is Marshall demonstrating, and why is he careful that the broken pieces are small and numerous? (The Band-Aids on his feet are for humor!)

7. Why is blood pressure measured in the upper arm, at the elevation of your heart?
8. Why does your body get more rest when you're lying down than when you're sitting? Is blood pressure in your legs greater?
9. When you are standing, blood pressure in your legs is greater than in your upper body. Would this be true for an astronaut in orbit? Defend your answer.
10. If water faucets upstairs and downstairs are turned fully on, will more water per second flow out of the upstairs faucets or the downstairs faucets?
11. How does water pressure 1 m beneath the surface of a lake compare with water pressure 1 m beneath the surface of a swimming pool?
12. The sketch shows a reservoir that supplies water to a farm. It is made of wood and is reinforced with metal hoops. (a) Why is it elevated? (b) Why are the hoops closer together near the bottom part of the tank?

13. Which teapot holds more liquid?

14. A block of aluminum with a volume of 10 cm^3 is placed in a beaker of water filled to the brim. Water overflows. The same is done in another beaker with a 10-cm^3 block of lead. Does the lead displace more, less, or the same amount of water?
15. A block of aluminum with a mass of 1 kg is placed in a beaker of water filled to the brim. Water overflows. The same is done in another beaker with a 1-kg block of lead. Does the lead displace more, less, or the same amount of water?
16. A block of aluminum with a weight of 10 N is placed in a beaker of water filled to the brim. Water overflows. The same is done in another beaker with a 10-N block of lead. Does the lead displace more, less, or the same amount of water? (Why are your answers to this exercise and to Exercise 15 different from your answer to Exercise 14?)
17. In 1960, the U.S. Navy's bathyscaphe *Trieste* (a submersible) descended to a depth of nearly 11 km in the Marianas Trench near the Philippines in the Pacific Ocean. Instead of a large viewing window, it had a small circular window 15 cm in diameter. What is your explanation for so small a window?
18. There is a legend of a Dutch boy who bravely held back the whole North Sea by plugging a hole in a dike with his finger. Is this possible and reasonable? (See also Problem 4.)
19. There is a story about Pascal's assistant climbing a ladder and pouring a small container of water into a tall, thin, vertical pipe inserted into a wooden barrel full of water below. The barrel burst when the water in the pipe reached about 12 m. This was all the more intriguing because the weight of added water in the tube was very small. What is your explanation, and how does this relate to Plug-and-Chug 4?
20. If you've wondered about the flushing of toilets on the upper floors of city skyscrapers, how do you suppose the plumbing is designed so that there is not an enormous impact of sewage arriving at the basement level? (Check your speculations with someone who is knowledgeable about architecture.)
21. Why does water "seek its own level"?
22. Suppose that you wish to lay a level foundation for a home on hilly and bushy terrain. How can you use a garden hose filled with water to determine equal elevations for distant points?
23. When you are sunbathing on a stony beach, why do the stones hurt your feet less when you're standing in deep water?
24. If liquid pressure were the same at all depths, would there be a buoyant force on an object submerged in the liquid? Explain.
25. A can of diet soda floats in water, whereas a can of regular soda sinks. Explain this phenomenon first in terms of density, then in terms of weight versus buoyant force.
26. Why will a block of iron float in mercury but sink in water?
27. The mountains of the Himalayas are slightly less dense than the mantle material upon which they "float." Do you suppose that, like floating icebergs, they are deeper than they are high?
28. Why is a high mountain composed mostly of lead an impossibility on Earth?
29. How much force is needed to hold a nearly weightless but rigid 1-L carton beneath the surface of water?

30. Why will a volleyball held beneath the surface of water have more buoyant force than if it is floating?

31. Why does an inflated beach ball pushed beneath the surface of water swiftly shoot above the water surface when released?

32. Why is it inaccurate to say that heavy objects sink and that light objects float? Give exaggerated examples to support your answer.

33. Why is the buoyant force on a submerged submarine appreciably greater than the buoyant force on it while it is floating?

34. A piece of iron placed on a block of wood makes it float lower in the water. If the iron were instead suspended beneath the wood, would the wood float as low, lower, or higher? Defend your answer.

35. Compared with an empty ship, would a ship loaded with a cargo of Styrofoam sink deeper into the water or rise in the water? Defend your answer.

36. If a submarine starts to sink, will it continue to sink to the bottom if no changes are made? Explain.

37. A barge filled with scrap iron is in a canal lock. If the iron is thrown overboard, does the water level at the side of the lock rise, fall, or remain unchanged? Explain.

38. Would the water level in a canal lock go up or down if a battleship in the lock sank?

39. Will a rock gain or lose buoyant force as it sinks deeper in water? Or will the buoyant force remain the same at greater depths? Defend your answer.

40. Will a swimmer gain or lose buoyant force as she swims deeper in the water? Or will her buoyant force remain the same at greater depths? Defend your answer, and contrast it with your answer to Exercise 39.

41. A balloon is weighted so that it is barely able to float in water. If it is pushed beneath the surface, will it return to the surface, stay at the depth to which it is pushed, or sink? Explain. (*Hint:* Does the balloon's density change?)

42. The density of a rock doesn't change when it is submerged in water, but your density changes when you are submerged. Explain.

43. In answering the question of why bodies float higher in saltwater than in freshwater, your friend replies that the reason is that saltwater is denser than freshwater. (Does your friend often answer questions by reciting only factual statements that relate to the answers but don't provide any concrete reasons?) How would you answer the same question?

44. A ship sailing from the ocean into a freshwater harbor sinks slightly deeper into the water. Does the buoyant force on the ship change? If so, does it increase or decrease?

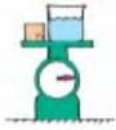
45. Suppose that you are given the choice between two life preservers that are identical in size, the first a light one filled with Styrofoam and the second a very heavy one filled with gravel. If you submerge these life preservers in the water, upon which will the buoyant force be greater? Upon which will the buoyant force be ineffective? Why are your answers different?

46. The weight of the human brain is about 15 N. The buoyant force supplied by fluid around the brain is about 14.5 N. Does this mean that the weight of fluid surrounding the brain is at least 14.5 N? Defend your answer.

47. The relative densities of water, ice, and alcohol are 1.0, 0.9, and 0.8, respectively. Do ice cubes float higher or lower in a mixed alcoholic drink? What comment can you make about a cocktail in which the ice cubes lie submerged at the bottom of the glass?

48. When an ice cube in a glass of water melts, does the water level in the glass rise, fall, or remain unchanged? Does your answer change if the ice cube has many air bubbles? How about if the ice cube contains many grains of heavy sand?

49. When the wooden block is placed in the beaker, what happens to the scale reading? Answer the same question for an iron block.



50. A small aquarium half-filled with water is on a spring scale. Will the reading of the scale increase or remain the same if a fish is placed in the aquarium? (Will your answer be different if the aquarium is initially filled to the brim?)

51. If the gravitational field of Earth were to increase, would a fish float to the surface, sink, or stay at the same depth?

52. What would you experience when swimming in water in an orbiting space habitat where simulated gravity is g? Would you float in the water as you do on Earth?

53. We say that the shape of a liquid is that of its container. But, with no container and no gravity, what is the natural shape of a blob of water? Why?

54. If you release a Ping-Pong ball beneath the surface of water, it will rise to the surface. Would it do the same if it were inside a big blob of water floating weightless in an orbiting spacecraft?

55. So you're on a run of bad luck, and you slip quietly into a small, calm pool as hungry crocodiles lurking at the bottom are relying on Pascal's principle to help them to detect a tender morsel. What does Pascal's principle have to do with their delight at your arrival?

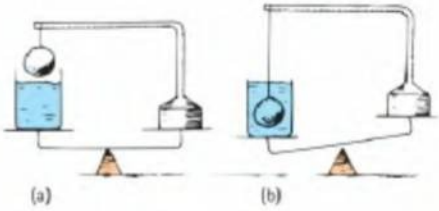
56. In the hydraulic arrangement shown, the larger piston has an area that is 50 times that of the smaller piston. The strong man hopes to exert enough force on the large piston to raise the 10 kg that rest on the small piston. Do you think he will be successful? Defend your answer.

57. In the hydraulic arrangement shown in Figure 13.22, the multiplication of force is equal to the ratio of the areas of the large and small pistons. Some people are surprised to learn that the area of the liquid surface in the reservoir of the arrangement shown in Figure 13.23 is immaterial. What is your explanation to resolve this confusion?

58. Why will water flow more readily than cold water through small leaks in a car radiator?

59. A chunk of steel will sink in water. But a steel razor blade, carefully placed on the surface of water, will not sink. What is your explanation?

60. The weight of the container of water, as shown in (a), is equal to the weight of the stand and the suspended solid iron ball. When the suspended ball is lowered into the water, as shown in (b), the balance is upset. Challenge your friends and ask if the additional weight needed on the right side to restore balance is greater than, equal to, or less than the weight of the solid iron ball.



PROBLEMS

1. Calculate the average force per nail when Sarah (Figure 13.2), who weighs 120 pounds, lies on a bed of nails and is supported by 600 nails.

2. Suppose that you balance a 5-kg ball on the tip of your finger, which has an area of 1 cm^2. Show that the pressure on your finger is 50 N/cm^2, which is 500 kPa.

3. A 6-kg piece of metal displaces 1 L of water when submerged. Show that its density is 6000 kg/m^3. How does this compare with the density of water?

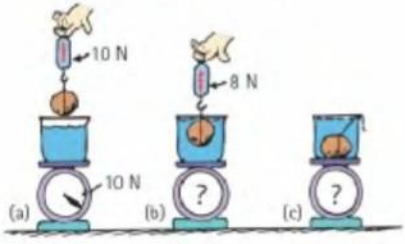
4. A dike in Holland springs a leak through a hole of area 1 cm^2 at a depth of 2 m below the water surface. How much force must a boy apply to the hole with his thumb to stop the leak? Could he do it?

5. In lab you find that a 1-kg rock suspended above water weighs 10 N. When the rock is suspended beneath the surface of the water, the scale reads 8 N.

a. What is the buoyant force on the rock?

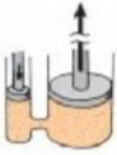
b. If the container of water weighs 10 N on the weighing scale, what is the scale reading when the rock is suspended beneath the surface of the water?

c. What is the scale reading when the rock is released and rests at the bottom of the container?



6. A merchant in Katmandu sells you a solid gold 1-kg statue for a very reasonable price. When you get home, you wonder whether or not you got a bargain, so you lower the statue into a container of water and measure the volume of displaced water. Show that, for pure gold, the volume of water displaced will be 51.8 cm^3.

7. In the sketch, the small hydraulic piston has a diameter of 2 cm. The large piston has a diameter of 6 cm. For each newton of force applied to the small piston, how many newtons of force are exerted by the large piston?



• **8.** Your friend of mass 100 kg can just barely float in freshwater. Calculate her approximate volume.

CHAPTER 13 ONLINE RESOURCES

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14 Gases

1 The forces due to atmospheric pressure are nicely shown by Swedish father-and-son physics professors, P. O. and Johan Zetterberg, who pull on a classroom model of the Magdeburg hemispheres. 2 A print shows the famous 1654 demonstration of atmospheric pressure with the original Magdeburg hemispheres. Two teams of horses couldn't pull the evacuated hemispheres apart. 3 Air in motion is a different story, as Maitreya Suchocki blows across the top of the paper reducing air pressure so that the slightly greater pressure beneath pushes the paper upward.

Can a vacuum, a condition of nothingness, exist? And how great is the pressure of air? In this chapter we'll learn how a German man in 1654 answered these questions. After inventing the first suction and air pumps that produced partial vacuums, he performed the widely attended and celebrated demonstration of the "Magdeburg hemispheres," as shown in the engraving above. He placed together two copper hemispheres about 1/2 meter in diameter to form a sphere, with an airtight joint composed of an oil-soaked leather gasket. When he evacuated the sphere with his vacuum pump, two teams of eight horses were unable to pull the hemispheres apart. (Some accounts say it took thirty horses to do the job.) Witnesses were astonished to see stunning evidence of the great force of the atmosphere. This man was Otto Guericke, later raised in rank to Otto von Guericke.

Like most successful scientists at the time, Guericke was born into a wealthy family. Except for benevolent benefactors, science as a profession back then didn't exist. People with time on their hands did science as a hobby, not unlike the way we play computer games today. At age 15, Guericke studied at Leipzig University in Germany. With the early stages of the Thirty Years War threatening, he and his family moved to Helmstedt, where he studied law. His studies were interrupted by the death of his father, whereupon Guericke moved to Leiden, Netherlands. He didn't complete any degree and instead went on a 9-month journey through France and England, as young men of noble houses were entitled to do.

Otto von Guericke continued his fascination with reduced air pressure. Influenced by the astronomy of Copernicus, he studied the nature of space and the possibility of empty space. Like his contemporaries Torricelli and Pascal (profiled at the beginning of the previous chapter), he became convinced that the height of the column of mercury in a barometer was a measure of air pressure. He made forecasts of the weather based on his observations over a period of years and proposed a network of stations to make systematic reports of the barometer readings and weather. He died in 1686 at the age of 83.

Interestingly, von Guericke's demonstration preceded knowledge of Newton's third law. The forces on the hemispheres would have been the same if he used only one team of horses and tied the other end of the rope to a tree!

The Atmosphere

The thickness of our atmosphere is determined by two competing factors: the kinetic energy of its molecules, which tends to spread the molecules apart, and gravity, which tends to hold them near Earth. If Earth gravity were somehow shut off, atmospheric molecules would dissipate and disappear. Or if gravity acted but the molecules moved too slowly to form a gas (as might occur on a remote, cold planet), our "atmosphere" would be a liquid or solid layer, just so much more matter lying on the ground. There would be nothing to breathe. The atmosphere keeps us alive and warm, and without it, we would perish within minutes.

But our atmosphere is a happy compromise between energetic molecules that tend to fly away and gravity that holds them back. Without solar energy, air molecules would lie on Earth's surface the way popcorn settles at the bottom of a popcorn machine. But, if heat is added to the popcorn and to the atmospheric gases, both will bumble their way up to higher altitudes. Pieces of popcorn in a popper attain speeds of a few kilometers per hour and reach altitudes up to a meter or two; molecules in the air move at speeds of about 1600 kilometers per hour and bumble up to many kilometers in altitude. Fortunately, there is an energizing Sun, there is gravity, and Earth has an atmosphere.

fyi

- Gases as well as liquids flow; hence, both are called *fluids*. A gas expands indefinitely and fills all space available to it. Only when the quantity of gas is very large, such as in the atmosphere of a planet or a star, do gravitational forces limit the size or shape of a gas.

The exact height of the atmosphere has no real meaning, for the air gets progressively thinner and thinner the higher one travels upward. Eventually, it thins out to emptiness in interplanetary space. Even in the vacuous regions of interplanetary space, however, there is a gas density of about one molecule per cubic centimeter. This is primarily hydrogen, the most plentiful element in the universe. About 50% of the atmosphere is below an altitude of 5.6 km (18,000 ft), 75% is below 11 km (36,000 ft), 90% is below 18 km (60,000 ft), and 99% is below about 30 km (100,000 ft) (Figure 14.1). A detailed description of the atmosphere can be found on various web sites.

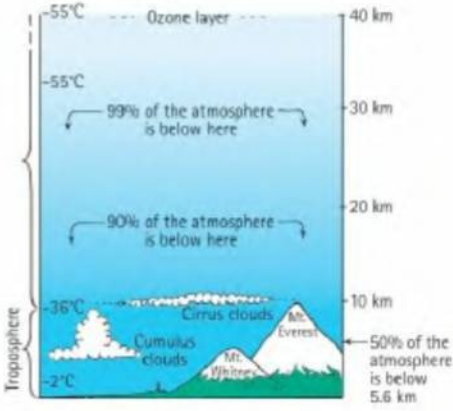

FIGURE 14.1

The atmosphere. Air is more compressed at sea level than at higher altitudes. Like feathers in a huge pile, what's at the bottom is more squashed than what's nearer the top.

That's right. Ninety-nine percent of Earth's atmosphere is below an altitude of 30 km (only 0.5% of Earth's radius).

CHECK POINT

Why do your ears sometimes pop when you change altitude, say in a skyscraper elevator or descending in an airplane?

Check Your Answer

A change in altitude means a change in air pressure, as discussed in the next section, and this causes a temporary imbalance in the pressures on the two sides of your eardrum.

Atmospheric Pressure

We live at the bottom of an ocean of air. The atmosphere, much like water in a lake, exerts pressure. As mentioned at the beginning of this chapter, the strength of atmospheric pressure was convincingly demonstrated by Otto von Guericke. Similarly, when the air pressure inside a cylinder like the one shown in Figure 14.2 is reduced, there is an upward force on the piston from the air outside. This force is large enough to lift a heavy weight. If the inside diameter of the cylinder is 10 cm or greater, a person can be suspended by this force.

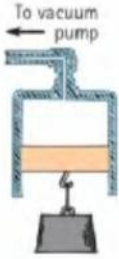

FIGURE 14.2
Is the piston that supports the load pulled up or pushed up?

Contrary to common thought, what the experiment of Figure 14.2 does *not* show is "force of suction." If we say there is a force of suction, then we assume that a vacuum can exert a force. But what is a vacuum? It is an absence of matter; it is a condition of nothingness. How can nothing exert a force? The hemispheres in von Guericke's demonstration were not sucked together, nor is the piston holding the weight up in Figure 14.2 sucked upward. The hemispheres and the piston are pushed by the weight of the atmosphere.

Just as water pressure is caused by the weight of water, **atmospheric pressure** is caused by the weight of the air. We have adapted so completely to the invisible air that we don't feel it and sometimes forget that it has weight. Perhaps a fish "forgets" about the weight of water in the same way. The reason we don't feel this weight crushing against our bodies is that the pressure inside our bodies balances out the pressure of the surrounding air. There is no net force for us to sense.

fyi

- Many deep-sea creatures experience enormous water pressures on their bodies, but they suffer no ill effects. Like us at the bottom of Earth's atmosphere, no net force or strain occurs because the pressures inside their bodies match the surrounding fluid pressure. For many creatures, but not all, problems occur when they change depth too suddenly. Scuba divers, for example, who make the mistake of rising to the surface too quickly experience pain and possible death from rapid decompression—a condition known as the bends. (*Scuba* is an acronym for Self-Contained Underwater Breathing Apparatus.) Marine biologists are looking for ways to bring depth-sensitive deep-sea creatures to the surface without killing them.

FIGURE 14.3
You don't notice the weight of a bag of water while you're submerged in water. Similarly, you aren't aware of the weight of air while you are submerged in an "ocean" of air.

At sea level, 1 m^3 of air has a mass of about 1.25 kg. So the air in your kid sister's small bedroom weighs about as much as she does! The density of air decreases with altitude. At 10 km, for example, 1 m^3 of air has a mass of about 0.4 kg. To compensate for this, airplanes are pressurized; the additional air needed to fully pressurize a modern jumbo jet, for example, is more than 1000 kg. Air is heavy if you have enough of it. If your kid sister doesn't believe that air has weight, you can show her why she falsely perceives the air to be weight-free. If you hand her a plastic bag of water, she'll tell you that it has weight. But, if you hand her the same bag of water while she's submerged in a swimming pool, she won't feel its weight. That's because she and the bag are surrounded by water. Likewise with the air that is all around us.

Consider the mass of air in an upright 30-km-tall bamboo pole that has an inside cross-sectional area of 1 cm^2. If the density of air inside the pole matches the density of air outside, the mass of enclosed air would be about 1 kg. The weight of this much air is about 10 N. So air pressure at the bottom of the bamboo pole would be about 10 N per square centimeter (10 N/cm^2). Of course, the same is true without the bamboo pole. There are 10,000 cm^2 in 1 m^2, so a column of air 1 m^2 in cross section that extends up through the atmosphere has a mass of about 10,000 kg. The weight of this air is about 100,000 N(10^5 N). This weight

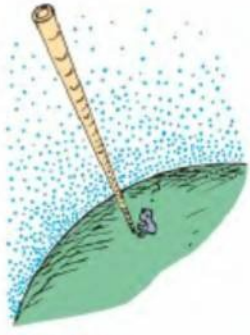

FIGURE 14.4
The mass of air that would occupy a bamboo pole that extends 30 km up—to the "top" of the atmosphere—is about 1 kg. This air weighs about 10 N.

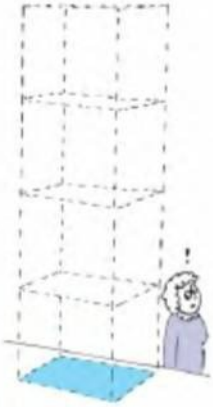

FIGURE 14.5
The weight of air bearing down on a 1-m^2 surface at sea level is about 100,000 N. In other words, atmospheric pressure is about $10^5 N/m^2$, or about 100 kPa.

produces a pressure of 100,000 N/m^2—or, equivalently, 100,000 pascals, or 100 kilopascals. To be more exact, the average atmospheric pressure at sea level is 101.3 kilopascals (101.3 kPa).[1]

The pressure of the atmosphere is not uniform. Besides altitude variations, atmospheric pressure varies from one locality to the next, and from day to day. This leads to moving weather fronts and storms that shape our weather. When a high-pressure system approaches, you can expect cooler temperatures and clear skies. When a low-pressure system approaches, then expect warmer weather, rain, and storms. Measurement of changing air pressure is important to meteorologists when predicting weather.

FIGURE 14.6
Ann Brandon fascinates her students when she rides on a cushion of air blown through a hole in the middle of this jumbo air puck.

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Videos
Air Has Weight
Air Is Matter

CHECK POINT

1. About how many kilograms of air occupy a classroom that has a 200-m^2 floor area and a 4-m-high ceiling? (Assume a chilly temperature of 10°C.)
2. Why doesn't the pressure of the atmosphere break windows?

Check Your Answers

1. The mass of air is 1000 kg. The volume of air is area × height = 200 m^2 × 4 m = 800 m^3; each cubic meter of air has a mass of about 1.25 kg, so 800 m^3 × 1.25 kg/m^3 = 1000 kg.
2. Atmospheric pressure is exerted on both sides of a window, so no net force is exerted on the glass. If, for some reason, the pressure is reduced or increased on one side only, as when a tornado passes by, then watch out! Reduced outside air pressure created by a tornado can be disastrous.

TABLE 14.1
Densities of Various Gases

Gas	Density (kg/m^3)*
Dry air	
0°C	1.29
10°C	1.25
20°C	1.21
30°C	1.16
Hydrogen	0.090
Helium	0.178
Nitrogen	1.25
Oxygen	1.43

*At sea-level atmospheric pressure and at 0°C (unless otherwise specified)

The Barometer

In 1643, Italian physicist and mathematician Evangelista Torricelli found a way to measure the pressure that air exerts—he invented the first **barometer.** A simple mercury barometer is illustrated in Figure 14.7. It consists of a mercury-filled

[1]The pascal (1 N/m^2) is the SI unit of pressure. The average pressure at sea level (101.3 kPa) is often called 1 atmosphere. In British units, the average atmospheric pressure at sea level is 14.7 lb/in^2.

glass tube, somewhat longer than 76 cm, that is immersed in a dish (reservoir) of mercury. When Torricelli tipped the mercury-filled tube upside down and placed it mouth downward in a dish of mercury, the mercury in the tube dropped to a level where the weight of mercury in the tube was balanced by the atmospheric force exerted on the reservoir. The empty space trapped above, except for some mercury vapor, is a vacuum. The vertical height of the mercury column remains constant even when the tube is tilted, unless the top of the tube is less than 76 cm above the level in the dish—in which case the mercury completely fills the tube.

The balance of mercury in a barometer is similar to the way a playground seesaw will balance when the torques of people at its two ends are equal. The barometer "balances" when the weight of the liquid in the tube exerts the same pressure as the atmosphere outside. Whatever the width of the tube, a 76-cm column of mercury weighs the same as the air that would fill a super-tall 30-km tube of the same width. If the atmospheric pressure increases, then the atmosphere pushes down harder on the mercury and the column of mercury is pushed higher than 76 cm. The mercury is literally pushed up into the tube of a barometer by the weight of the atmosphere. Atmospheric pressure was originally measured in millimeters of mercury, easily read on a barometer. Today it is measured in kilopascals.

Could water be used to make a barometer? The answer is *yes*, but the glass tube would have to be much longer—13.6 times as long, to be exact. You may recognize this number as the density of mercury relative to that of water. A volume of water 13.6 times that of mercury is needed to provide the same weight as the mercury in the tube. So the tube would have to be at least 13.6 times taller than the mercury column. A water barometer would have to be 13.6×0.76 m, or 10.3 m high—too tall to be practical.

What happens in a barometer is similar to what happens during the process of drinking through a straw. By sucking on the straw placed in the drink, you reduce the air pressure in the straw. The weight of the atmosphere on the drink pushes liquid up into the reduced-pressure region inside the straw. Strictly speaking, the liquid is not sucked up; it is pushed up by the pressure of the atmosphere. If the atmosphere is prevented from pushing on the surface of the drink, as in the party-trick bottle with the straw passing through an airtight cork stopper, one can suck and suck and get no drink.

If you understand these ideas, you can understand why there is a 10.3-m limit on the height that water can be lifted with vacuum pumps. The old-fashioned farm-type pump, like the one shown in Figure 14.9, operates by producing a partial vacuum in a pipe that extends down into the water below. The weight of the atmosphere on the surface of the water simply pushes the water up into the region of reduced pressure inside the pipe. Can you see that, even with a perfect vacuum, the maximum height to which water can be lifted is 10.3 m?

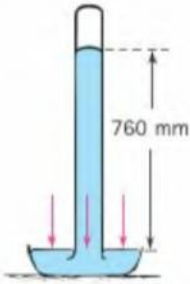


FIGURE 14.7
A simple mercury barometer.

FIGURE 14.8
Strictly speaking, these two do not suck the soda up the straws. They instead reduce pressure in the straws and allow the weight of the atmosphere to press the liquid up into the straws. Could they drink a soda this way on the Moon?

When the handle is pumped, air in the pipe is "thinned" as it expands to fill a larger volume. Atmospheric pressure on the well surface pushes water up into the pipe, causing water to overflow at the spout.

FIGURE 14.9
The atmosphere pushes water from below up into a pipe that is partially evacuated of air by the pumping action.

FIGURE 14.10
An aneroid barometer (top) and its cross section (bottom).

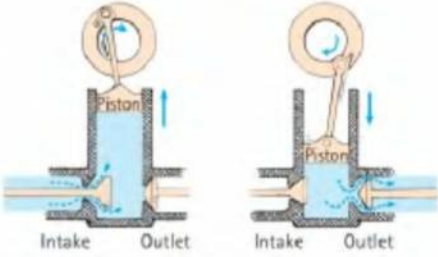
A small portable instrument that measures atmospheric pressure is the *aneroid barometer*. The classic model shown in Figure 14.10 uses a metal box that is partially exhausted of air and has a slightly flexible lid that bends in or out with changes in atmospheric pressure. The motion of the lid is indicated on a scale by a mechanical spring-and-lever system. Since the atmospheric pressure decreases with increasing altitude, a barometer can be used to determine elevation. An aneroid barometer calibrated for altitude is called an *altimeter* (altitude meter). Some altimeters are sensitive enough to indicate a change in elevation of less than a meter.

Vacuums are produced by pumps, which work by virtue of a gas tending to fill its container. If a space with less pressure is provided, gas will flow from the region of higher pressure to the region of lower pressure. A vacuum pump simply provides a region of lower pressure into which fast-moving gas molecules randomly move. The air pressure is repeatedly lowered by piston and valve action (Figure 14.11). The best vacuums attainable with mechanical pumps are about 1 Pa. Better vacuums, down to 10^{-8} Pa, are attainable with vapor-diffusion or vapor-jet pumps. Sublimation pumps can reach 10^{-12} Pa. Greater vacuums are very difficult to attain.

fyi

- For international flights on aircraft, a cabin pressure of three-quarters normal atmospheric pressure is the least permitted.

FIGURE 14.11
A mechanical vacuum pump. When the piston is lifted, the intake valve opens and air moves in to fill the empty space. When the piston is moved downward, the outlet valve opens and the air is pushed out. What changes would you make to convert this pump into an air compressor?



CHECK POINT

What is the maximum height to which water can be sucked up through a straw?

Check Your Answer

At sea level, however strong your lungs may be, or whatever device you use to make a vacuum in the straw, the water cannot be pushed up by the atmosphere higher than 10.3 m.

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Air Has Pressure

Boyle's Law

The air pressure inside the inflated tires of an automobile is considerably more than the atmospheric pressure outside. The density of the air inside is also more than the density of the air outside. To understand the relation between *pressure* and *density*, think of the molecules of air (primarily nitrogen and oxygen) inside the tire, which behave like tiny Ping-Pong balls—perpetually moving helter-skelter and banging against one another and against the inner walls. Their impacts produce a jittery force that appears to our coarse senses as a steady push. This pushing force averaged over a unit of area provides the pressure of the enclosed air.

FIGURE 14.12
When the density of gas in the tire is increased, pressure is increased.

Suppose that there are twice as many molecules in the same volume (Figure 14.12). Then the air density is doubled. If the molecules move at the same average speed—or, equivalently, if they have the same temperature—then the number of

collisions will be doubled. This means that the pressure is doubled. So pressure is proportional to density.

We can also double the air density by compressing air to half its volume. Consider the cylinder with the movable piston in Figure 14.13. If the piston is pushed downward so that the volume is half the original volume, the density of molecules will double and the pressure will correspondingly double. Decrease the volume to a third of its original value, and the pressure increases by three, and so forth (provided that the temperature remains the same).

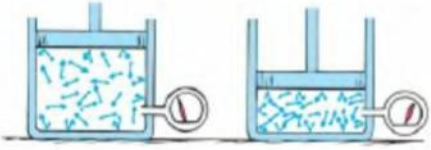

FIGURE 14.13
When the volume of gas is decreased, density and therefore pressure are increased.

Is atmospheric pressure actually different over a few centimeters' difference in altitude? The fact that it is is demonstrated with any helium-filled balloon that rises in air. Atmospheric pressure up against the bottom surface of the balloon is greater than atmospheric pressure down against the top.

Notice in these examples involving the piston that *pressure and volume are inversely proportional;* if you double one, for example, you halve the other:[2]

$$P_1V_1 = P_2V_2$$

Here P_1 and V_1 represent the original pressure and volume, respectively, and P_2 and V_2 represent the second pressure and volume. Or, put more graphically,

$$PV = P_V$$

In general, we can say that the product of pressure and volume for a given mass of gas is a constant as long as the temperature doesn't change. This relationship is called **Boyle's law,** after physicist Robert Boyle, who, with the help of fellow physicist Robert Hooke, made this discovery in the 17th century. Boyle's law applies to ideal gases. An ideal gas is one in which the disturbing effects of the forces between molecules and the finite size of the individual molecules can be neglected. Air and other gases under normal pressures approach ideal-gas conditions.

fyi

- A tire pressure gauge at a service station doesn't measure absolute air pressure. A flat tire registers zero pressure on the gauge, but a pressure of about 1 atmosphere exists there. Gauges read "gauge" pressure—pressure greater than atmospheric pressure.

Workers in underwater construction toil in an environment of compressed air. The air pressure in their underwater chambers is at least as much as the combined pressure of water and atmosphere outside.

CHECK POINT

1. A piston in an airtight pump is withdrawn so that the volume of the air chamber is increased 3 times. What is the change in pressure?
2. A scuba diver 10.3 m deep breathes compressed air. If she were to hold her breath while returning to the surface, by how much would the volume of her lungs tend to increase?

Check Your Answers

1. The pressure in the piston chamber is reduced to one-third. This is the principle that underlies a mechanical vacuum pump.
2. Atmospheric pressure can support a column of water 10.3 m high, so the pressure in water due to its weight alone equals atmospheric pressure at a depth of 10.3 m. Taking the pressure of the atmosphere at the water's surface into account, the total pressure at this depth is twice atmospheric pressure. Unfortunately for the scuba diver, her lungs tend to inflate to twice their normal size if she holds her breath while rising to the surface. A first lesson in scuba diving is not to hold your breath when ascending. To do so can be fatal.

[2]A general law that takes temperature changes into account is $P_1V_1/T_1 = P_2V_2/T_2$, where T_1 and T_2 represent the first and second *absolute* temperatures, measured in the SI unit called the *kelvin* (Chapters 15 and 18).

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Buoyancy of Air

Buoyancy of Air

A crab lives at the bottom of its ocean of water and looks upward at jellyfish floating above it. Similarly, we live at the bottom of our ocean of air and look upward at balloons drifting above us. A balloon is suspended in air and a jellyfish is suspended in water for the same reason: Each is buoyed upward by a displaced weight of fluid equal to its own weight. In one case, the displaced fluid is air; and in the other case, it is water. As discussed in the previous chapter, objects in water are buoyed upward because the pressure acting up against the bottom of the object exceeds the pressure acting down against the top. Likewise, air pressure acting up against an object in air is greater than the pressure above pushing down. The buoyancy, in both cases, is numerically equal to the weight of fluid displaced. **Archimedes' principle** holds for air just as it does for water:

An object surrounded by air is buoyed up by a force equal to the weight of the air displaced.

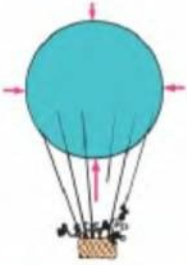


FIGURE 14.14
All bodies are buoyed up by a force equal to the weight of the air they displace. Why, then, don't all objects float like this balloon?

We know that a cubic meter of air at ordinary atmospheric pressure and room temperature has a mass of about 1.2 kg, so its weight is about 12 N. Therefore, any 1-m^3 object in air is buoyed up with a force of 12 N. If the mass of the 1-m^3 object is greater than 1.2 kg (so that its weight is greater than 12 N), it falls to the ground when released. If an object of this size has a mass less than 1.2 kg, it rises in the air. Any object that has a mass that is less than the mass of an equal volume of air will rise in air. Another way to say this is that any object less dense than air will rise in air. Gas-filled balloons that rise in air are less dense than air.

Greatest buoyancy would be achieved if a balloon were evacuated, but this isn't practical. The weight of a structure needed to keep an evacuated balloon from collapsing would more than offset the advantage of the extra buoyancy. So balloons are filled with gas less dense than ordinary air, which keeps the balloon from collapsing while keeping it light. In sport balloons, the gas is simply heated air. In balloons intended to reach very high altitudes or to stay up for a long time, helium is usually used. Its density is small enough so that the combined weight of helium, balloon, and whatever the cargo happens to be is less than the weight of the air it displaces.[3] Low-density gas is used in a balloon for the same reason that cork or Styrofoam is used in a swimmer's life preserver. The cork or Styrofoam possesses no strange tendency to be drawn toward the surface of water, and the gas possesses no strange tendency to rise. Both are buoyed upward like anything else. They are simply light enough for the buoyancy to be significant.

fyi
- A typical good-sized cloud bank contains a million or so tons of water, all in the form of suspended water drops.

Unlike water, the atmosphere has no definable surface. There is no "top." Furthermore, unlike water, the atmosphere becomes less dense with altitude. Whereas cork will float to the surface of water, a released helium-filled balloon does not rise to any atmospheric surface. How high will a balloon rise? We can state the answer in several ways. A gas-filled balloon will rise only so long as it displaces a weight of air greater than its own weight. Because air becomes less dense with altitude, a lesser weight of air is displaced per given volume as the balloon rises. When the weight of displaced air equals the total weight of the balloon, upward motion of the balloon will cease. We can also say that when the buoyant force on the balloon equals its weight, the balloon will cease rising. Equivalently, when the density of the balloon (including its load) equals the density of the surrounding air, the balloon will cease rising. Helium-filled toy balloons usually break when released in the air because the expansion of the helium they contain stretches the rubber until it ruptures. Large dirigible airships are designed so that when they are loaded, they will slowly rise in air; that is, their total

[3]Hydrogen is the least dense gas, but, because it is highly flammable, it is seldom used.

weight is a little less than the weight of air displaced. When in motion, the ship may be raised or lowered by means of horizontal "elevators."

Thus far, we have treated pressure only as it applies to stationary fluids. Motion produces an additional influence.

FIGURE 14.15

(Left) At ground level, the balloon is partially inflated. (Right) The same balloon is fully inflated at high altitudes where surrounding pressure is less.

CHECK POINT

1. Is there a buoyant force acting on you? If there is, why are you not buoyed up by this force?
2. (This one calls for your best thinking!) How does buoyancy change as a helium-filled balloon ascends?

Check Your Answers

1. There is a buoyant force acting on you, and you *are* buoyed upward by it. You don't notice it only because your weight is so much greater.
2. If the balloon is free to expand as it rises, the increase in volume is counteracted by a decrease in the density of higher-altitude air. So, interestingly, the greater volume of displaced air doesn't weigh more, and buoyancy stays the same. If a balloon is not free to expand, buoyancy will decrease as a balloon rises because of the less-dense displaced air. Usually, balloons expand as they rise initially, and, if they don't finally rupture, the stretching of their fabric reaches a maximum, and they settle where their buoyancy matches their weight.

Bernoulli's Principle

Consider a continuous flow of water through a pipe. Because water doesn't "bunch up," the amount of water that flows past any given section of the pipe is the same as the amount that flows past any other section of the same pipe—even if the pipe widens or narrows. For continuous flow, a fluid speeds up when it goes from a wide to a narrow part of the pipe. This is evident in a broad, slow-moving river that flows more swiftly as it enters a narrow gorge. It is also evident when water flowing from a garden hose speeds up when you squeeze the end of the hose to make the stream narrower.

FIGURE 14.16

Because the flow is continuous, water speeds up when it flows through the narrow and/or shallow part of the brook.

The motion of a fluid in steady flow follows imaginary *streamlines*, represented by thin lines in Figure 14.17 and in other figures that follow. Streamlines are the smooth paths of bits of fluid. The lines are closer together in narrower regions, where the flow speed is greater. (Streamlines are visible when smoke or other visible fluids are passed through evenly spaced openings, as in a wind tunnel.)

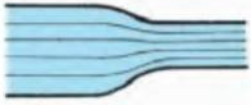


FIGURE 14.17

Water speeds up when it flows into the narrower pipe. The close-together streamlines indicate increased speed and decreased internal pressure.

Daniel Bernoulli, an 18th-century Swiss scientist, studied fluid flow in pipes. His discovery, now called **Bernoulli's principle,** can be stated as follows:

Where the speed of a fluid increases, internal pressure in the fluid decreases.

Where streamlines of a fluid are closer together, flow speed is greater and pressure within the fluid is less. Changes in internal pressure are evident in water containing air bubbles. The volume of an air bubble depends on the surrounding water pressure. Where water gains speed, pressure is lowered and bubbles become bigger. In water that slows, pressure is greater and bubbles are squeezed to a smaller size.

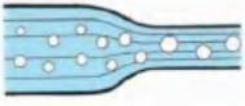


FIGURE 14.18

Internal pressure is greater in slower-moving water in the wide part of the pipe, as evidenced by the more-squeezed air bubbles. The bubbles are bigger in the narrow part because internal pressure there is less.

fyi

- Because the volume of water flowing through a pipe of different cross-sectional areas A remains constant, speed of flow v is high where the area is small, and the speed is low where the area is large. This is stated in the equation of continuity.

$$A_1v_1 = A_2v_2$$

The product A_1v_1 at any point 1 equals the product A_2v_2 at point 2.

Recall from Chapter 6 that a large change in momentum is associated with a large impulse. So when water from a fireman's hose hits you, the impulse can knock you off your feet. Interestingly, the pressure *within* that water is relatively small!

Bernoulli's principle is a consequence of the conservation of energy, although, surprisingly, he developed it long before the concept of energy was formalized.[4] The full energy picture for a fluid in motion is quite complicated. Simply stated, more speed and kinetic energy mean less pressure, and more pressure means less speed and kinetic energy.

Bernoulli's principle applies to a smooth, steady flow (called *laminar* flow) of constant-density fluid. At speeds above some critical point, however, the flow may become chaotic (called *turbulent* flow) and follow changing, curling paths called *eddies*. This exerts friction on the fluid and dissipates some of its energy. Then Bernoulli's equation doesn't apply well.

The decrease of fluid pressure with increasing speed may at first seem surprising, particularly if you fail to distinguish between the pressure *within* the fluid, internal pressure, and the pressure *by* the fluid on something that interferes with its flow. Internal pressure within flowing water and the external pressure it can exert on whatever it encounters are two different pressures. When the momentum of moving water or anything else is suddenly reduced, the impulse it exerts is relatively huge. A dramatic example is the use of high-speed jets of water to cut steel in modern machine shops. The water has very little internal pressure, but the pressure the stream exerts on the steel interrupting its flow is enormous.

A fire hose is fat when it is not spurting water. When the water is turned on and the hose spurts, why does it become thinner?

APPLICATIONS OF BERNOULLI'S PRINCIPLE

Hold a sheet of paper in front of your mouth, as shown in Figure 14.19. When you blow across the top surface, the paper rises. That's because the internal pressure of moving air across the curved top of the paper is less than the atmospheric pressure beneath it.

FIGURE 14.19
The paper rises when Tim blows across its top surface.

Anyone who has ridden in a convertible car with the canvas top up has noticed that the roof puffs upward as the car moves. This is Bernoulli's principle again. Pressure outside against the top of the fabric, where air is moving, is less than the static atmospheric pressure inside the car. The result is an upward net force on the fabric. Atmospheric pressure beneath the paper pushes it upward, sweet and simple (Maitreya showed the same in the photo that opened this chapter).

[4] In mathematical form: $1/2mv^2 + mgy + pV =$ constant (along a streamline); where m is the mass of some small volume V, v its speed, g the acceleration due to gravity, y its elevation, and p its internal pressure. If mass m is expressed in terms of density, ρ, where $\rho = m/V$, and each term is divided by V, Bernoulli's equation reads: $1/2\rho v^2 + \rho gy + p =$ constant. Then all three terms have units of pressure. If y does not change, an increase in v means a decrease in p, and vice versa. Note when v is zero Bernoulli's equation reduces to $\Delta p = -\rho g \Delta y$ (weight density × depth).

Consider wind blowing across a peaked roof. The wind gains speed as it flows over the roof, as the crowding of streamlines in the sketch indicates. Pressure along the streamlines is reduced where they are closer together. The greater pressure inside the roof can lift it off the house. During a severe storm, the difference in outside and inside pressure doesn't need to be very much. A small pressure difference over a large area produces a force that can be formidable.

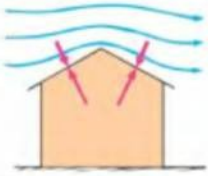


FIGURE 14.20
Air pressure above the roof is less than air pressure beneath the roof.

If we think of the blown-off roof as an airplane wing, we can better understand the lifting force that supports a heavy aircraft. In both cases, a greater pressure below pushes the roof or the wing into a region of lesser pressure above. Wings come in a variety of designs. What they all have in common is that air is made to flow faster over the wing's top surface than under its lower surface. This is mainly accomplished by a tilt in the wing, called its *angle of attack*. Then air flows faster over the top surface for much the same reason that air flows faster in a narrowed pipe or in any other constricted region. Often, but not always, different speeds of airflow over and beneath a wing are enhanced by a difference in the curvature *(camber)* of the upper and lower surfaces of the wing. The result is more crowded streamlines along the top wing surface than along the bottom. When the average pressure difference over the wing is multiplied by the surface area of the wing, we have a net upward force—lift.[5] Lift is greater when there is a large wing area and when the plane is traveling fast. A glider has a very large wing area relative to its weight, so it does not have to be going very fast for sufficient lift. At the other extreme, a fighter plane designed for high-speed flight has a small wing area relative to its weight. Consequently, it must take off and land at high speeds.

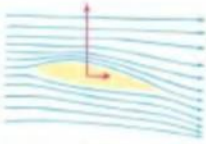


FIGURE 14.21
The vertical vector represents the net upward force (lift) that results from more air pressure below the wing than above the wing. The horizontal vector represents air drag.

We all know that a baseball pitcher can impart a spin on a ball to make it curve off to one side as it approaches home plate. Similarly, a tennis player can hit a ball so it curves. A thin layer of air is dragged around the spinning ball by friction, which is enhanced by the baseball's threads or the tennis ball's fuzz. The moving layer of air produces a crowding of streamlines on one side. Note, in Figure 14.22b, that the streamlines are more crowded at B than at A for the direction of spin shown. Air pressure is greater at A, and the ball curves as shown.

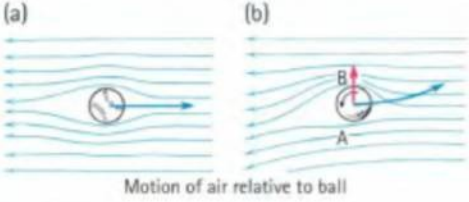


FIGURE 14.22
(a) The streamlines are the same on either side of a nonspinning baseball. (b) A spinning ball produces a crowding of streamlines. The resulting "lift" (red arrow) causes the ball to curve, as shown by the blue arrow.

Recent findings show that many insects increase lift by employing motions similar to those of a curving baseball. Interestingly, most insects do not flap their wings up and down. They flap them forward and backward, with a tilt that provides an angle of attack. Between flaps, their wings make semicircular motions to create lift.

A familiar hand-operated sprayer, such as a perfume atomizer, utilizes Bernoulli's principle. When you squeeze the bulb, air rushes across the open end of a tube inserted into the perfume. This reduces the pressure in the tube, whereupon atmospheric pressure on the liquid below pushes it up into the tube, where it is carried away by the stream of air.

FIGURE 14.23
Why does the liquid in the reservoir go up the tube?

[5]Pressure differences are only one way to understand wing lift. Another way uses Newton's third law. The wing forces air downward (action) and the air forces the wing upward (reaction). Air is deflected downward by the wing tilt, the angle of attack—even when flying upside down! When riding in a car, place your hand out the window and pretend it's a wing. Tip it up slightly so air is forced downward. Up goes your hand! Air lift provides a nice example to remind us that there is often more than one way to explain the behavior of nature.

Practicing Physics

Fold the end of a filing card down to make a little bridge or tunnel. Place it on a table and blow through the arch as shown. No matter how hard you blow, you will not succeed in blowing the card off the table (unless you blow against the side of it). Try this with your friends who have not taken physics. Then explain it to them!

Bernoulli's principle explains why trucks passing closely on the highway are drawn to each other, and why passing ships run the risk of a sideways collision. Water flowing between the ships travels faster than water flowing past the outer sides. Streamlines are closer together between the ships than outside, so water pressure acting against the hulls is reduced between the ships. Unless the ships are steered to compensate for this, the greater pressure against the outer sides of the ships forces them together. Figure 14.24 shows how to demonstrate this in your kitchen sink or bathtub.

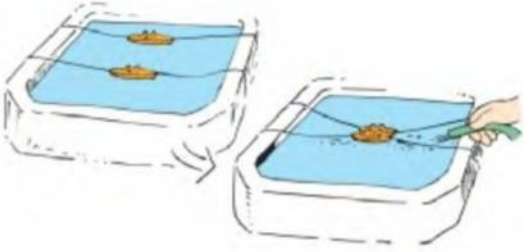


FIGURE 14.24
Loosely moor a pair of toy boats side by side in your sink. Then direct a stream of water between them. The boats will draw together and collide. Why?

FIGURE 14.25
Pressure is greater in the stationary fluid (air) than in the moving fluid (water stream). The atmosphere pushes the ball into the region of reduced pressure.

Bernoulli's principle plays a small role when your bathroom shower curtain swings toward you in the shower when the water is on full blast. The pressure in the shower stall is reduced with fluid in motion, and the relatively greater pressure outside the curtain pushes it inward. Like so much in the complex real world, this is but one physics principle that applies in this situation. More important is the convection of air in the shower. In any case, the next time you're taking a shower and the curtain swings in against your legs, think of Daniel Bernoulli.

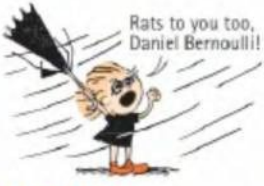
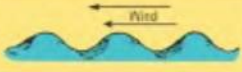


FIGURE 14.26
The curved shape of an umbrella can be disadvantageous on a windy day.

CHECK POINT

A windy day makes for waves in a lake or the ocean. How does Bernoulli's principle help to explain the height of the waves?



Check Your Answer

The troughs of the waves are partially shielded from the wind, so air travels faster over the crests. Pressure over the crests is therefore lower than down below in the troughs. The greater pressure in the troughs pushes water up into the crests.

Plasma

In addition to solids, liquids, and gases, there is a fourth phase of matter—**plasma** (not to be confused with the clear liquid part of blood, also called plasma). It is the least common phase in our everyday environment, but it is the most prevalent phase of matter in the universe as a whole. The Sun and other stars are largely plasma.

A plasma is an electrified gas. The atoms that make it up are *ionized*, stripped of one or more electrons, with a corresponding number of free electrons. Recall that a neutral atom has as many positive protons inside the nucleus as it has negative electrons outside the nucleus. When one or more of these electrons is stripped from the atom, the atom has more positive charge than negative charge and becomes a *positive ion*. (Under some conditions, it may have extra electrons, in which case it is a *negative ion*.) Although the electrons and ions are themselves electrically charged, the plasma as a whole is electrically neutral because there are still equal numbers of positive and negative charges, just as there are in an ordinary gas. Nevertheless, a plasma and a gas have very different properties. The plasma readily conducts electric current, absorbs certain kinds of radiation that pass unhindered through a gas, and can be shaped, molded, and moved by electric and magnetic fields.

Our Sun is a ball of hot plasma. Plasmas on Earth are created in laboratories by heating gases to very high temperatures, making them so hot that electrons are "boiled" off the atoms. Plasmas may also be created at lower temperatures by bombarding atoms with high-energy particles or radiation.

FIGURE 14.27
Streets are illuminated at night by glowing plasmas.

PLASMA IN THE EVERYDAY WORLD

If you're reading this by light emitted by a fluorescent lamp or a compact fluorescent bulb, you don't have to look far to see plasma in action. Within the glowing tube is plasma that contains argon and mercury ions (as well as many neutral atoms of these elements). When you turn the lamp on, a high voltage between electrodes at each end of the tube causes electrons to flow. These electrons ionize some atoms, forming plasma, which provides a conducting path that keeps the current flowing. The current activates some mercury atoms, causing them to emit radiation, mostly in the invisible ultraviolet region. This radiation causes the phosphor coating on the tube's inner surface to glow with visible light.

Similarly, the neon gas in an advertising sign becomes a plasma when its atoms are ionized by electron bombardment. Neon atoms, after being activated by electric current, emit predominantly red light. The different colors seen in these signs correspond to plasmas made up of different kinds of atoms. Argon, for example, glows blue, and helium glows pink. Sodium vapor lamps used in street lighting emit yellow light stimulated by glowing plasmas (Figure 14.27).

Flat plasma TV screens are composed of many thousands of pixels, each of which is composed of three separate subpixel cells. One cell has a phosphor that fluoresces red, another has a phosphor that fluoresces green, and the other blue. The pixels are sandwiched between a network of electrodes that are charged thousands of times in a small fraction of a second, producing electric currents that flow through gases in the cells. As in a fluorescent lamp, the gases convert to glowing plasmas that release ultraviolet light that stimulates the phosphors. The image on the screen is the blend of pixel colors activated by the TV control signal.

FIGURE 14.28
In a plasma TV, hundreds of thousands of tiny pixels are lit up red, green, and/or blue by glowing plasmas. By combining these colors in different proportions, the entire color spectrum can be produced.

fyi

- High-frequency radio and TV waves pass through the atmosphere and out into space. Hence you have to be in the "line of sight" of broadcasting or relay antennas to pick up FM and TV signals. But layers of plasma some 80 km high, making up the ionosphere, reflect lower-frequency radio waves. That explains why you can pick up radio stations long distances away on your lower-frequency AM radio. At night, when the plasma layers are settled closer together and are more reflective, you can sometimes receive very distant stations on your AM radio.

The aurora borealis and the aurora australis (called the northern and southern lights, respectively) are glowing plasmas in the upper atmosphere. Layers of low-temperature plasma encircle the whole Earth. Occasionally, showers of electrons from outer space and radiation belts enter "magnetic windows" near Earth's poles, crashing into the layers of plasma and producing light.

PLASMA POWER

A higher-temperature plasma is the exhaust of a jet engine, a weakly ionized plasma. But when small amounts of potassium salts or cesium metal are added, it becomes a very good conductor and, when directed into a magnet, can generate electricity! This is MHD power, the **magnetohydrodynamic** interaction between a plasma and a magnetic field. (We will treat the mechanics of generating electricity in this way in Chapter 25.) Low-pollution MHD power is in operation at a few places in the world already. Looking forward, perhaps we will see more plasma power with MHD.

An even more promising achievement will be plasma power of a different kind—the controlled fusion of atomic nuclei. We will treat the physics of fusion in Chapter 34. The benefits of controlled fusion may be far-reaching. Fusion power may not only make electrical energy abundant but may also provide the energy and means to recycle and even synthesize elements.

Humankind has come a long way with the mastery of the first three phases of matter. Our mastery of the fourth phase may bring us much farther.

SUMMARY OF TERMS

Atmospheric pressure The pressure exerted against bodies immersed in the atmosphere. It results from the weight of air pressing down from above. At sea level, atmospheric pressure is about 101 kPa.

Barometer Any device that measures atmospheric pressure.

Boyle's law The product of pressure and volume is a constant for a given mass of confined gas, as long as temperature remains unchanged:

$$P_1V_1 = P_2V_2$$

Archimedes' principle (for air) An object in the air is buoyed up with a force equal to the weight of displaced air.

Bernoulli's principle When the speed of a fluid increases, internal pressure in the fluid decreases.

Plasma An electrified gas containing ions and free electrons. Most of the matter in the universe is in the plasma phase.

REVIEW QUESTIONS

The Atmosphere

1. What is the energy source for the motion of gas in the atmosphere? What prevents atmospheric gases from flying off into space?
2. How high would you have to go in the atmosphere for half of the mass of air to be below you?

Atmospheric Pressure

3. What is the cause of atmospheric pressure?
4. What is the mass of a cubic meter of air at room temperature (20°C)?
5. What is the approximate mass of a column of air 1 cm^2 in area that extends from sea level to the upper atmosphere? What is the weight of this amount of air?
6. What is the pressure at the bottom of the column of air referred to in the previous question?

The Barometer

7. How does the pressure at the bottom of a 76-cm column of mercury in a barometer compare with air pressure at the bottom of the atmosphere?
8. How does the weight of mercury in a barometer compare with the weight of an equal cross section of air from sea level to the top of the atmosphere?
9. Why would a water barometer have to be 13.6 times taller than a mercury barometer?
10. When you drink liquid through a straw, is it more accurate to say the liquid is pushed up the straw rather than sucked up the straw? What exactly does the pushing? Defend your answer.
11. Why will a vacuum pump not operate for a well that is more than 10.3 m deep?
12. Why is it that an aneroid barometer is able to measure altitude as well as atmospheric pressure?

Boyle's Law

13. By how much does the density of air increase when it is compressed to half its volume?
14. What happens to the air pressure inside a balloon when it is squeezed to half its volume at constant temperature?
15. What is an ideal gas?

Buoyancy of Air

16. A balloon that weighs 1 N is suspended in air, drifting neither up nor down. (a) How much buoyant force acts on it? (b) What happens if the buoyant force decreases? (c) If it increases?
17. Does the air exert buoyant force on all objects in air or only on objects such as balloons that are very light for their size?

Bernoulli's Principle

18. What are streamlines? Is pressure greater or less in regions where streamlines are crowded?
19. What happens to the internal pressure in a fluid flowing in a horizontal pipe when its speed increases?
20. Does Bernoulli's principle refer to changes in internal pressure of a fluid or to pressures the fluid may exert on objects?

Applications of Bernoulli's Principle

21. How does Bernoulli's principle apply to the flight of airplanes?
22. Why does a spinning ball curve in its flight?
23. Why do ships passing close together run a risk of sideways collisions?

Plasma

24. How does a plasma differ from a gas?

Plasma in the Everyday World

25. Cite at least three examples of plasma in your daily environment.

Plasma Power

26. What can be produced when a plasma beam is directed into a magnet?

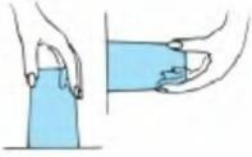
PROJECTS

1. Compare the pressure exerted by the tires of your car on the road with the air pressure in the tires. For this project, you need the weight of your car, which you can get from a manual or a dealer. You divide the weight by 4 to get the approximate weight held up by one tire. You can closely approximate the area of contact of a tire with the road by tracing the edges of tire contact on a sheet of paper marked with 1-inch squares beneath the tire. After you calculate the pressure of the tire against the road, compare it with the air pressure in the tire. Are they nearly equal? If not, which is greater?

2. You ordinarily pour water from a full glass into an empty glass simply by placing the full glass above the empty glass and tipping. Have you ever poured air from one glass into another? The procedure is similar. Lower two glasses in water, mouths downward. Let one fill with water by tilting its mouth upward. Then hold the water-filled glass mouth downward above the air-filled glass. Slowly tilt the lower glass and let the air escape, filling the upper glass. You will be pouring air from one glass into another!

3. Hold a glass under water, allowing it to fill with water. Then turn it upside down and raise it, but with its mouth beneath the surface. Why does the water not flow out of the glass? How tall would a glass have to be before water began to flow out? (If you could find such a glass, you might need to cut holes in your ceiling and roof to make room for it!)

4. Place a card over the open top of a glass filled to the brim with water and invert it. Why does the card stay in place? Try it sideways.



5. Invert a water-filled pop bottle or a small-necked jar. Notice that the water doesn't simply fall out but gurgles out of the container. Air pressure won't let it escape until some air has pushed its way up inside the bottle to occupy the space above the liquid. How would an inverted, water-filled bottle empty on the Moon?
6. Heat a small amount of water to boiling in an aluminum soda-pop can and invert it quickly into a dish of cooler water. Surprisingly dramatic!
7. Lower a narrow glass tube or drinking straw into water and place your finger over the top of the tube. Lift the tube from the water and then lift your finger from the top of the tube. What happens? (You'll do this often if you enroll in a chemistry lab.)

8. Push a pin through a small card and place it in the hole of a thread spool. Try to blow the card from the spool by blowing through the hole. Try it in all directions.

9. Hold a spoon in a stream of water as shown and feel the effect of the differences in pressure.

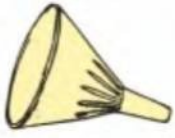
RANKING

1. Rank the volume of air in the glass, from greatest to least, when it is held
   a. near the surface as shown.
   b. 1 m beneath the surface.
   c. 2 m beneath the surface.

2. Rank the buoyant force supplied by the atmosphere on the following, from most to least:
   a. An elephant
   b. A helium-filled party balloon
   c. A skydiver at terminal velocity
3. Rank from most to least, the amount of lift on the following airplane wings:
   a. Area 1000 m^2 with atmospheric pressure difference of 2.0 N/m^2
   b. Area 800 m^2 with atmospheric pressure difference of 2.4 N/m^2
   c. Area 600 m^2 with atmospheric pressure difference of 3.8 N/m^2

EXERCISES

1. It is said that a gas fills all the space available to it. Why, then, doesn't the atmosphere go off into space?
2. Why is there no atmosphere on the Moon?
3. Why is the pressure in an automobile's tires slightly greater after the car has been driven several kilometers?
4. If you count the tires on a large tractor-trailer that is unloading food at your local supermarket, you may be surprised to count 18 tires. Why so many tires? (*Hint:* Consider Project 1.)
5. The valve stem on a tire must exert a certain force on the air within to prevent any of that air from leaking out. If the diameter of the valve stem were doubled, by how much would the force exerted by the valve stem increase?
6. Why is a soft, underinflated football at sea level much firmer when it is taken to a high elevation in the mountains?
7. What is the purpose of the ridges that prevent the funnel from fitting tightly in the mouth of a bottle?

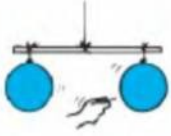


8. How does the density of air in a deep mine compare with the air density at Earth's surface?
9. When an air bubble rises in water, what happens to its mass, volume, and density?
10. Two teams of eight horses each were unable to pull the Magdeburg hemispheres apart (shown at the top of the opening page of this chapter). Suppose that two teams of nine horses each could pull them apart. Then would one team of nine horses succeed if the other team were replaced with a strong tree? Defend your answer.
11. When boarding an airplane, you bring a bag of chips (or any other item packaged in an airtight foil package) and, while you are in flight, you notice that the bag puffs up. Explain why this happens.
12. Why do you suppose that airplane windows are smaller than bus windows?
13. We can understand how pressure in water depends on depth by considering a stack of bricks. The pressure below the bottom brick is determined by the weight of the entire stack. Halfway up the stack, the pressure is half because the weight of the bricks above is half. To explain atmospheric pressure, we should consider compressible bricks, like those made of foam rubber. Why is this so?

14. The "pump" in a vacuum cleaner is merely a high-speed fan. Would a vacuum cleaner pick up dust from a rug on the Moon? Explain.
15. Suppose that the pump shown in Figure 14.9 operated with a perfect vacuum. From how deep a well could water be pumped?

16. If a liquid only half as dense as mercury were used in a barometer, how high would its level be on a day of normal atmospheric pressure?
17. Why does the size of the cross-sectional area of a mercury barometer not affect the height of the enclosed mercury column?
18. From how deep a container could mercury be drawn with a siphon?
19. If you could somehow replace the mercury in a mercury barometer with a denser liquid, would the height of the liquid column be greater than or less than the height of the mercury? Why?
20. Would it be slightly more difficult to draw soda through a straw at sea level or on top of a very high mountain? Explain.
21. The pressure exerted against the ground by an elephant's weight distributed evenly over its four feet is less than 1 atmosphere. Why, then, would you be crushed beneath the foot of an elephant, while you're unharmed by the pressure of the atmosphere?
22. Your friend says that the buoyant force of the atmosphere on an elephant is significantly greater than the buoyant force of the atmosphere on a small helium-filled balloon. What do you say?
23. Which will register the greater weight: an empty flattened balloon or the same balloon filled with air? Defend your answer, then try it and see.
24. On a sensitive balance, weigh an empty, flat, thin plastic bag. Then weigh the bag filled with air. Will the readings differ? Explain.
25. Why is it so difficult to breathe when snorkeling at a depth of 1 m and practically impossible at a 2-m depth? Why can't a diver simply breathe through a hose that extends to the surface?
26. A little girl sits in a car at a traffic light holding a helium-filled balloon. The windows are closed and the car is relatively airtight. When the light turns green and the car accelerates forward, her head pitches backward but the balloon pitches forward. Explain why.

27. How does the concept of buoyancy complicate the old question "Which weighs more, a pound of lead or a pound of feathers"?
28. Why does the weight of an object in air differ from its weight in a vacuum (remembering that weight is the force exerted against a supporting surface)? Cite an example in which this would be an important consideration.
29. Would a bottle of helium gas weigh more or less than an identical bottle filled with air at the same pressure? Than an identical bottle with the air pumped out?
30. When you replace helium in a balloon with less-dense hydrogen, does the buoyant force on the balloon change if the balloon remains the same size? Explain.
31. A steel tank filled with helium gas doesn't rise in air, but a balloon containing the same helium rises easily. Why?
32. If the number of gas atoms in a container is doubled, the pressure of the gas doubles (assuming constant temperature and volume). Explain this pressure increase in terms of molecular motion of the gas.
33. What, if anything, happens to the volume of gas in an atmospheric research-type balloon when it is heated?
34. What, if anything, happens to the pressure of the gas in a rubber balloon when the balloon is squeezed smaller?
35. What happens to the size of the air bubbles released by a diver as they rise?
36. You and Tim float a long string of closely spaced helium-filled balloons over his used-car lot. You secure the two ends of the long string of balloons to different points on the ground so that the balloons float over the lot in an arc. What is the name of this arc? (Why could this exercise have been included in Chapter 12?)
37. The gas pressure inside an inflated rubber balloon is always greater than the air pressure outside. Explain.
38. Two identical balloons of the same volume are pumped up with air to more than atmospheric pressure and suspended on the ends of a stick that is horizontally balanced. One of the balloons is then punctured. Is the balance of the stick upset? If so, which way does it tip?



39. Two balloons that have the same weight and volume are filled with equal amounts of helium. One is rigid and the other is free to expand as the pressure outside decreases. When released, which will rise higher? Explain.
40. The force of the atmosphere at sea level against the outside of a 10-m^2 store window is about a million N. Why does this not shatter the window? Why might the window shatter in a strong wind blowing past the window?
41. Why does the fire in a fireplace burn more briskly on a windy day?
42. What happens to the pressure in water as it speeds up when it is ejected by the nozzle of a garden hose?
43. Why do airplanes normally take off facing the wind?
44. What provides the lift to keep a Frisbee in flight?
45. Imagine a huge space colony that consists of a rotating air-filled cylinder. How would the density of air at "ground level" compare to the air densities "above"?
46. Would a helium-filled balloon "rise" in the atmosphere of a rotating space habitat? Defend your answer.
47. When a steadily flowing gas flows from a larger-diameter pipe to a smaller-diameter pipe, what happens to (a) its speed, (b) its pressure, and (c) the spacing between its streamlines?
48. Compare the spacing of streamlines around a tossed baseball that doesn't spin in flight with the spacing of streamlines around one that does. Why does the spinning baseball veer from the course of a nonspinning one?
49. Why is it easier to throw a curve with a tennis ball than a baseball?
50. Why do airplanes extend wing flaps that increase the area and the angle of attack of the wing during takeoffs and

landings? Why are these flaps pulled in when the airplane has reached cruising speed?

51. How is an airplane able to fly upside down?
52. Why are runways longer for takeoffs and landings at high-altitude airports, such as those in Denver and Mexico City?
53. How will two dangling vertical sheets of paper move when you blow between them? Try it and see.
54. What physics principle underlies these three observations? When passing an oncoming truck on the highway, your car tends to sway toward the truck. The canvas roof of a convertible automobile bulges upward when the car is traveling at high speeds. The windows of older trains sometimes break when a high-speed train passes by on the next track.
55. Wharves are made with pilings that permit the free passage of water. Why would a solid-walled wharf be disadvantageous to ships attempting to pull alongside?

56. Is lower pressure the result of fast-moving air, or is fast-moving air the result of lower pressure? Give one example supporting each point of view. (In physics, when two things are related—such as force and acceleration or speed and pressure—it is usually arbitrary which one we call *cause* and which one we call *effect*.)

PROBLEMS

1. What change in pressure occurs in a party balloon that is squeezed to one-third its volume with no change in temperature?
2. Estimate the buoyant force that air exerts on you. (To do this, you can estimate your volume by knowing your weight and by assuming that your weight density is a bit less than that of water.)
3. A mountain-climber friend with a mass of 80 kg ponders the idea of attaching a helium-filled balloon to himself to effectively reduce his weight by 25% when he climbs. He wonders what the approximate size of such a balloon would be. Hearing of your physics skills, he asks you. Share with him your calculations that show the volume of the balloon to be about 17 m^3 (slightly more than 3 m in diameter for a spherical balloon).
4. On a perfect fall day, you are hovering at low altitude in a hot-air balloon, accelerated neither upward nor downward. The total weight of the balloon, including its load and the hot air in it, is 20,000 N.
   a. Show that the weight of the displaced air is 20,000 N.
   b. Show that the volume of the displaced air is 1700 m^3.
5. Consider an airplane with a total wing surface of 100^2 m. At a certain speed the difference in air pressure below and above the wings is 4% of atmospheric pressure. Show that the lift on the airplane is 400,000 N.
• 6. The weight of the atmosphere above 1 m^2 of Earth's surface is about 100,000 N. Density, of course, becomes less with altitude. But suppose the density of air were a constant 1.2 kg/m^3. Calculate where the top of the atmosphere would be.

CHAPTER 14 ONLINE RESOURCES

PhysicsPlace.com

Videos

- Air Has Weight
- Air Is Matter
- Air Has Pressure
- Buoyancy of Air

Quizzes

Flashcards

Links

PART TWO MULTIPLE-CHOICE PRACTICE EXAM

Choose the best answer to the following:

1. If two protons and two neutrons are removed from the nucleus of neon-20, a nucleus of which element remains?
   (a) Magnesium-22.
   (b) Magnesium-20.
   (c) Oxygen-18.
   (d) Oxygen-16.
2. The nucleus of an electrically neutral iron atom contains 26 protons. The number of electrons this iron atom has is
   (a) 52.
   (b) 26.
   (c) 24.
   (d) None.
3. How many electrons are there in the third shell of sodium, Na (atomic number 11)?
   (a) None.
   (b) One.
   (c) Two.
   (d) Three.
4. The crystals that make up minerals are composed of
   (a) atoms with a definite geometrical arrangement.
   (b) molecules that perpetually move.
   (c) X-ray patterns.
   (d) three-dimensional chessboards.
5. If the volume of an object were to double, with no change in mass, its density would
   (a) halve.
   (b) double.
   (c) be the same.
   (d) None of these.
6. According to Hooke's law, if you hang by a tree branch and note how much it bends, then hanging with twice the weight produces
   (a) half the bend.
   (b) the same bend if the branch doesn't break.
   (c) twice the bend.
   (d) 4 times the bend.
7. When you bend the branch of a tree by hanging on its end, the top side of the branch is under
   (a) tension.
   (b) compression.
   (c) Both.
   (d) Neither.
8. When you scale up an object to 3 times its linear size, the surface area increases by
   (a) 3 and the volume by 9.
   (b) 3 and the volume by 27.
   (c) 9 and the volume by 27.
   (d) 4 and the volume by 8.
9. Pumice is a volcanic rock that floats in water. The density of pumice compared with water is
   (a) less.
   (b) equal.
   (c) more.
   (d) none, for it sinks.
10. The pressure at the bottom of a pond does NOT depend on the
    (a) acceleration due to gravity.
    (b) water density.
    (c) depth of the pond.
    (d) surface area of the pond.
11. A completely submerged object always displaces its own
    (a) weight of fluid.
    (b) volume of fluid.
    (c) density of fluid.
    (d) All of these.
12. A rock suspended by a weighing scale weighs 5 N out of water and 3 N when submerged in water. What is the buoyant force on the rock?
    (a) 3 N.
    (b) 5 N.
    (c) 8 N.
    (d) None of these.
13. In a vacuum, an object has no
    (a) buoyant force.
    (b) mass.
    (c) weight.
    (d) All of these.
14. Atmospheric pressure is due to the weight
    (a) of the atmosphere.
    (b) and volume of the atmosphere.
    (c) density and volume of the atmosphere.
    (d) of planet Earth itself.
15. Consider two mercury barometers, one having a cross-sectional area of 1 cm^2 and the other 2 cm^2. The height of mercury in the narrower tube is
    (a) half.
    (b) twice.
    (c) the same.
    (d) None of these.
16. A barometer that uses water instead of mercury will be
    (a) shorter.
    (b) taller.
    (c) equal in height.
    (d) inoperable.
17. When you squeeze an air-filled party balloon you increase its
    (a) volume.
    (b) mass.
    (c) weight.
    (d) density.
18. In a hydraulic press operation, the output piston cannot
    (a) move farther than the input piston.
    (b) exceed the force input.
    (c) exceed the input piston's speed.
    (d) produce increased energy.
19. The flight of a blimp best illustrates
    (a) Archimedes' principle.
    (b) Pascal's principle.
    (c) Bernoulli's principle.
    (d) Boyle's law.
20. When wind speeds up as it blows over the top of a hill, atmospheric pressure there
    (a) increases.
    (b) decreases.
    (c) isn't affected.
    (d) reduces to zero.

After you have made thoughtful choices, and discussed them with your friends, find the answers on page 681.

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Part Three
Heat

Although the temperature of these sparks exceeds 2000°C, the heat they impart when striking my skin is very small—which illustrates that *temperature* and *heat* are different concepts. Learning to distinguish between closely related concepts is the challenge and essence of *Conceptual Physics*.

15 Temperature, Heat, and Expansion

1 Hot materials, such as lava and cinders bursting from a volcano, are composed of fast-moving atoms and molecules. 2 Anette Zetterberg asks her students to predict whether or not the ball can pass through the hole when the ring is heated. 3 A testament to Daniel Gabriel Fahrenheit is shown outside his home (now in Gdansk, Poland). 4 The six-sided structure of a snowflake is a result of the six-sided ice crystals that make it up.

I remember, as a child, that whenever my family drove past the Massachusetts Institute of Technology in Cambridge, a few miles from my home in Saugus, the name RUMFORD inscribed at the top of one of the prominent buildings was pointed out to me. I was told that our family is descended from this great scientist and diplomat.

Rumford was born Benjamin Thompson in Woburn, Massachusetts, in 1753. By age 13 he demonstrated unusual skill with mechanical devices and had an almost faultless command of language and grammar. Soon he was attending science lectures at Harvard University. At the age of 19 he became a schoolmaster in Concord (earlier called Rumford), New Hampshire. There he met and married a rich widow 14 years his senior. Then, during the outbreak of the American Revolution, he sided with those loyal to England, for a time spying on their behalf. Facing arrest in 1776, he abandoned his wife and daughter and fled just ahead of a mob armed with hot tar and bags of feathers. He made his way to Boston during the evacuation of British troops and caught a ship to England. Once there, his scientific career prospered. His experiments with gunpowder were so successful that at age 26 he was elected

to the prestigious Royal Society. He eventually made his way to Bavaria, where he was made a count by the Bavarian prince for whom he was making cannons. He chose the name Count Rumford, after Rumford, New Hampshire.

A cannon is made by first casting a large metal cylinder in a foundry. The cylinder is then turned on a lathe, where the barrel is bored by advancing a stationary drill bit down the casting. Rumford's lathe was horse-driven, as was common at the time. Rumford was puzzled about the huge amounts of heat given off in the process. The notion of heat at the time, a hypothetical fluid called caloric, didn't fit the evidence. With a dull drill, the amount of heat was greater. As long as the horses kept at their work, more and more heat was produced. The source of heat was not something in the metal, but the motion of the horses. This discovery occurred long before friction was seen as a force, and before the concept of energy and its conservation were understood. Rumford's careful measurements convinced him of the falseness of the caloric theory of heat. Nevertheless, the caloric theory of heat as a fluid held sway for many years. Over time, his experiments were repeated and led to the connection between heat and work.

Rumford's achievements weren't limited to science. For example, while in Munich, he put unemployed beggars to work making uniforms for the Army. He also put them to work on public projects, one of which is now the famous English Gardens. A bronze statue of Count Rumford stands there as testimony of the gratitude of the citizens of Munich.

Rumford's many inventions made him a wealthy man. In 1796, he gave $5,000 each to the Royal Society of Great Britain and to the American Academy of Arts and Sciences to fund medals to be awarded every two years for outstanding scientific research on heat or light. Over the years, a galaxy of scientific stars in Europe and America have received the medals, including Michael Faraday, James Maxwell, Louis Pasteur, and Thomas Edison. The residue of Rumford's estate was left to Harvard University where it was used to establish the present Rumford Professorship.

Rumford was honored worldwide. In 1805 he wooed and married Madame Lavoisier, widow of Antoine Lavoisier. The marriage was brief and they soon separated. Rumford settled in Paris and continued his scientific work, extending the long list of his many inventions, until his death in 1814.

What an incredible relative!

Temperature

All matter—solid, liquid, and gas—is composed of continuously jiggling atoms or molecules. Because of this random motion, the atoms and molecules in matter have kinetic energy. The average kinetic energy of the individual particles produces an effect we can sense—warmth. The quantity that indicates warmth with respect to some standard is called **temperature.** The first "thermal meter" for measuring temperature, the *thermometer,* was invented by Galileo in 1602 (the word *thermal* is from the Greek term for "heat"). The once familiar mercury-in-glass thermometer came into widespread use some 70 years later. (Mercury thermometers are being phased out because of the danger of mercury poisoning.) We express the temperature of some quantity of matter by a number that corresponds to its degree of hotness or coldness on some chosen scale.

FIGURE 15.1

Can we trust our sense of hot and cold? Will both fingers feel the same temperature when placed in the warm water?

Nearly all materials expand when their temperature is raised and contract when their temperature is lowered. Most thermometers measure temperature by means of the expansion or contraction of a liquid, usually mercury or colored alcohol, in a glass tube with a scale.

On the most widely used temperature scale, the international scale, the number 0 is assigned to the temperature at which water freezes and the number 100 to the temperature at which water boils (at standard atmospheric pressure). The space between is divided into 100 equal parts called *degrees;* hence, a thermometer so calibrated has been called a *centigrade thermometer* (from *centi,* "hundredth," and *gradus,* "step"). However, it is now called a *Celsius thermometer* in honor of the man who first suggested the scale, the Swedish astronomer Anders Celsius (1701–1744).

PhysicsPlace.com™
Video
Low Temperatures with Liquid Nitrogen

Another temperature scale is popular in the United States. On this scale, the number 32 is assigned to the temperature at which water freezes, and the number 212 is

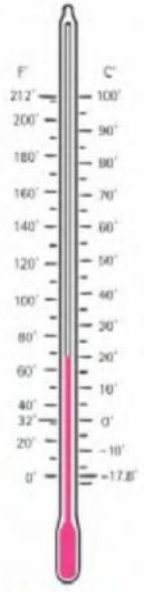

FIGURE 15.2
Fahrenheit and Celsius scales on a thermometer.

assigned to the temperature at which water boils. Such a scale makes up a Fahrenheit thermometer, named after its illustrious originator, the German physicist Gabriel Daniel Fahrenheit (1686–1736). The Fahrenheit scale will become obsolete if and when the United States goes metric.[1]

The temperature scale favored by scientists is the Kelvin scale, named after the Scottish physicist William Thomson, 1st Baron Kelvin (1824–1907). This scale is calibrated not in terms of the freezing and boiling points of water but in terms of energy itself. The number 0 is assigned to the lowest possible temperature—**absolute zero,** at which a substance has absolutely no kinetic energy to give up.[2] Absolute zero corresponds to −273°C on the Celsius scale. Units on the Kelvin scale have the same size increments as degrees on the Celsius scale, so the temperature of melting ice is 273 K. There are no negative numbers on the Kelvin scale. We won't treat this scale further until we study thermodynamics in Chapter 18.

Arithmetic formulas used for converting from Fahrenheit to Celsius, and vice versa, are popular in classroom exams. Such arithmetic exercises are not really physics, and the probability that you'll have the occasion to do this task elsewhere is small, so we will not be concerned with them here. Besides, this conversion can be very closely approximated by simply reading the corresponding temperature from the side-by-side scales in Figure 15.2.

Temperature is related to the random motion of atoms and molecules in a substance. (For brevity, hereafter in this chapter we'll simply say *molecules* to mean *atoms and molecules.*) More specifically, temperature is proportional to the average "translational" kinetic energy of random molecular motion (motion that carries the molecule from one place to another). Molecules may also rotate or vibrate, with associated rotational or vibrational kinetic energy—but these motions are not translational and don't define temperature.

CHECK POINT

True or false? Temperature is a measure of the total kinetic energy in a substance.

Check Your Answer

False. Temperature is a measure of the *average* (not *total*) translational kinetic energy of molecules in a substance. For example, there is twice as much total molecular kinetic energy in 2 L of boiling water as in 1 L—but the temperatures of the two volumes of water are the same because the *average* translational kinetic energy per molecule is the same in each.

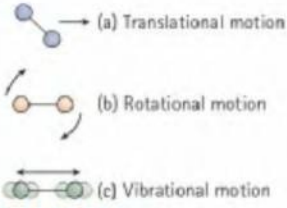

FIGURE 15.3
Particles in matter move in different ways. They move from one place to another, they rotate, and they vibrate to and fro. All these modes of motion, plus potential energy, contribute to the overall energy of a substance. Temperature, however, is defined by translational motion.

The effect of translational kinetic energy versus rotational and vibrational kinetic energy is dramatically demonstrated by a microwave oven. The microwaves that

[1]The conversion to Celsius would put the United States in step with the rest of the world, where the Celsius scale is the standard. Americans are slow to convert. Changing any long-established custom is difficult, and the Fahrenheit scale does have some advantages in everyday use. For example, its degrees are smaller (1°F = 5/9°C), which gives greater accuracy when reporting the weather in whole-number temperature readings. Then, too, people somehow attribute a special significance to numbers increasing by an extra digit. Thus, when the temperature of a hot day is reported to reach 100°F, the idea of heat is conveyed more dramatically than by stating that the temperature is 38°C. Like so much of the British system of measure, the Fahrenheit scale is geared to human beings.

[2]Even at absolute zero, a substance has what is called "zero-point energy," which is unavailable energy that cannot be transferred to a different substance. Helium, for example, has enough motion at absolute zero to avoid freezing. The explanation for this involves quantum theory.

bombard your food cause certain molecules in the food, mainly water molecules, to flip to and fro and to oscillate with considerable rotational kinetic energy. But oscillating molecules don't cook food. What does raise the temperature and cook the food, and swiftly, is the translational kinetic energy imparted to neighboring molecules that are bounced off the oscillating water molecules. (To picture this, imagine a bunch of marbles set flying in all directions after encountering the spinning blades of a fan—also, see page 398.) If neighboring molecules didn't interact with the oscillating water molecules, the temperature of the food would be no different than before the microwave oven was turned on.

Interestingly, what a thermometer really displays is its *own* temperature. When a thermometer is in thermal contact with something whose temperature we wish to know, energy will flow between the two until their temperatures are equal and thermal equilibrium is established. If we know the temperature of the thermometer, we then know the temperature of what is being measured. A thermometer should be small enough that it doesn't appreciably alter the temperature of what is being measured. If you are measuring the air temperature of a room, then your thermometer is small enough. But, if you are measuring the temperature of a drop of water, contact between the drop and the thermometer may change the drop's temperature—a classic case of the measuring process changing the thing that is being measured.

Heat

If you touch a hot stove, energy enters your hand because the stove is warmer than your hand. When you touch a piece of ice, however, energy transfers from your hand into the colder ice. The direction of spontaneous energy transfer is always from a warmer object to a neighboring cooler object. The energy transferred from one object to another because of a temperature difference between them is called **heat.**

It is important to point out that matter does not *contain* heat. This was discovered by Rumford in his cannon-boring experiments, as mentioned earlier. Rumford, and investigators that followed, realized that matter contains molecular kinetic energy and possibly potential energy, *not heat.* Heat is *energy in transit* from a body of higher temperature to one of lower temperature. Once transferred, the energy ceases to be heat. (As an analogy, work is also energy in transit. A body does not *contain* work. It *does* work or has work done on it.) In previous chapters, we called the energy resulting from heat flow *thermal energy* to make clear its link to heat and temperature. In this chapter, we will use the term that scientists prefer, *internal energy.*

FIGURE 15.4
There is more molecular kinetic energy in the container filled with warm water than in the small cupful of higher-temperature water.

Internal energy is the grand total of all energies inside a substance. In addition to the translational kinetic energy of jostling molecules in a substance, there is energy in other forms. There is rotational kinetic energy of molecules and kinetic energy due to internal movements of atoms within molecules. There is also potential energy due to the forces between molecules. So a substance does not contain heat—it contains internal energy.

When a substance absorbs or gives off heat, the internal energy of the substance increases or decreases. In some cases, as when ice is melting, the added heat does not increase molecular kinetic energy but goes instead into other forms of energy. The substance undergoes a change of phase, which we will cover in detail in Chapter 17.

Just as dark is the absence of light, cold is the absence of internal energy.

For two things in thermal contact, heat flow is from the higher-temperature substance to the lower-temperature substance. This is not necessarily a flow from a

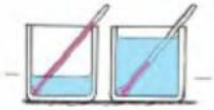

FIGURE 15.5

Although the same quantity of heat is added to both containers, the temperature increases more in the container with the smaller amount of water.

substance with more internal energy to a substance with less internal energy. There is more internal energy in a bowl of warm water than there is in a red-hot thumbtack; yet, if the tack is immersed in the water, heat flows from the hot tack to the warm water and not the other way around. Heat never flows of itself from a lower-temperature substance into a higher-temperature substance.

How much heat flows depends not only on the temperature difference between substances but on the amount of material as well. For example, a barrelful of hot water will transfer more heat to a cooler substance than will a cupful of water. There is more internal energy in the larger volume of water.

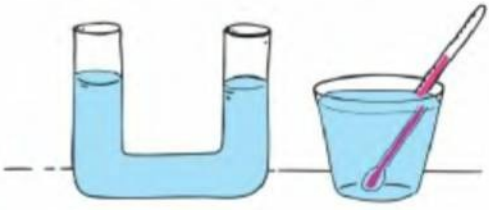

FIGURE 15.6

Just as water in the two arms of the U-tube seeks a common level (where the pressures at any given depth are the same), the thermometer and its immediate surroundings reach a common temperature (at which the average molecular KE is the same for both).

CHECK POINT

1. Suppose you apply a flame to 1 L of water for a certain time and its temperature rises by 2°C. If you apply the same flame for the same time to 2 L of water, by how much will its temperature rise?
2. If a fast marble hits a random scatter of slow marbles, does the fast marble usually speed up or slow down? Which lose(s) kinetic energy and which gain(s) kinetic energy—the initially fast-moving marble or the initially slow ones? How do these questions relate to the direction of heat flow?

Check Your Answers

1. Its temperature will rise by only 1°C, because there are twice as many molecules in 2 L of water, and each molecule receives only half as much energy on the average.
2. A fast-moving marble slows when it hits slower-moving marbles. It transfers some of its kinetic energy to the slower ones. Likewise with the flow of heat. Molecules with more kinetic energy that are in contact with molecules having less kinetic energy transfer some of their excess energy to the less energetic ones. The direction of energy transfer is from hot to cold. For both the marbles and the molecules, however, the *total* energy before and after contact is the same.

MEASURING HEAT

Temperature is measured in degrees; heat is measured in joules.

So heat is the flow of energy from one thing to another due to a temperature difference. Since heat energy is in transit, it is measured in joules. In the United States, a more common unit of heat is the *calorie*. The calorie is defined as the amount of heat required to change the temperature of 1 gram of water by 1 Celsius degree.[3]

The energy ratings of foods and fuels are determined by burning them and measuring the energy released. (Your body "burns" food at a slow rate.) The heat unit used to label foods is actually the kilocalorie, which is 1000 calories (the heat required to raise the temperature of 1 kilogram of water by 1°C). To distinguish this unit from the smaller calorie, the food unit is sometimes called a *Calorie* (written with a capital *C*). It is important to remember that the calorie and Calorie are units of energy. These names are historical carryovers from the early idea that heat is an

[3]A less common unit of heat is the British thermal unit (BTU). The BTU is defined as the amount of heat required to change the temperature of 1 lb of water by 1 Fahrenheit degree. One BTU equals 1054 J.

invisible fluid called *caloric*. This view persisted, even after Rumford's experiments to the contrary, into the 19th century.

We now know that heat is a form of energy transfer, not a separate substance, so it doesn't need its own separate unit. Someday the calorie may give way to the joule, an SI unit, as the common unit for measuring heat. (The relationship between calories and joules is that 1 calorie = 4.184 joules.) In this book, we'll learn about heat with the conceptually simpler calorie—but, in the lab, you may use the joule equivalent, where an input of 4.184 joules raises the temperature of 1 gram of water by 1°C.

FIGURE 15.7
To the weight watcher, the peanut contains 10 Calories; to the physicist, it releases 10,000 calories (or 41,840 joules) of energy when burned or consumed.

CHECK POINT

An iron thumbtack and a big iron bolt are removed from a hot oven. Both are red-hot and have the same temperature. When dropped into identical containers of water of equal temperature, which one raises the water temperature more?

Check Your Answer

The big iron bolt has more internal energy to impart to the water and warms it more than the thumbtack. Although they have the same initial temperature (the same *average* kinetic energy per molecule), the more massive bolt has more molecules and therefore more *total* energy—internal energy. This example underscores the difference between temperature and internal energy.

Both heat and work are ways in which energy can be transferred from one substance to another. Although they are measured in joules, they shouldn't be confused with energy itself.

Specific Heat Capacity

You've likely noticed that some foods remain hotter much longer than others do. If you remove a piece of toast from a toaster and pour hot soup into a bowl at the same time, a few minutes later the soup is still pleasantly warm, while the toast has cooled off considerably. Similarly, if you wait a short while before eating a slice of hot roast beef and a scoop of mashed potatoes, both initially at the same temperature, you'll find that the meat has cooled off more than the potatoes.

Different substances have different capacities for storing internal energy. If we heat a pot of water on a stove, we might find that it requires 15 minutes to raise it from room temperature to its boiling temperature. But if we put an equal mass of iron on the same flame, we would find that it would rise through the same temperature range in only about 2 minutes. For silver, the time would be less than a minute.

Different materials require different quantities of heat to raise the temperature of a given mass of the material by a specified number of degrees. This is partly due to different materials absorbing energy in different ways. The energy may be spread around among several kinds of energy, including molecular rotation and potential energy, which raises the temperature less. Except for special cases such as helium gas, the energy is always shared among different kinds of motion, but in varying degrees.

Whereas 1 gram of water requires 1 calorie of energy to raise its temperature 1 Celsius degree, it takes only about one-eighth as much energy to raise the temperature of a gram of iron by the same amount. Water absorbs more heat per gram than iron for the same change in temperature. We say water has a higher **specific heat capacity** (sometimes simply called *specific heat*).[4]

FIGURE 15.8
The filling of hot apple pie may be too hot to eat even though the crust is not.

If you add 1 calorie of heat to 1 gram of water, you'll raise its temperature by 1°C.

The specific heat capacity of any substance is defined as the quantity of heat required to change the temperature of a unit mass of the substance by 1 degree.

[4]If we know the specific heat capacity c, the formula for the quantity of heat Q involved when a mass m of a substance undergoes a change in temperature ΔT is $Q = cm\Delta T$. Or, heat transferred = specific heat capacity × mass × temperature change.

We can think of specific heat capacity as thermal inertia. Recall that inertia is a term used in mechanics to signify the resistance of an object to a change in its state of motion. Specific heat capacity is a sort of thermal inertia since it signifies the resistance of a substance to a change in its temperature.

THE HIGH SPECIFIC HEAT CAPACITY OF WATER

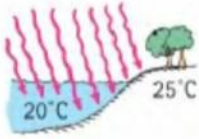

FIGURE 15.9

Because water has a high specific heat capacity and is transparent, it takes more energy to warm the water than to warm the land. Solar energy incident on the land is concentrated at the surface, but because sunlight on water extends beneath the surface, it is "diluted."

Water has a much higher capacity for storing energy than all but a few uncommon materials. A relatively small amount of water absorbs a large quantity of heat for a correspondingly small temperature rise. Because of this, water is a very useful cooling agent in the cooling systems of automobiles and other engines. If a liquid of lower specific heat capacity were used in cooling systems, its temperature would rise higher for a comparable absorption of heat.

Water also takes a long time to cool, a fact that explains why, in previous times, hot-water bottles were employed on cold winter nights. In many places, electric blankets have replaced them. This tendency on the part of water to resist changes in temperature improves the climate in many locations. The next time you are looking at a world globe, notice the high latitude of Europe. If water did not have a high specific heat capacity, the countries of Europe would be as cold as the northeastern regions of Canada, for both Europe and Canada receive about the same amount of sunlight per square kilometer. The Atlantic current known as the Gulf Stream carries warm water northeast from the Caribbean. It retains much of its internal energy long enough to reach the North Atlantic off the coast of Europe, where it then cools. The energy released, about 1 calorie per degree for each gram of water that cools, transfers to the air, where it is carried by the westerly winds over the European continent.

A similar effect occurs in the United States. The winds in the latitudes of North America are westerly. On the West Coast, air moves from the Pacific Ocean to the land. Because of water's high specific heat capacity, an ocean does not vary much in temperature from summer to winter. The water is warmer than the air in the winter and cooler than the air in the summer. In winter, the water warms the air that moves over it, and the air warms the coastal regions of North America. In summer, the water cools the air, and the coastal regions are cooled. On the East Coast, air moves from the land to the Atlantic Ocean. Land, with a lower specific heat capacity, gets hot in the summer but cools rapidly in the winter. As a result of water's high specific heat capacity and the wind directions, the West Coast city of San Francisco is

Climate is about average behavior while weather is about the fluctuations. Climate is what we expect and weather is what we get.

FIGURE 15.10

Many ocean currents, shown in blue, distribute heat from the warmer equatorial regions to the colder polar regions.

warmer in the winter and cooler in the summer than the East Coast city of Washington, D.C., which is at about the same latitude.

Islands and peninsulas that are more or less surrounded by water do not have the same extremes of temperatures that are observed in the interior of a continent. When air is hot in summer months, water cools it. When air is cold in winter months, water warms it. Water moderates temperature extremes. The high summer and low winter temperatures common in Manitoba and the Dakotas, for example, are largely due to the absence of large bodies of water. Europeans, islanders, and people living near ocean air currents should be glad that water has such a high specific heat capacity. San Franciscans are!

FIGURE 15.11

The temperature of the sparks is very high, about 2000°C. That's a lot of energy per molecule of spark. Because of the few molecules per spark, however, internal energy is safely small. Temperature is one thing; transfer of energy is another.

CHECK POINT

Which has a higher specific heat capacity, water or sand?

Check Your Answer

Water has a higher specific heat capacity. Water has more thermal inertia and takes a longer time to warm in the hot sunlight and a longer time to cool on a cold night. Sand has a low heat capacity, as evidenced by how quickly the surface warms in the morning sunlight and how quickly it cools at night. (Walking or running barefoot across scorching sand in the daytime is a much different experience than walking on cool sand in the evening.)

Thermal Expansion

When the temperature of a substance is increased, its molecules or atoms jiggle faster and move farther apart, on the average. The result is an expansion of the substance. With few exceptions, all forms of matter—solids, liquids, gases, and plasmas—generally expand when they are heated and contract when they are cooled.

In most cases involving solids, these changes in volume are not very noticeable, but careful observation usually detects them. Telephone wires become longer and sag more on a hot summer day than on a cold winter day. A metal lid on a glass jar can often be loosened by heating the lid under hot water. If one part of a piece of glass is heated or cooled more rapidly than adjacent parts, the resulting expansion or contraction may break the glass, especially if the glass is thick. Pyrex heat-resistant glassware is an exception because it's specially formulated to expand very little with increasing temperature (about a third as much as ordinary glass).

The expansion of substances must be accommodated in structures and devices of all kinds. A dentist uses filling material that has the same rate of expansion as teeth. The aluminum pistons of some automobile engines are just a bit smaller in diameter than the steel cylinders to allow for the much greater expansion rate of aluminum. Civil engineers use reinforcing steel with the same expansion rate as concrete. Long steel bridges commonly have one end fixed while the other end rests on rockers (Figure 15.12). The Golden Gate Bridge in San Francisco contracts more than a meter in cold weather. The roadway itself is segmented with tongue-and-groove–type gaps called *expansion joints* (Figure 15.13). Similarly, concrete roadways and sidewalks are intersected by gaps, sometimes filled with tar, so that the concrete can expand freely in summer and contract in winter.

FIGURE 15.12

One end of the bridge is fixed, while the end shown rides on rockers to allow for thermal expansion.

In times past, railroad tracks were laid in 39-foot segments connected by joint bars, with gaps for thermal expansion. In summer months, the tracks expanded and the gaps were narrow. In winter, the gaps widened, which was responsible for a more

FIGURE 15.13
This gap in the roadway of a bridge is called an expansion joint; it allows the bridge to expand and contract.

pronounced clickity-clack when the trains rolled along the tracks. We don't hear clickity-clacks these days because someone got the bright idea to eliminate the gaps by welding the tracks together. Doesn't expansion in the summer heat cause the welded tracks to buckle, as shown in Figure 15.14? Not if the tracks are laid and welded on the hottest summer days! Track shrinkage on cold winter days stretches the tracks, which doesn't cause buckling. Stretched tracks are okay.

FIGURE 15.14
Thermal expansion. The extreme heat of a July day in Asbury Park, New Jersey, caused the buckling of these railroad tracks. *(Wide World Photos)*

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How a Thermostat Works

Different substances expand at different rates. When two strips of different metals—say, one of brass and the other of iron—are welded or riveted together, the greater expansion of one metal results in the bending of the strip, as shown in Figure 15.15. Such a compound thin bar is called a *bimetallic strip*. When the strip is heated, one side of the double strip becomes longer than the other, causing the strip to bend into a curve. On the other hand, when the strip is cooled, it tends to bend in the opposite direction, because the metal that expands more also shrinks more. The movement of the strip may be used to turn a pointer, regulate a valve, or close a switch. Bimetallic strips are used in oven thermometers, electric toasters, and a variety of devices.

FIGURE 15.15
A bimetallic strip. Brass expands more when heated than iron does and contracts more when cooled. Because of this behavior, the strip bends as shown.

A practical application of different rates of expansion is the thermostat (Figure 15.16). The back-and-forth bending of the bimetallic coil opens and closes an electric circuit. When the room becomes too cold, the coil bends toward the brass side, which activates an electrical switch that turns on the heat. When the room becomes too warm, the coil bends toward the iron side, which activates an electrical switch that turns off the heating unit. Refrigerators are equipped with thermostats to prevent them from becoming either too warm or too cold.

Liquids expand appreciably with increases in temperature. In most cases, the expansion of liquids is greater than the expansion of solids. The gasoline overflowing a car's tank on a hot day is evidence for this. If the tank and contents expanded at the same rate, they would expand together and no overflow would occur. Similarly, if the expansion of the glass of a thermometer were as great as the expansion of the mercury, the mercury would not rise with increasing temperature. The reason the mercury in a thermometer rises with increasing temperature is that the expansion of liquid mercury is greater than the expansion of glass.

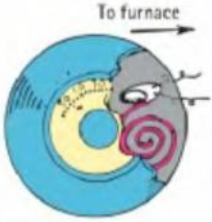


FIGURE 15.16
A thermostat. When the bimetallic coil expands, the drop of liquid mercury rolls away from the electrical contacts and breaks the electrical circuit. When the coil contracts, the mercury rolls against the contacts and completes the circuit.

CHECK POINT

Why is it advisable to allow telephone lines to sag when stringing them between poles in summer?

Check Your Answer

Telephone lines are longer in summer, when they are warmer, and shorter in winter, when they are cooler. They therefore sag more on hot summer days than in winter. If the telephone lines are not strung with enough sag in summer, they might contract too much and snap during the winter.

FIGURE 15.17
Place a dented Ping-Pong ball in boiling water, and you'll remove the dent. Why?

EXPANSION OF WATER

Water, like most other substances, expands when heated. But, interestingly, it *doesn't* expand in the temperature range between 0°C and 4°C. Something quite fascinating happens in this range. Ice has a crystalline structure, with open-structured crystals. Water molecules in this open structure occupy a greater volume than in the liquid phase (Figure 15.18). This means that ice is less dense than water.

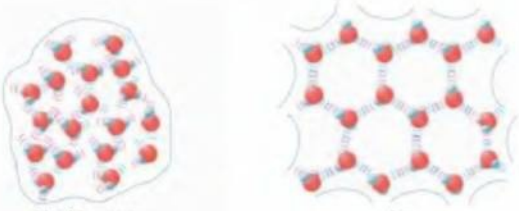


FIGURE 15.18
Liquid water is more dense than ice because water molecules in a liquid are closer together than water molecules frozen in ice, where they have an open crystalline structure.

CHECK POINT

What's inside the open spaces of the water crystals shown in Figure 15.18? Is it air, water vapor, or nothing?

Check Your Answer

There's nothing at all in the open spaces. It's empty space—a void. If there were air or vapor in the open spaces, the illustration should show molecules there—oxygen and nitrogen for air and H_2O for water vapor.

fyi

- Snowflakes form mainly from water vapor rather than liquid water. Truly symmetrical snowflakes are the exception, rather than the rule. Many mechanisms interrupt perfect snowflake growth. In 1611, the astronomer Kepler wrote a paper on six-cornered snowflakes. Fifty-four years later, physicist Robert Hooke used his early microscope to sketch the forms of snowflakes.

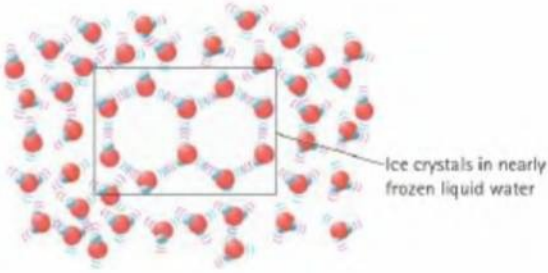


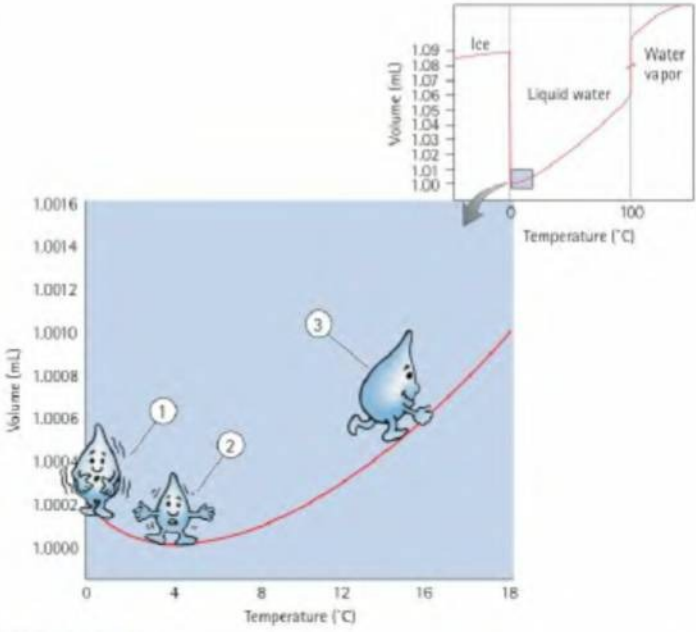
FIGURE 15.19

Close to 0°C, liquid water contains crystals of ice. The open structure of these 3-D cagelike crystals increases the volume of the water slightly.

fyi

- How does rock salt spread on icy roads in winter help to melt ice? It so happens that salt in water separates into sodium and chlorine ions, which when joining water molecules, give off energy that melts microscopic parts of an icy surface. The pressure of automobiles rolling along the salt-covered icy surface forces the salt into the ice, enhancing the melting process. The only difference between the rock salt and the salt you sprinkle on popcorn is the size of the crystals.

When ice melts, not all the open-structured crystals collapse. Some microscopic crystals remain in the ice-water mixture, making up a microscopic slush that slightly "bloats" the water, increasing its volume slightly (Figure 15.19). This results in ice water being less dense than slightly warmer water. As the temperature of water at 0°C is increased, more of the remaining ice crystals collapse. The melting of these crystals further decreases the volume of the water. The water undergoes two processes at the same time—contraction and expansion. Volume tends to decrease as ice crystals collapse, while volume tends to increase due to greater molecular motion. The collapsing effect dominates until the temperature reaches 4°C. After



(1) Liquid water below 4°C is bloated with ice crystals.

(2) Upon warming, the crystals collapse, resulting in a smaller volume for the liquid water.

(3) Above 4°C, liquid water expands as it is heated because of greater molecular motion.

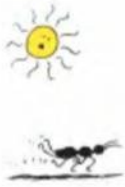
FIGURE 15.20

Between 0°C and 4°C, the volume of liquid water decreases as temperature increases. Above 4°C, water behaves the way other substances do: Its volume increases as its temperature increases. The volumes shown here are for a 1-gram sample.

Life at the Extremes

Some deserts, such as those on the plains of Spain, the Sahara in Africa, and the Gobi Desert in central Asia, reach surface temperatures of 60°C (140°F). Too hot for life? Not for certain species of ants of the genus Cataglyphis, which thrive at this searing temperature. At this extremely high temperature, the desert ants can forage for food without the presence of lizards, which would otherwise prey upon them. Resistant to heat, these ants can withstand higher temperatures than any other creatures in the desert (except microbes). How they are able to do this is currently being researched. They scavenge the desert surface for the corpses of those creatures that did not find cover in time, touching the hot sand as little as possible while often sprinting on four legs with two held high in the air. Although their foraging paths zigzag over the desert floor, their return paths are almost straight lines to their nest holes. They attain speeds of 100 body lengths per second. During an average 6-day life, most of these ants retrieve 15 to 20 times their weight in food.

From deserts to glaciers, a variety of creatures have invented ways to survive the harshest corners of the world. A species of worm thrives in the glacial ice in the Arctic. There are insects in the Antarctic ice that pump their bodies full of antifreeze to ward off becoming frozen solid. Some fish that live beneath the ice are able to do the same. Then there are bacteria that thrive in boiling hot springs as a result of having heat-resistant proteins.



An understanding of how creatures survive at the extremes of temperature can provide clues for practical solutions to the physical challenges faced by humans. Astronauts who venture from Earth, for example, will need all the techniques available for coping with unfamiliar environments.

that, expansion overrides contraction, because most of the microscopic ice crystals have melted by then (Figure 15.20).

When ice water freezes to become solid ice, its volume increases by nearly 10% and its density is lowered. That's why ice floats on water. Like most other substances, solid ice contracts with further cooling. This behavior of water is very important in nature. If water were most dense at 0°C, it would settle to the bottom of a pond or lake. Water at 0°C, however, is less dense and "floats" at the surface. That's why ice forms at the surface.

So a pond freezes from the surface downward. In a cold winter, the ice will be thicker than in a milder winter. Water at the bottom of an ice-covered pond is 4°C, which is relatively warm for the organisms that live there. Interestingly, very deep bodies of water are not ice covered even in the coldest of winters. This is because all the water must be cooled to 4°C before lower temperatures can be reached. For deep water, the winter is not long enough to reduce an entire pond to 4°C. Any 4°C water lies at the bottom. Because of water's high specific heat capacity and poor ability to conduct heat, the bottom of a deep body of water in a cold region remains at a constant 4°C year-round. Fish should be glad that this is so.

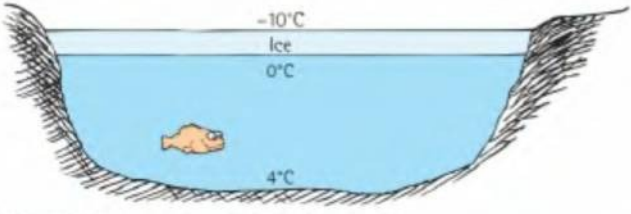


FIGURE 15.21

As water is cooled at the surface, it sinks until the temperature of the entire lake is 4°C. Only then can the surface water cool to 0°C without sinking. Once ice has formed, temperatures lower than 4°C can extend down into the lake.

CHECK POINT

1. What was the precise temperature at the bottom of Lake Michigan, where the water is deep and the winters long, on New Year's Eve in 1901?
2. Why do fish benefit from water being most dense at 4°C?

Check Your Answers

1. 4°C, because the temperature at the bottom of any body of water containing any 4°C water has a bottom temperature of 4°C, for the same reason that rocks are at the bottom. Rocks are more dense than water, and 4°C water is more dense than water at any other temperature. So both rocks and 4°C water sink to the bottom. Water is also a poor heat conductor, so if the body of water is deep and in a region of long winters and short summers, the water at the bottom likely remains a constant 4°C year-round.
2. Since water is most dense at 4°C, colder water rises and freezes on the surface, which means that fish remain in relative warmth!

SUMMARY OF TERMS

Temperature A measure of the average translational kinetic energy per molecule in a substance, measured in degrees Celsius or Fahrenheit or in kelvins (K).

Absolute zero The lowest possible temperature that a substance may have—the temperature at which molecules of the substance have their minimum kinetic energy.

Heat The energy that flows from a substance of higher temperature to a substance of lower temperature, commonly measured in calories or joules.

Internal energy The total of all molecular energies, kinetic plus potential, that are internal to a substance.

Specific heat capacity The quantity of heat per unit mass required to raise the temperature of a substance by 1 Celsius degree.

REVIEW QUESTIONS

1. Why does a penny become warmer when it is struck by a hammer?

Temperature

2. What are the temperatures for freezing water on the Celsius and Fahrenheit scales? For boiling water?
3. What are the temperatures for freezing water and boiling water on the Kelvin temperature scale?
4. What is meant by "translational" kinetic energy?
5. Which defines temperature—translational kinetic energy, rotational kinetic energy, vibrational kinetic energy, or all of these?
6. What is meant by the statement that a thermometer measures its own temperature?

Heat

7. When you touch a cold surface, does cold travel from the surface to your hand or does energy travel from your hand to the cold surface? Explain.
8. Distinguish between temperature and heat.
9. Distinguish between heat and internal energy.
10. What determines the direction of heat flow?

Measuring Heat

11. How is the energy value of foods determined?
12. Distinguish between a calorie and a Calorie.
13. Distinguish between a calorie and a joule.

Specific Heat Capacity

14. Which warms up faster when heat is applied—iron or silver?
15. Does a substance that heats up quickly have a high or a low specific heat capacity?
16. Does a substance that cools off quickly have a high or a low specific heat capacity?
17. How does the specific heat capacity of water compare with the specific heat capacities of other common materials?
18. Northeastern Canada and much of Europe receive about the same amount of sunlight per unit area. Why, then, is Europe generally warmer in the winter?
19. According to the law of conservation of energy, if ocean water cools, something else should warm. What is it that warms?
20. Why is the temperature fairly constant for land masses surrounded by large bodies of water?

Thermal Expansion

21. Why do substances expand when temperature is increased?
22. Why does a bimetallic strip bend with changes in temperature?
23. Which generally expands more for an equal increase in temperature—solids or liquids?

Expansion of Water

24. When the temperature of ice-cold water is increased slightly, does it undergo a net expansion or a net contraction?
25. What is the reason for ice being less dense than water?
26. Does "microscopic slush" in water tend to make it more dense or less dense?
27. What happens to the amount of "microscopic slush" in cold water when its temperature is increased?
28. At what temperature do the combined effects of contraction and expansion produce the smallest volume for water?
29. Why does all the water in a lake have to be cooled to 4°C before surface water can be cooled below 4°C?
30. Why does ice form at the surface of a body of water instead of at the bottom?

PROJECT

Write a letter to Grandpa describing how you're learning to see the connections in nature. Also give him examples of how you're learning to distinguish between closely related ideas. Use temperature and heat as examples.

EXERCISES

1. In a meeting room, there are chairs, a table, and people. Which of these things has a temperature (a) lower than, (b) greater than, or (c) equal to the temperature of the air?
2. Which is greater—an increase in temperature of 1 Celsius degree or an increase of 1 Fahrenheit degree?
3. In a glass of water at room temperature, do all the molecules have the same speed?
4. Why wouldn't you expect all the molecules in a gas to have the same speed?
5. Why can't you establish whether you are running a high temperature by touching your own forehead?
6. Which has more kinetic energy—a molecule in a gram of ice water or a molecule in a gram of steam? Defend your answer.
7. Which has the greater amount of internal energy—an iceberg or a cup of hot coffee? Defend your answer.
8. When a mercury thermometer is heated, the mercury expands and rises in the thin tube of glass. What does this indicate about the relative rates of expansion for mercury and glass? What would happen if their expansion rates were the same?
9. Which is the largest unit of heat transfer—Calorie, calorie, or joule?
10. If you drop a hot rock into a pail of water, the temperature of the rock and the water will change until both are equal. The rock will cool and the water will warm. Does this hold true if the hot rock is dropped into the Atlantic Ocean? Explain.
11. Consider two glasses, one filled with water and the other half-full, with the water in the two glasses being at the same temperature. In which glass are the water molecules moving faster? In which is there greater internal energy? In which will more heat be required to increase the temperature by 1°C?
12. Would you expect the temperature of water at the bottom of Niagara Falls to be slightly higher than the temperature at the top of the falls? Why?
13. Thermometers in a physics lab often use gas rather than mercury. Whereas changes in volume indicate temperature in a mercury thermometer, what changes in a gas do you think indicate temperature in a gas thermometer?
14. Why does the pressure of gas enclosed in a rigid container increase as the temperature increases?
15. Adding the same amount of heat to two different objects does not necessarily produce the same increase in temperature. Why not?
16. A certain quantity of heat is supplied to both a kilogram of water and to a kilogram of iron. Which undergoes the greater change in temperature? Defend your answer.
17. Which has the greater specific heat capacity—an object that cools quickly, or an object of the same mass that cools more slowly?
18. If the specific heat capacity of water were less, would a nice hot bath be a longer or a shorter experience?
19. Heat added to a substance goes partly into the translational kinetic energy of its molecules, which directly elevates temperature. For some substances, large proportions of heat also go into vibrations and rotations of the molecules. Would you expect materials in which a lot of energy goes into nontranslational molecular motions to have a high or a low specific heat capacity? Defend your answer.
20. Why does a piece of watermelon stay cool for a longer time than sandwiches do when both are removed from a picnic cooler on a hot day?
21. Ethyl alcohol has about one-half the specific heat capacity of water. If equal masses of each at the same temperature are supplied with equal quantities of heat, which will undergo the greater change in temperature?
22. When a 1-kg metal pan containing 1 kg of cold water is removed from the refrigerator and set on a table, which absorbs more heat from the room—the pan or the water?
23. In times past, on a cold winter night, it was common to bring a hot object to bed with you. Which would keep

you warmer through the cold night—a 10-kg iron brick or a 10-kg jug of hot water at the same temperature? Explain.

24. Bermuda is about as far north of the equator as North Carolina, but, unlike North Carolina, it has a subtropical climate year-round. Why is this so?

25. Iceland, so named to discourage conquest by expanding empires, is not at all ice covered like Greenland and parts of Siberia, even though it is not far from the Arctic Circle. The average winter temperature of Iceland is considerably higher than it is in regions at the same latitude in eastern Greenland and central Siberia. Why is this so?

26. Why does the presence of large bodies of water tend to moderate the climate of nearby land—to make it warmer in cold weather and cooler in hot weather?

27. If the winds at the latitude of San Francisco and Washington, D.C., were from the east rather than from the west, why might San Francisco be able to grow only cherry trees and Washington, D.C., both cherry trees and palm trees?

28. Desert sand is very hot in the day and very cool at night. What does this indicate about its specific heat capacity?

29. Cite an exception to the claim that all substances expand when heated.

30. Would a bimetallic strip function if the two different metals have the same rates of expansion? Is it important that they expand at different rates? Explain.

31. Steel plates are commonly attached to each other with rivets, which are slipped into holes in the plates and rounded over with hammers. The hotness of the rivets makes them easier to round over, but their hotness has another important advantage in providing a tight fit. What is it?

32. An old method for breaking boulders was to put them in a hot fire and then to douse them with cold water. Why would this fracture the boulders?

33. After you have driven a car for some distance, why does the air pressure in the tires increase?

34. Structural groaning noises are sometimes heard in the attic of old buildings on cold nights. Give an explanation in terms of thermal expansion.

35. An old remedy for a pair of nested drinking glasses that stick together is to run water at different temperatures into the inner glass and over the surface of the outer glass. Which water should be hot, and which cold?

36. Why is it important that glass mirrors used in astronomical observatories be composed of glass with a low "coefficient of expansion"?

37. In terms of thermal expansion, why is it important that a key and its lock be made of the same or similar materials?

38. Any architect will tell you that chimneys are never used as a weight-bearing part of a wall. Why?

39. Looking at the expansion joint in the photo of Figure 15.13, would you say it was taken on a warm day or a cold day? Why?

40. Would you or the gas company gain by having gas warmed before it passed through your gas meter?

41. After filling your gas tank to the top and parking your car in direct hot sunlight, why does the gasoline overflow?

42. A metal ball is just able to pass through a metal ring. When Anette increases the temperature of the ball, however, it will not pass through the ring. What would happen if she instead increased the temperature of the ring, rather than the ball? Will the size of the hole increase, stay the same, or decrease?

43. Consider a pair of brass balls of the same diameter, one hollow and the other solid. Both are heated with equal increases in temperature. Compare the diameters of the heated balls.

44. After a machinist very quickly slips a hot, snugly fitting iron ring over a very cold brass cylinder, there is no way that the two can be separated intact. Can you explain why this is so?

45. Suppose that you cut a small gap in a metal ring. If you were to heat the ring, would the gap become wider or narrower?

46. When a mercury thermometer is warmed, the mercury level momentarily goes down before it rises. Can you give an explanation for this?

47. Why do long steam pipes often have one or more relatively large U-shaped sections of pipe?

48. Why are incandescent bulbs typically made of very thin glass?

49. One of the reasons the first lightbulbs were expensive was due to the platinum electrical lead wires into the bulb, necessary because they expanded at about the same rate as glass when heated. Why is it important that the metal leads and the glass have the same coefficient of expansion?

50. After you measure the dimensions of a plot of land with a steel tape on a hot day, you return and remeasure the same plot on a cold day. On which day do you determine the larger area for the land?

51. What was the precise temperature at the bottom of Lake Superior at 12:01 AM on October 31, 2000?

52. Suppose that water is used in a thermometer instead of mercury. If the temperature is at 4°C and then changes, why can't the thermometer indicate whether the temperature is rising or falling?

53. A piece of solid iron sinks in a container of molten iron. A piece of solid aluminum sinks in a container of molten aluminum. Why does a piece of solid water (ice) not sink in a container of "molten" (liquid) water? Explain, using molecular terms.

54. How would the shape of the 0°C–18°C curve in Figure 15.20 differ if density rather than volume were plotted against temperature? Make a rough sketch.

55. What happens to the volume of water as it is cooled from 3°C to 1°C?

56. How does the combined volume of the billions and billions of hexagonal open spaces in the structures of ice crystals in a piece of ice compare with the portion of ice that floats above the waterline?

57. State whether water at the following temperatures will expand or contract when warmed a little: 0°C; 4°C; 6°C.

58. Why is it important to protect water pipes in the winter so that they don't freeze?

59. If water had a lower specific heat capacity, would ponds be more likely to freeze or less likely to freeze?

60. If cooling occurred at the bottom of a pond instead of at the surface, would the pond freeze from the bottom up? Explain.

PROBLEMS

1. What would be the final temperature of a mixture of 50 g of 20°C water and 50 g of 40°C water?

2. Suppose that a brass rod 1.0 m long expands 0.5 cm when its temperature is increased a certain amount. By how much will a brass rod 100 m long expand with the same change of temperature?

3. Steel expands 11 parts in a million for each 1°C change. Think about the 1.3-km main span of steel for the Golden Gate Bridge. If the span had no expansion joints, show that the span would be 0.21 m longer for a 15°C increase in temperature. [Use the formula $\Delta L = \alpha L_o \Delta T$, where L_o is the original length, α is the "coefficient of expansion" that for steel is (1/1,000,000) per °C, and ΔT is the change in temperature.]

• **4.** Consider a 40,000-km steel pipe that forms a ring to fit snugly all around the circumference of the Earth. Suppose people along its length breathe on it so as to raise its temperature 1°C. The pipe gets longer. It also is no longer snug. How high does it stand above ground level? (To simplify, consider only the expansion of its radial distance from the center of Earth, and apply the geometry formula that relates circumference C and radius r, $C = 2\pi r$. The result is surprising!)

CHAPTER 15 ONLINE RESOURCES

PhysicsPlace.com

Videos

- Low Temperatures with Liquid Nitrogen
- How a Thermostat Works

Quizzes

Flashcards

Links

16 Heat Transfer

1 Rocket scientist Helen Yan, when she was my student in the 1980s, showing how a hole in the box looks perfectly black and indicates a black interior. 2 The snow-covered mailboxes raise a question: What physics explains why the light-colored ones are snow covered, while the black ones are free of snow? 3 More recent photos of Helen who shows the same box—yes, with a white interior.

When Helen Yan was the top-scoring student in my physics class back in 1984, and then became my teaching assistant, I half-seriously suggested she continue in physics and become a rocket scientist. She may have taken me seriously, for after getting both a B.S. and M.S. in physics, today she *is* a rocket scientist. Back then she posed for the above pair of photos at the left, which first appeared in the fifth edition of *Conceptual Physics*, when all physics books were printed in only black ink. Color didn't occur in this book until the seventh edition. Helen then posed again for the same pair of photos in full color, and these photos have continued in editions since then.

In the pair of photos she is illustrating a property of radiation and, interestingly, today she specializes in radiation in the infrared part of the spectrum. Her science career began when she monitored the details of rocket launches with Lockheed Martin. Presently, in addition to teaching physics part-time at City College of San Francisco, and ballroom/swing dancing, she is involved in the designs of imaging sensors that are carried in satellites for viewing details of Earth's surface.

Helen is a personal merit badge in my teaching career, and a role model for others. So when you encounter a bright girl or young woman unsure of a career objective, suggest she follow Helen's path and, yes, even become a rocket scientist!

Conduction

Suppose you're roasting marshmallows on the end of a long metal fork over a campfire. While waiting to toast a crunchy surface on the marshmallow, the fork becomes a bit hot to hold. Heat enters the fork at the end that is kept in the flames and is transmitted along the entire length to your hand. The transmission of heat in this manner is called **conduction.** The fire causes the atoms at the heated end of the fork to move more rapidly. These atoms vibrate against neighboring atoms, which, in turn, do the same. More important, free electrons that can drift through the metal are made to jostle and transfer energy by colliding with atoms and other free electrons within the material.

How well a metal fork or any solid object conducts heat depends on the bonding within its atomic or molecular structure. Solids built of atoms that have one or more "loose" outer electrons conduct heat (and electricity) well. Metals have the "loosest" outer electrons, which are free to carry energy by collisions throughout the metal. That is why metals are excellent conductors of heat and electricity. Silver is the best conductor, copper is next, and, among the common metals, aluminum and then iron are next in order. Wool, wood, straw, paper, cork, and Styrofoam, on the other hand, are poor conductors of heat. The outer electrons in the atoms of these materials are firmly attached. Poor conductors are called *insulators.*

Because wood is a good insulator (poor conductor) of heat, it is used for handles of cookware. Even when it is hot, you can grasp the wooden handle of a pot with your bare hand and quickly remove the pot from a hot stove without harm. Grasping an iron handle of the same temperature would surely burn your hand. Wood is a good insulator even when very hot, which is why firewalkers can walk barefoot on red-hot wooden coals without burning their feet. (CAUTION: Don't try this on your own; even experienced firewalkers sometimes receive bad burns when conditions aren't just right—bits of coals sticking to the feet, for example.) The principal factor in firewalking is the low conductivity of wood—even red-hot wood. Although its temperature is high, relatively little heat is conducted to the feet, just as little heat is conducted by air when you put your hand briefly in a hot pizza oven. If you touch metal in the hot oven—OUCH! Similarly, a firewalker who steps on a hot piece of metal or another good conductor will be burned. Evaporation of moisture on wet feet can play a role in firewalking too, as we'll see in the next chapter.

Most liquids and gases are poor conductors of heat. Air is a very poor conductor, which is why your hand isn't harmed if placed briefly in a hot oven. The good insulating properties of such things as wool, fur, and feathers are largely due to the air spaces they contain. Other porous substances such as fiberglass are likewise good insulators because of their many small air spaces. Be glad that air is a poor conductor; if it weren't, you'd feel quite chilly on a 20°C (68°F) day!

Snow is a poor conductor (a good insulator)—about the same as dry wood. Hence, a blanket of snow can literally keep the ground warm in winter. Snowflakes are formed of crystals, which collect into feathery masses, imprisoning air and thereby interfering with the escape of heat from Earth's surface. Traditional Arctic winter dwellings are shielded from the cold by their snow covering. Animals in the forest find shelter from the cold in snowbanks and in holes in the snow. The snow doesn't provide warmth; it simply slows down the loss of the heat that the animals generate.

Heat is transmitted from a higher to a lower temperature. We often hear people say that they wish to keep the cold out of their homes. A better way to state this is to say that they want to prevent the heat from escaping. There is no "cold" that flows into a warm home (unless a cold wind blows into it). A home becomes colder

fyi

- The spontaneous transfer of heat is always from warmer objects to cooler objects and is brought about in three ways: by *conduction*, by *convection*, and by *radiation*.

FIGURE 16.1

When you touch a nail stuck in ice, does cold flow from the nail to your hand, or does energy flow from your hand to the nail?

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Video

The Secret to Walking on Hot Coals

The feeling of warmth or cold for different materials involves rates of heat transfer, not necessarily temperatures.

FIGURE 16.2

The tile floor feels colder than the wooden floor, even though both floor materials are at the same temperature. This is because tile is a better conductor of heat than wood, and so heat is more readily conducted out of the foot touching the tile.

FIGURE 16.3
Snow patterns on the roof of a house show areas of conduction and insulation. Bare parts show where heat from inside has leaked through the roof and melted the snow.

because heat flows out. Homes are insulated with rock wool to prevent heat loss rather than to prevent cold from entering. It is important to note that no insulator can totally prevent heat loss. An insulator merely reduces the rate at which heat penetrates. In winter, even the best-insulated warm homes will gradually cool. Insulation slows heat transfer.

PhysicsPlace.com™
Video
Air Is a Poor Conductor

CHECK POINT

1. In desert regions that are hot in the daytime and cold at nighttime, the walls of houses are often made of mud. Why is it important that the mud walls be thick?
2. Why is it that you can place your hand briefly inside a hot oven without harm, but you are burned if you touch the metal sides of the oven?

Check Your Answers

1. A wall of appropriate thickness keeps the house warm at night by slowing the flow of heat from inside to outside, and it keeps the house cool in the daytime by slowing the flow of heat from outside to inside. Such a wall has "thermal inertia."
2. When your hand is in the air of the hot oven, you're not harmed mainly because air is a poor conductor—heat doesn't travel well between the hot air and your hand. Touching the hot metal sides of the oven is another story, for metal is an excellent conductor and considerable heat flows into your hand.

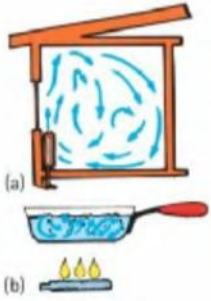


FIGURE 16.4
(a) Convection currents in air.
(b) Convection currents in liquid.

Convection

Liquids and gases transmit heat mainly by **convection,** which is heat transfer due to the actual motion of the fluid itself. Unlike conduction (in which heat is transferred by successive collisions of electrons and atoms), convection involves the motion of "blobs" of matter—the overall movement of molecules of a fluid.

Convection can occur in all fluids, whether liquids or gases. Whether we heat water in a pan or heat air in a room, the process is the same (Figure 16.4). As the fluid is heated from below, the molecules at the bottom begin moving faster, spreading apart more, becoming less dense, and are buoyed upward. Denser, cooler fluid moves in to take the place of the warmer fluid at the bottom. In this way, convection currents keep the fluid stirred up as it heats—warmer fluid moving away from the heat source and cooler fluid moving toward the heat source.

Convection currents occur in the atmosphere and affect the weather. When air is warmed, it expands. In expanding, it becomes less dense than the surrounding air. Like a balloon, it is buoyed upward. When the rising air reaches an altitude at which its density matches that

Convection ovens are simply ovens with a fan inside, which speeds up cooking by the circulation of warmed air.

FIGURE 16.5
A heater at the tip of a J-tube submerged in water produces convection currents, which are revealed as shadows (caused by deflections of light in water of different temperatures).

of the surrounding air, it no longer rises. This is evident when we see smoke from a fire rise and then level off as it cools to match the density of the surrounding air. Rising warm air expands as it rises because less atmospheric pressure squeezes it at higher altitudes. As the air expands, it cools. (Do the following experiment right now. With your mouth open, blow on your hand. Your breath is warm. Now repeat, but this time pucker your lips to make a small hole so your breath expands as it leaves your mouth. Note that your breath is appreciably cooler! Expanding air cools.) This is the opposite of what occurs when air is compressed. If you've ever compressed air with a tire pump, you probably noticed that both air and pump become quite hot.

We can understand the cooling of expanding air by thinking of molecules of air as tiny Ping-Pong balls bouncing against one another. A ball picks up speed when it is hit by another that approaches with a greater speed. But when a ball collides with one that is receding, its rebound speed is reduced. Likewise for a Ping-Pong ball moving toward a paddle: It picks up speed when it hits an approaching paddle, but it loses speed when it hits a receding paddle. The same idea applies to a region of air that is expanding: Molecules collide, on average, with more molecules that are receding than with molecules that are approaching (Figure 16.7). Thus, in expanding air, the average speed of the molecules decreases and the air cools.[1]

A dramatic example of cooling by expansion occurs with steam expanding through the nozzle of a pressure cooker (Figure 16.8). The cooling effect of both expansion and rapid mixing with cooler air allows you to hold your hand comfortably in the jet of condensed vapor. (*Caution:* If you try this, be sure to place your hand high above the nozzle at first and then lower it to a comfortable distance. If you put your hand at the nozzle where no steam appears, watch out! Steam is invisible near the nozzle before it has sufficiently expanded and cooled. The cloud of "steam" that you see is actually condensed water vapor, which is much cooler.)

Convection currents stirring the atmosphere result in winds. Some parts of Earth's surface absorb heat from the Sun more readily than others, and, as a result, the air near the surface is heated unevenly and convection currents form. This is evident at the seashore. In the daytime, the shore warms more easily than the water; air over the shore is pushed up (we say it rises) by cooler air that comes in from above the water to take its place. The result is a sea breeze. At night, the process reverses, because the shore cools off more quickly than the water, and then the warmer air is over the sea (Figure 16.9). If you build a fire on the beach, you'll notice that the smoke sweeps landward during the day and seaward at night.

FIGURE 16.6

Blow warm air onto your hand from your wide-open mouth. Now reduce the opening between your lips so that the air expands as you blow. Do you notice a difference in air temperature?

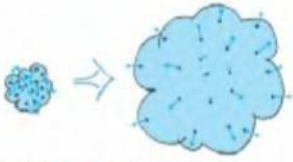


FIGURE 16.7

Molecules in a region of expanding air collide more often with receding molecules than with approaching ones. Their rebound speeds therefore tend to decrease and, as a result, the expanding air cools.

FIGURE 16.8

The hot steam expands from the pressure cooker and is cool to Millie's touch.

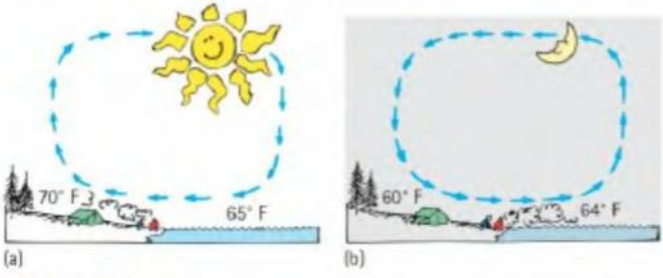


FIGURE 16.9

Convection currents produced by unequal heating of land and water. (a) During the day, warm air above the land rises, and cooler air over the water moves to replace it. (b) At night, the direction of air flow is reversed because then the water is warmer than the land.

[1]Where does the energy go in this case? We will see, in Chapter 18, that it goes into work done on the surrounding air as the expanding air pushes outward.

Convection occurs wherever fluids are subjected to temperature differences. It produces clouds in the sky and contributes to oceanic currents in deep ocean waters. In Earth's interior, the convection of semimolten material is the likely cause of sliding tectonic plates, which produce events such as earthquakes and volcanic eruptions. Convection plays a large role in the Sun. Convection is a central player in much that occurs around us.

CHECK POINT

You can hold your fingers beside the candle flame without harm, but not above the flame. Why?

Check Your Answer

Hot air travels upward by air convection. Since air is a poor conductor, very little heat travels sideways to your fingers.

Radiation

Energy from the Sun passes through space and then through Earth's atmosphere and warms Earth's surface. This energy does not pass through the atmosphere by conduction, because air is a poor conductor. Nor does it pass through by convection, for convection begins only after Earth is warmed. We also know that neither convection nor conduction is possible in the empty space between our atmosphere and the Sun. We can see that energy must be transmitted by some other means—by **radiation.**[2] The energy so radiated is called *radiant energy.*

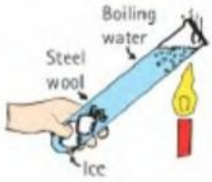
FIGURE 16.10
Types of radiant energy (electromagnetic waves).

Radiant energy is in the form of *electromagnetic waves.* It includes radio waves, microwaves, infrared radiation, visible light, ultraviolet radiation, X-rays, and gamma rays. These types of radiant energy are listed in order of wavelength, from longest to shortest. Infrared (below-the-red) radiation has longer wavelengths than visible light. The longest visible wavelengths are for red light, and the shortest are for violet light. Ultraviolet (beyond-the-violet) radiation has shorter wavelengths. (Wavelength is treated in more detail in Chapter 19, and electromagnetic waves are covered in more detail in Chapters 25 and 26.)

[2]The radiation we are talking about here is electromagnetic radiation, including visible light. Don't confuse this with radioactivity, a process of the atomic nucleus that we'll discuss in Part 7.

Practicing Physics

Hold the bottom end of a test tube full of cold water in your hand. Heat the top part in a flame until the water boils. The fact that you can still hold the bottom of the test tube shows that glass and water are poor conductors of heat and that convection does not move the hot water downward. This is even more dramatic when you wedge chunks of ice at the bottom with some steel wool; then the water above can be brought to a boil without melting the ice. Try it and see.



The wavelength of radiation is related to the *frequency* of radiation. Frequency is the rate of vibration of a wave. The girl in Figure 16.11 shakes a rope at a low frequency (left) and at a higher frequency (right). Note that the low-frequency shake produces a long, lazy wave and the higher-frequency one produces shorter waves. Likewise with electromagnetic waves. We will see, in Chapter 26, that vibrating electrons emit electromagnetic waves. Low-frequency vibrations produce long waves and high-frequency vibrations produce shorter waves.

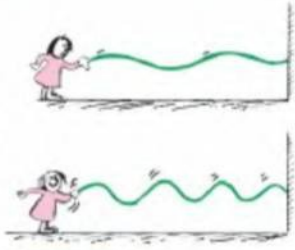


FIGURE 16.11

A wave of long wavelength is produced when the rope is shaken gently (at a low frequency). When it is shaken more vigorously (at a high frequency), a wave of shorter wavelength is produced.

EMISSION OF RADIANT ENERGY

All substances at any temperature above absolute zero emit radiant energy. The peak frequency $\bar{f}$ of the radiant energy is directly proportional to the absolute (Kelvin) temperature T of the emitter (Figure 16.12):

$$\bar{f} \sim T$$

If an object is hot enough, some of the radiant energy it emits is in the range of visible light. At a temperature of about 500°C an object begins to emit the longest waves we can see, red light. Higher temperatures produce a yellowish light. At about 1500°C all the different waves to which the eye is sensitive are emitted and we see an object as "white-hot." A blue-hot star is hotter than a white-hot star, and a red-hot star is less hot. Since a blue-hot star has twice the light frequency of a red-hot star, it therefore has twice the surface temperature of a red-hot star.[3]

Radiation by Earth is *terrestrial radiation*. Radiation by the Sun is *solar radiation*. Both are regions in the electromagnetic spectrum. (What do you call radiation from that special someone?)

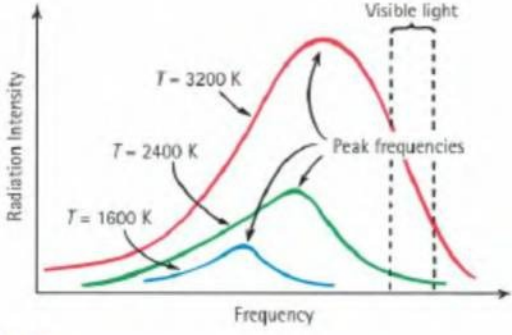


FIGURE 16.12

INTERACTIVE FIGURE

Radiation curves for different temperatures. The peak frequency of radiant energy is directly proportional to the absolute temperature of the emitter.

[3]The *amount* of radiant energy Q emitted by an object is proportional to the fourth power of the Kelvin temperature, $Q \sim T^4$.

FIGURE 16.13
Both the Sun and Earth emit the same kind of radiant energy. The Sun's glow is visible to the eye; Earth's glow consists of longer waves and isn't visible to the eye.

Because the surface of the Sun has a high temperature (by earthly standards), it therefore emits radiant energy at a high frequency—much of it in the visible portion of the *electromagnetic spectrum*. The surface of Earth, by comparison, is relatively cool, and so the radiant energy it emits has a frequency lower than that of visible light. The radiation emitted by Earth is in the form of *infrared waves*—below our threshold of sight. Radiant energy emitted by Earth is called **terrestrial radiation.**

The Sun's radiant energy stems from nuclear reactions in its deep interior. Likewise, nuclear reactions in Earth's interior warm Earth (visit the depths of any mine and you'll find it's warm down there—year-round). Much of this internal energy conducts to the surface to become terrestrial radiation.

All objects—you, your instructor, and everything in your surroundings—continually emit radiant energy over a range of frequencies. Objects with everyday temperatures emit mostly low-frequency infrared waves. When the higher-frequency infrared waves are absorbed by your skin, as when standing beside a hot stove, you feel the sensation of heat. So it is common to refer to infrared radiation as *heat radiation*. Common infrared sources that give the sensation of heat are the Sun, a lamp filament, and burning embers in a fireplace.

Heat radiation underlies infrared thermometers. You simply point the thermometer at something whose temperature you want, press a button, and a digital temperature reading appears. The radiation emitted by the object in question provides the reading. Typical classroom infrared thermometers operate in the range of about −30°C to 200°C.

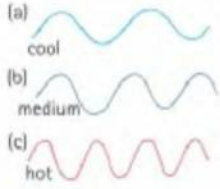


FIGURE 16.14
(a) A low-temperature (cool) source emits primarily low-frequency, long-wavelength waves. (b) A medium-temperature source emits primarily medium-frequency, medium-wavelength waves. (c) A high-temperature (hot) source emits primarily high-frequency, short-wavelength waves.

CHECK POINT

Do any of the following *not* give off radiant energy? (a) The Sun. (b) Lava from a volcano. (c) Red-hot coals. (d) This book that you're reading.

Check Your Answer

Let's hope you didn't answer (d), the book. Why? Because the book, like the other substances listed, has temperature—though not as much. According to the rule $f \sim T$, it therefore emits radiation whose peak frequency f is quite *low* compared with the radiation frequencies emitted by the other substances. Everything with any temperature above absolute zero emits electromagnetic radiation. That's right—*everything!*

ABSORPTION OF RADIANT ENERGY

If everything is emitting energy, why doesn't everything finally run out of it? The answer is that everything is also absorbing energy. Good emitters of radiant energy are also good absorbers; poor emitters are poor absorbers. For example, a radio antenna constructed to be a good emitter of radio waves is also, by its very design, a good receiver (absorber) of them. A poorly designed transmitting antenna is also a poor receiver.

FIGURE 16.15
An infrared thermometer measures the infrared radiant energy emitted by a body and converts it to temperature.

The surface of any material, hot or cold, both absorbs and emits radiant energy. If the surface absorbs more energy than it emits, it is a net absorber and its temperature rises. If it emits more than it absorbs, it is a net emitter and its temperature drops. Whether a surface plays the role of net emitter or net absorber depends on whether its temperature is above or below that of its surroundings. If the surface is hotter than its surroundings, it will be a net emitter and will cool. If its surface is colder than its surroundings, it will be a net absorber and become warmer. Every surface, hot or cold, both absorbs and emits radiant energy.

You can verify this with a pair of metal containers of the same size and shape, one having a white or mirrorlike surface and the other having a blackened surface

(Figure 16.16). Fill the containers with hot water and place a thermometer in each. You will find that the black container cools faster. The blackened surface is a better emitter. Coffee or tea stays hot longer in a shiny pot than in a blackened one. The same experiment can be done in reverse. This time, fill each container with ice water and place the containers in front of a fireplace, outside on a sunny day, or wherever there is a good source of radiant energy. You'll find that the black container warms up faster. As said, an object that emits well also absorbs well.

FIGURE 16.16
When the containers are filled with hot (or cold) water, the blackened one cools (or warms) faster.

CHECK POINT

1. If a good absorber of radiant energy were a poor emitter, how would its temperature compare with the temperature of its surroundings?
2. A farmer turns on the propane burner in his barn on a cold morning and heats the air to 20°C (68°F). Why does he still feel cold?

Check Your Answers

1. If a good absorber were not also a good emitter, there would be a net absorption of radiant energy and the temperature of the absorber would remain higher than the temperature of the surroundings. Things around us approach a common temperature only because good absorbers are, by their very nature, also good emitters.
2. The walls of the barn are still cold. The farmer radiates more energy to the walls than the walls radiate back, and he is chilled. (Inside your home or your classroom, you are comfortable only if the walls are warm, not just the air.)

Emission and absorption in the visible part of the spectrum are affected by color, whereas the infrared part of the spectrum is more affected by surface texture. A dull finish emits/absorbs better in the infrared than a polished one, whatever its color.

REFLECTION OF RADIANT ENERGY

Absorption and reflection are opposite processes. A good absorber of radiant energy reflects very little radiant energy, including visible light. Hence, a surface that reflects very little or no radiant energy looks dark. So a good absorber appears dark and a perfect absorber reflects no radiant energy and appears completely black. The pupil of the eye, for example, allows light to enter with no reflection, which is why it appears black. (An exception occurs in flash photography when pupils appear red, which occurs when very bright light is reflected off the eye's inner red surface and back through the pupil.)

Look at the open ends of pipes in a stack; the holes appear black. Look at open doorways or windows of distant houses in the daytime, and they, too, look black. Openings appear black because the light that enters them is reflected back and forth on the inside walls many times and is partly absorbed at each reflection. As a result, very little or none of the light remains to come back out of the opening and travel to your eyes (Figure 16.17). Helen Yan nicely illustrates this in the chapter-opening photos.

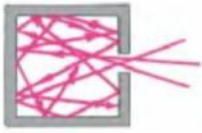


FIGURE 16.17
Radiation that enters the cavity has little chance of exiting because most of it is absorbed. For this reason, the opening to any cavity looks black to us.

Good reflectors, on the other hand, are poor absorbers. Clean snow is a good reflector and therefore does not melt rapidly in sunlight. If the snow is dirty, it absorbs radiant energy from the Sun and melts faster. Dropping black soot from an aircraft onto snow-covered mountains is a technique sometimes used in flood control. Controlled melting at favorable times, rather than a sudden runoff of melted snow, is thereby accomplished.

A hot pizza placed outside on a winter day is a net emitter. The same pizza placed in a hotter oven is a net absorber.

COOLING AT NIGHT BY RADIATION

Bodies that radiate more energy than they receive become cooler. This happens at night when solar radiation is absent. An object left out in the open at night radiates energy into

FIGURE 16.18
Most of the heat provided by a heating radiator is accomplished by convection, so color makes little difference (a better name for this type of heater would be a *convector*). For optimum efficiency, however, a silver-painted radiator will radiate less, become and remain hotter, and do a better job of heating the air. So paint your radiator silver!

FIGURE 16.19
Patches of frost crystals betray the hidden entrances to mouse burrows. Each cluster of crystals is frozen mouse breath!

space and, because of the absence of any warmer bodies in the vicinity, receives very little energy from space in return. Thus, it gives out more energy than it receives and becomes cooler. But if the object is a good conductor of heat—such as metal, stone, or concrete—heat conducts to the ground, which somewhat stabilizes its temperature. On the other hand, materials such as wood, straw, and grass are poor conductors and little heat is conducted into them from the ground. These insulating materials are net radiators and get *colder than the air.* It is common for frost to form on these kinds of materials even when the temperature of the air does not go down to freezing. Have you ever seen a frost-covered lawn or field on a chilly but above-freezing morning before the Sun is up? The next time you see this, notice that the frost forms only on the grass, straw, or other poor conductors, while none forms on the cement, stone, or other good conductors.

Serious gardeners will cover their favorite plants with a tarp when they expect a frost. The plants radiate just as before, but now they are receiving radiant energy from the tarp rather than from the dark night sky. Because the tarp radiates as an object at the temperature of the surroundings rather than at the temperature of the cold, dark sky, frost doesn't form on the plants' leaves. This is the same reason that plants on a covered porch won't have frost on them, whereas plants exposed to the open sky will.

Earth itself exchanges radiation with its surroundings. The Sun is a dominant part of Earth's surroundings during the day. The sunlit half of Earth absorbs more radiant energy than it emits. At night, if the air is relatively transparent, Earth radiates more energy to deep space than it receives in return. As the Bell Laboratories researchers Arno Penzias and Robert Wilson learned in 1965, outer space has a temperature—about 2.7 K (2.7 degrees above absolute zero). Space itself emits weak radiation characteristic of that low temperature.[4]

fyi

- In any given hour, more energy from the Sun reaches Earth than the entire energy used from all sources by the whole human population in any given year.

CHECK POINT

1. Which is likely to be colder—a night when you can see the stars or a night when you cannot?
2. In winter, why does the road surface on a bridge tend to be more icy than the road surfaces at either end of the bridge?

Check Your Answers

1. It is colder on the starry night, when Earth's surface radiates directly to frigid deep space. On a cloudy night, net radiation is less, because the clouds radiate energy back to Earth's surface.
2. Energy radiated by roads on land is partly replenished by heat conducted from the warmer ground below the pavement. But there's an absence of thermal contact between the road surfaces of bridges and the ground, so they receive very little, if any, replenishing energy conducted from the ground. This is why road surfaces on bridges get colder than roads on land, which increases the chance of ice formation on bridges. Understanding heat transfer can make you a safer driver!

[4]Penzias and Wilson shared a Nobel Prize for this discovery of "cosmic background radiation," deemed to be a relic of the Big Bang. Its temperature has now been measured to the incredible accuracy of 2.725 K, and it is revealing much about the early history of the universe and its present composition.

Newton's Law of Cooling

Left to themselves, objects hotter than their surroundings eventually cool to match the surrounding temperature. The rate of cooling depends on how much hotter the object is than its surroundings. A hot apple pie will cool more each minute if it is put in a cold freezer than if it is left on the kitchen table. That's because, in the freezer, the temperature difference between the pie and its surroundings is greater. Similarly, the rate at which a warm house leaks internal energy to the cold outdoors depends on the difference between the inside and outside temperatures.

The rate of cooling of an object—whether by conduction, by convection, or by radiation—is approximately proportional to the temperature difference ΔT between the object and its surroundings.

$$\text{Rate of cooling} \sim \Delta T$$

This is known as **Newton's law of cooling.** (Guess who is credited with discovering this?) The law applies also to warming. If an object is cooler than its surroundings, its rate of warming up is also proportional to ΔT.[5] Frozen food will warm up faster in a warm room than in a cold room.

The rate of cooling we experience on a cold day can be increased by the added convective effect of the wind. We speak of this in terms of *windchill.* For example, a windchill of −20°C means we are losing heat at the same rate as if the temperature were −20°C without wind.

FIGURE 16.20
The long stem of a wine glass helps to prevent heat from the hand from warming the wine.

Interestingly, Newton's law of cooling is an empirical relationship, and not a fundamental law like Newton's laws of motion.

CHECK POINT

Since a hot cup of tea loses heat more rapidly than a lukewarm cup of tea, would it be correct to say that a hot cup of tea will cool to room temperature before a lukewarm cup of tea will?

Check Your Answer

No! Although the rate of cooling is greater for the hotter cup, it has farther to cool to reach thermal equilibrium. The extra time is equal to the time it takes to cool to the initial temperature of the lukewarm cup of tea. Cooling *rate* and cooling *time* are not the same thing.

The Greenhouse Effect

An automobile parked in the street in the bright Sun on a hot day with closed windows can get very hot inside—appreciably hotter than the outside air. This is an example of the **greenhouse effect,** so named for the same temperature-raising effect in florists' glass greenhouses. Understanding the greenhouse effect requires knowing about two concepts.

The first concept has been previously stated—that all things radiate, and the frequency and wavelength of radiation depend on the temperature of the object emitting the radiation. High-temperature objects radiate short waves; low-temperature

A significant role of glass in a florist's greenhouse is preventing convection of cooler outside air with warmer inside air. So the greenhouse effect actually plays a bigger role in global warming than it does in the warming of florists' greenhouses.

[5]A warm object that contains a source of energy may remain warmer than its surroundings indefinitely. The internal energy it emits doesn't necessarily cool it, and Newton's law of cooling doesn't apply. Thus an automobile engine that is running remains warmer than the automobile's body and the surrounding air. But after the engine is turned off, it cools in accordance with Newton's law of cooling and gradually approaches the same temperature as its surroundings. Likewise, the Sun will remain hotter than its surroundings as long as its nuclear furnace is functioning—another 5 billion years or so.

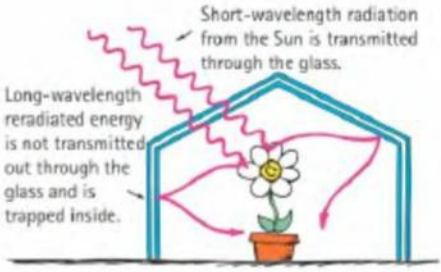


FIGURE 16.21

Glass is transparent to short-wavelength radiation but opaque to long-wavelength radiation. Reradiated energy from the plant is of long wavelength because the plant has a relatively low temperature.

objects radiate long waves. The second concept we need to know is that the transparency of things such as air and glass depends on the wavelength of radiation. Air is transparent to both infrared (long) waves and visible (short) waves, unless the air contains excess water vapor and carbon dioxide, in which case it is opaque to infrared. Glass is transparent to visible light waves, but is opaque to infrared waves. (The physics of transparency and opacity is discussed in Chapter 26.)

Now to why that car gets so hot in bright sunlight: Compared with the car, the Sun's temperature is very high. This means the waves radiated by the Sun are very short. These short waves easily pass through both Earth's atmosphere and the glass windows of the car. So energy from the Sun gets into the car interior, where, except for reflection, it is absorbed. The interior of the car warms up. The car interior radiates its own waves, but, since it is not as hot as the Sun, the waves are longer. The reradiated long waves encounter glass that isn't transparent to them. So the reradiated energy remains in the car, which makes the car's interior even warmer (which is why leaving your pet in a car on a hot sunny day is a no-no).

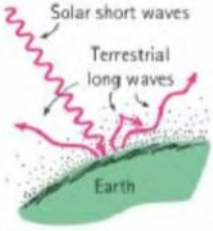


FIGURE 16.22

INTERACTIVE FIGURE

The hot Sun emits short waves, and the cool Earth emits long waves. Water vapor, carbon dioxide, and other "greenhouse gases" in the atmosphere retain heat that would otherwise be radiated from Earth to space.

The same effect occurs in Earth's atmosphere, which is transparent to solar radiation. The surface of Earth absorbs this energy and reradiates part of this as longer-wavelength terrestrial radiation. Atmospheric gases (mainly water vapor and carbon dioxide) absorb and re-emit much of this long-wavelength terrestrial radiation back to Earth. Terrestrial radiation that cannot escape Earth's atmosphere keeps Earth from getting too cold. This greenhouse effect is very nice, for Earth would be a frigid −18°C otherwise. Over the last 500,000 years the average temperature of Earth has fluctuated between 19°C and 27°C and is presently at the high point, 27°C—and climbing.

Although H_2O is the major greenhouse gas in the atmosphere, the second most abundant greenhouse gas, CO_2, is notorious because its contribution from humans has been steadily increasing. Unhappily, further warming by CO_2 can trigger more H_2O as well. So our present environmental concern is the combination of growing amounts of both these molecules in the atmosphere, which would further increase the temperature and produce a new thermal balance unfavorable to the biosphere.

An important credo is "You can never change only one thing." Change one thing, and you change another. A slightly higher Earth temperature means slightly warmer oceans, which means changes in weather and storm patterns. The consensus among scientists is that Earth's climate is getting too warm too fast. This phenomenon is called *global warming*. How this will play out is not known. At one extreme, corrections can be made and life will be fine for Earth's inhabitants. At the other extreme, we are reminded of the planet Venus, which in earlier times may have had a climate somewhat similar to Earth's. A runaway greenhouse effect is thought to have occurred on Venus, which today finds its atmosphere 96% carbon dioxide, with an average surface temperature of 460°C. Venus is the hottest planet in the solar system. We certainly don't want to follow its course. Our fate likely lies between these extremes. We don't know.

Volcanoes put more particulate matter into the atmosphere, by far, than industries and all human activity.

What we do know is that energy consumption and modifying our atmosphere is related to population size. We are seriously questioning the idea of continued

growth. (Please take the time to read Appendix E, "Exponential Growth and Doubling Time"—very important material.)

Solar power is what you have once solar energy has been converted to electricity. This can be done by photovoltaic cells or by changing water to steam to spin a generator.

CHECK POINT

1. What eventually happens to the solar energy that falls on Earth?
2. What does it mean to say that the greenhouse effect is like a one-way valve?

Check Your Answers

1. Sooner or later, it will be radiated back into space. Energy is always in transit—you can rent it, but you can't own it.
2. The transparent material—atmosphere for Earth and glass for the greenhouse—allows only incoming short waves and blocks outgoing long waves. As a result, radiant energy is trapped within the "greenhouse."

Solar Power

If you step from the shade into the sunshine, you're noticeably warmed. The warmth you feel isn't so much because the Sun is hot, for its surface temperature of 6000°C is no hotter than the flames of some welding torches. We are warmed principally because the Sun is so *big*.[6] As a result, it emits enormous amounts of energy, less than one part in a billion of which reaches Earth. Nonetheless, the amount of radiant energy received each second over each square meter at right angles to the Sun's rays at the top of the atmosphere is 1400 joules (1.4 kJ). This input of energy is called the **solar constant.** This is equivalent, in power units, to 1.4 kilowatts per square meter (1.4 kW/m^2). **Solar power** is the rate at which solar energy is received from the Sun. The amount of solar power that reaches the ground is attenuated by the atmosphere and reduced by nonperpendicular elevation angles of the Sun. Also, of course, it ceases at night. The solar power received in the United States, averaged over day and night, summer and winter, is about 13% of the solar constant (0.18 kW/m^2). This amount of power, illuminating the roof of a typical American house, is twice the power needed to comfortably heat and cool the house year-round. More and more homes are capturing solar energy for space heating and water heating. Also gaining in popularity are photovoltaic shingles used in roofing buildings.

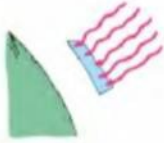


FIGURE 16.23
Over each square meter of area perpendicular to the Sun's rays at the top of the atmosphere, the Sun pours 1400 J of radiant energy each second. Hence the solar constant is 1.4 kJ/s/m^2, or 1.4 kW/m^2.

Photovoltaic systems convert light energy directly to electrical energy. They can be designed for power needs ranging from milliwatts to megawatts, powering a calculator or a generator in a power plant. They also can be located in remote areas not readily accessible to utility grid lines. Solar-energy collecting and concentration systems, whether arrays of mirrors or photovoltaic cells, are becoming competitive in cost with electrical power generated by conventional power sources.

FIGURE 16.24
Higher-tech solar water heaters are covered with glass to provide a greenhouse effect, which further heats the water. Why are the collectors a dark color?

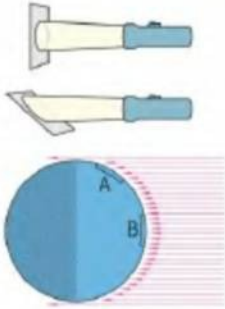
FIGURE 16.25
A simple and effective use of solar power.

[6]To visualize how big the Sun is, realize that its diameter is more than 3 times the distance between Earth and the Moon. So if Earth and the Moon were inside the Sun, with Earth at the solar center, the Moon would be deep inside. The Sun is *really* big!

Practicing Physics

Does the distance from the Sun, or the angle of the Sun's rays on Earth, account for frigid polar regions and tropical equatorial regions? You can see the answer for yourself if you hold a flashlight above a surface and note its brightness. When the light strikes perpendicularly, light energy is concentrated; but, when the surface is tipped, keeping the same distance, incident light is more spread out. Can you see that the same energy over a larger area is akin to the low temperatures of the Arctic and Antarctic regions of Earth?

The sketch to the right is of Earth with parallel rays of light coming from the Sun. Count the number of rays that strike Region A and equal-area Region B. Where is the energy per unit area less? How does this relate to climate?



Controlling Heat Transfer

A nice way to review the methods of heat transfer is by considering a device that inhibits all three methods: the vacuum bottle. A vacuum bottle (known by the trademark name Thermos) consists of a double-walled glass container with a vacuum between the walls and a close-fitting stopper of cork or plastic. (There is usually an outer covering as well.) The glass surfaces that face each other are silvered. Any liquid, hot or cold, in a vacuum bottle will remain close to its original temperature for many hours.

1. Heat transfer by *conduction* through the vacuum is impossible. Some heat escapes by conduction through the glass and stopper, but this is a slow process, as glass, plastic, and cork are poor conductors.
2. The vacuum has no fluid to convect, so there is no heat loss through the walls by *convection*.
3. Heat loss by *radiation* is reduced by the silvered surfaces of the walls, which reflect heat waves back into the bottle.

FIGURE 16.26
A Thermos bottle.

SUMMARY OF TERMS

Conduction The transfer of heat energy by molecular and electron collisions within a substance (especially a solid).

Convection The transfer of heat energy in a gas or liquid by means of currents in the heated fluid. The fluid moves, carrying energy with it.

Radiation The transfer of energy by means of electromagnetic waves.

Terrestrial radiation The radiation emitted by Earth to outer space.

Newton's law of cooling The rate of loss of heat from a warm object is proportional to the temperature difference between the object and its surroundings. (Similarly for the gain of heat by a cool object.)

Greenhouse effect Warming of the lower atmosphere by short-wavelength radiation from the Sun that penetrates the atmosphere is absorbed by Earth and is reradiated at longer wavelengths that cannot easily escape Earth's atmosphere.

Solar constant 1400 J/m^2 received from the Sun each second at the top of Earth's atmosphere on an area perpendicular to the Sun's rays; expressed in terms of power, 1.4 kW/m^2.

Solar power Energy per unit time derived from the Sun.

REVIEW QUESTIONS

Conduction

1. What is the role of "loose" electrons in heat conductors?
2. If you touch the metal sides inside of an oven with a bare hand, you're in trouble. But hold your hand briefly in the oven air and you're okay. What does this tell you about the relative conductivities of metal and air?
3. Explain why a firewalker can step quickly without harm on red-hot coals with bare feet.

4. Why are such materials as wood, fur, feathers, and even snow good insulators?
5. Does a good insulator prevent heat from escaping, or does it simply slow its passage?

Convection

6. What happens to the volume of air as it rises? What happens to its temperature?
7. When an air molecule is hit by an approaching faster-moving molecule, does its rebound speed increase or decrease? How about when it hits a receding molecule?
8. How are the speeds of molecules of air affected when the air is compressed by the action of a tire pump?
9. How are the speeds of molecules of air affected when the air rapidly expands?
10. Why is Millie's hand not burned when she holds it above the escape valve of the pressure cooker (Figure 16.8)?
11. Why does the direction of coastal winds change from day to night?

Radiation

12. In what form does radiant energy travel?
13. Relatively speaking, do high-frequency waves have long wavelengths or short wavelengths?

Emission of Radiant Energy

14. How does the frequency of radiant energy relate to the absolute temperature of the radiating source?
15. What is terrestrial radiation?
16. Cite a primary difference between waves of solar radiation and waves of terrestrial radiation.

Absorption of Radiant Energy

17. Since all objects emit energy to their surroundings, why don't the temperatures of all objects continuously decrease?
18. What determines whether an object is a net absorber or a net emitter of radiant energy at a given time?
19. Which will normally warm faster—a black pot of cold water or a silvered pot of cold water? Explain.

Reflection of Radiant Energy

20. Can an object be both a good absorber and a good reflector at the same time? Why, or why not?
21. Why does the pupil of the eye appear black?

Cooling at Night by Radiation

22. What happens to the temperature of something that radiates energy without absorbing the same amount in return?
23. An object radiating energy at night is in contact with the relatively warm Earth. How does its conductivity affect whether or not it becomes appreciably colder than the air?

Newton's Law of Cooling

24. Which will undergo the greater rate of cooling—a red-hot poker in a warm oven or a red-hot poker in a cold room (or do both cool at the same rate)?
25. Does Newton's law of cooling apply to warming as well as to cooling?

The Greenhouse Effect

26. What would be the consequence of completely eliminating the greenhouse effect?
27. In what way does glass act like a one-way valve for a conventional greenhouse? Does the atmosphere play the same role?

Solar Power

28. How much radiant energy from the Sun, on average, reaches each square meter at the top of Earth's atmosphere each second?
29. What is the function of a photovoltaic cell?

Controlling Heat Transfer

30. Cite three ways in which a Thermos bottle inhibits heat transfer.

PROJECTS

1. Wrap a piece of paper around a thick metal bar and place it in a flame. Notice that the paper will not catch fire. Can you explain this in terms of the conductivity of the metal bar? (Paper generally will not ignite until its temperature reaches about 230°C.)

2. Turn a common incandescent lamp on and off quickly while holding your hand a few inches from the bulb. You feel its heat, but, when you touch the bulb, it isn't hot. Explain this in terms of radiant energy and the bulb's transparency.
3. Write a letter to Grandma and share your knowledge about why air temperature is cooler on clear nights and warmer on cloudy nights. With reasoned examples, convince her that all things are continually emitting energy—and absorbing energy.

EXERCISES

1. On a cold day, why does a metal doorknob feel colder than the wooden door?
2. What is the explanation for feather beds being warm?
3. Wrap a fur coat around a thermometer. Will the temperature rise?
4. If 70°F air feels warm and comfortable to us, why does 70°F water feel cool when we swim in it?

5. At what common temperature will a block of wood and a block of metal both feel neither hot nor cold to the touch?
6. If you hold one end of a piece of metal against a piece of ice, the end in your hand soon becomes cold. Does cold flow from the ice to your hand? Explain.
7. What is the purpose of a layer of copper or aluminum on the bottom of stainless steel cookware?
8. In terms of physics, why do restaurants serve baked potatoes wrapped in aluminum foil?
9. Wood is a better insulator than glass, yet fiberglass is commonly used as an insulator in wooden buildings. Explain.
10. Many tongues have been injured by licking a piece of metal on a very cold day. Why would no harm result if a clean piece of wood were licked on the same day?
11. Visit a snow-covered cemetery and note that the snow does not slope upward against the gravestones. Instead, it forms depressions, as shown. Can you think of a reason for this?

12. Why are mittens warmer than gloves on a cold day?
13. If you were caught in freezing weather with only your own body heat as a source, would you be warmer in an Arctic igloo or in a wooden shack? Defend your answer.
14. Wood conducts heat very poorly—it has a very low conductivity. Does wood still have a low conductivity if it is hot? Could you quickly and safely grasp the wooden handle of a pan from a hot oven with your bare hand? Although the pan handle is hot, is much heat conducted from it to your hand if grasped briefly? Why would it be a poor idea to do the same with an iron handle? Explain.
15. Does wood have a low conductivity if it is very hot—that is, in the stage of smoldering, red-hot coals? Could you safely walk across a bed of red-hot wooden coals with bare feet? Although the coals are hot, does much heat conduct from them to your feet if you step quickly? Could you do the same on red-hot iron coals? Explain. (*Caution:* Coals can stick to your feet, so—OUCH!—don't try it!)
16. Is it possible for heat to flow between two objects with the same internal energy? Can heat flow from an object with less internal energy to one with more internal energy? Defend your answers.
17. When two cups of hot chocolate, one at 50°C and the other at 60°C, are poured into a bowl, why will the temperature of the mixture be between 50°C and 60°C?
18. Why is it incorrect to say that, when a hot object warms a cold object, temperature flows between them?
19. Why is it incorrect to say that, when a hot object warms a cold one, the increase in temperature of the cold one is equal to the decrease in temperature of the hot one? When is this statement correct?
20. A friend says that the molecules in a mixture of gas in thermal equilibrium have the same average kinetic energy. Do you agree or disagree? Explain.
21. Your friend states that the average speed of all hydrogen and nitrogen molecules in a gas is the same. Do you agree or disagree, and why?
22. Why would you not expect all the molecules of air in your room to have the same average speed?
23. In a mixture of hydrogen and oxygen gases at the same temperature, which molecules move faster? Why?
24. One container is filled with argon gas and the other with krypton gas. If both gases have the same temperature, in which container are the atoms moving faster? Why?
25. Which atoms, on average, move slower in a mixture, U-238 or U-235? How would this affect diffusion through a porous membrane of otherwise identical gases made from these isotopes?
26. Solid uranium can be converted chemically to uranium fluoride, UF_6, which can be cooked up into a dense vapor that diffuses through a porous barrier. Which is likely to diffuse at a greater rate, a gas with isotope U-235 or U-238?
27. Consider two equal-size rooms connected by an open door. One room is maintained at a higher temperature than the other one. Which room contains more air molecules?
28. In a still room, smoke from a candle will sometimes rise only so far, not reaching the ceiling. Explain why.
29. Soaring birds and glider pilots can remain aloft for hours without expending power. How do they do it?
30. Why does helium, released into the atmosphere, eventually disappear into space?
31. Ice cubes float in a glass of iced tea. Why would cooling be less if the cubes were instead on the bottom of the drink?
32. Release a single molecule in an evacuated region and it will fall as fast as, and no differently from, a baseball released in the same region. Explain.
33. Air density is normally less above any point in air than below, providing a "migration window" in air. How does this affect the movement of faster-moving molecules in air?
34. What does the high specific heat of water have to do with convection currents in the air at the seashore?
35. If we warm a volume of air, it expands. Does it then follow that if we expand a volume of air, it warms? Explain.
36. Ceiling fans can make you feel cooler in a warm room. Do ceiling fans reduce room temperature?
37. Some ceiling fans are reversible so that they drive air down or pull it up. In which direction should the fan drive the air during winter? In which direction for summer?
38. A snow-making machine used for ski areas blows a mixture of compressed air and water through a nozzle. The temperature of the mixture may initially be well above the freezing temperature of water, yet crystals of snow are formed as the mixture is ejected from the nozzle. Explain how this happens.
39. In which form of heat transfer is a medium not required?
40. Why does a good *emitter* of heat radiation appear black at room temperature?
41. Since energy is radiated by all objects, why can't we see them in the dark?
42. A number of bodies at different temperatures placed in a closed room share radiant energy and ultimately reach a common temperature. Would this thermal equilibrium be possible if good absorbers were poor emitters and poor absorbers were good emitters? Explain.
43. From the rules that a good absorber of radiation is a good radiator and a good reflector is a poor absorber, state a rule relating the reflecting and radiating properties of a surface.
44. The heat of volcanoes and natural hot springs comes from trace amounts of radioactive minerals in common rock in Earth's interior. Why isn't the same kind of rock at Earth's surface warm to the touch?

45. Even though metal is a good conductor, frost can be seen on parked cars in the early morning even when the air temperature is above freezing. Provide an explanation.
46. When there is morning frost on the grass in an open park, why is frost unlikely to be found on the ground directly beneath park benches?
47. Why is whitewash sometimes applied to the glass of florists' greenhouses in the summer?
48. On a very cold sunny day, you wear a black coat and a transparent plastic coat. Which coat should be worn on the outside for maximum warmth?
49. If the composition of the upper atmosphere were changed so that it permitted a greater amount of terrestrial radiation to escape, what effect would this have on Earth's climate?
50. Is it important to convert temperatures to the Kelvin scale when we use Newton's law of cooling? Why or why not?
51. Why is the insulation in an attic commonly thicker than the insulation in the walls of a house?
52. Suppose that, at a restaurant, you are served coffee before you are ready to drink it. In order that it be hottest when you are ready for it, should you add cream to the coffee right away or wait until you are ready to drink it?
53. If you wish to save fuel and you're going to leave your warm house for a half hour or so on a very cold day, should you turn your thermostat down a few degrees, turn it off altogether, or let it remain at the room temperature you desire?
54. If you wish to save fuel and you're going to leave your cool house for a half hour or so on a very hot day, should you turn your air-conditioning thermostat up a bit, turn it off altogether, or let it remain at the room temperature you desire?
55. As more energy from fossil fuels and other fuels is released on Earth, the overall temperature of Earth tends to rise. How does temperature equilibrium explain why Earth's temperature cannot rise indefinitely?
56. Make up a multiple-choice question that would test a classmate's understanding of the distinction between conduction and convection. Make another in which the term *radiation* is the correct answer.

PROBLEMS

1. In lab, Will burns a 0.6-g peanut beneath 50 g of water, which increases in temperature from 22°C to 50°C. The amount of heat absorbed by the water can be found with the equation $Q = cm\Delta T$, where Q is the amount of heat, c the specific heat of water, m the mass of water, and ΔT the change in the water's temperature.
   a. Assuming that 40% of the heat released makes its way to the water, show that the food value of the peanut is 3500 calories, or 3.5 Calories.
   b. What is the food value in calories per gram? In Calories per gram?
2. Radioactive decay of granite and other rocks in Earth's interior provides sufficient energy to keep the interior molten, to heat lava, and to provide warmth to natural hot springs. This is due to the average release of about 0.03 J per kilogram each year. Show that a 500°C increase in temperature for a thermally insulated chunk of granite takes about 13.3 million years. (Assume that the specific heat capacity c of granite is 800 J/kg·C°. Use the equation $Q = cm\Delta T$.)
3. In a 25°C room, hot coffee in a vacuum flask cools from 75°C to 50°C in 8 hours. Explain why you predict that its temperature after another 8 hours will be 37.5°C.
4. At a certain location, the solar power per unit area reaching Earth's surface is 200 W/m^2, averaged over a 24-hour day. If the average power requirement in your home is 3 kW and you can convert solar power to electric power with 10% efficiency, how large a collector area will you need to meet all your household energy requirements from solar energy? (Will a collector fit in your yard or on your roof?)
• 5. In lab you submerge 100 g of 40°C iron nails in 100 g of 20°C water (the specific heat of iron is 0.12 cal/g°C.) (a) Equate the heat gained by the water to the heat lost by the nails and show that the final temperature of the water becomes 22.1°C. (b) Your lab partner is surprised by the result and says that since the masses of iron and water are equal, the final water temperature should lie closer to 30°C, half-way between. What is your explanation?

CHAPTER 16 ONLINE RESOURCES

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- 16.12, 16.22

Videos

- The Secret to Walking on Hot Coals
- Air Is a Poor Conductor

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17 Change of Phase

1 Nephew John Suchocki walks barefoot without harm on hot coals (stepping quickly!). 2 Dean Baird demonstrates regelation, illustrated later in Figure 17.15. 3 Ron Hipschman at the Exploratorium removes a piece of ice from the Water Freezer exhibit. When room-temperature water was placed in the chamber and a vacuum was drawn, rapid evaporation cooled the water to ice, as we shall investigate in Figure 17.13.

A good measure of physics teacher effectiveness is the percentage of students in the school who take a course in physics. When Dean Baird began his teaching career at Rio Americano High School in Sacramento, California, in 1986, some 10% of graduates had taken a physics course. Today that percentage is more than 70%, with physics as an elective. Of the students who take Dean's Advanced Placement Physics courses, over 90% earn a passing grade of 3 or higher on the AP test. In addition to coaching science teams at his school, mentoring statewide workshops for new physics teachers, and advising the California State Board of Education regarding statewide science exams, he is the author of my physics and physical science laboratory manuals. A glance at his web site, www.phyz.org, indicates how busy a teacher can be! He is also an accomplished photographer. Dean has been recognized at the local, state, and national levels for outstanding service in physics education and was honored with its 2008 Distinguished Service Citation award by the American Association of Physics Teachers. Dean's specialties as a teacher are curricular diversity and skepticism. He mixes labs, demos, presentations, web video, and active assessment with critical thinking lessons to keep students engaged every day.

Dean loves thermal physics. He plays with hot and cold with a gusto his students love him for. He can't make snowballs in Sacramento, but in lab he can demonstrate regelation, as shown above. He shows how the metal wire slowly passes through the block of ice, refreezing as it goes, so that the ice remains intact. This chapter is about phases of matter and the changes in energy that occur whenever a change of phase occurs.

Phases of Matter

Matter around us exists in four common *phases* (or *states*). Ice, for example, is the *solid* phase of H_2O. Add energy, and you add motion to the rigid molecular structure, which breaks down to form H_2O in the *liquid* phase, water. Add more energy, and the liquid changes to the *gaseous* phase. Add still more energy, and the molecules break into ions and electrons, giving the *plasma* phase. The phase of matter depends on its temperature and the pressure that is exerted on it. Changes of phase almost always require a transfer of energy.

When water turns to a gas, we call it water vapor.

Evaporation

Water in an open pan will eventually evaporate, or dry up. The liquid that disappears becomes water vapor in the air. **Evaporation** is a change of phase from liquid to gas that occurs at the surface of a liquid.

Nearly 90% of Earth's atmospheric moisture comes from evaporation of its oceans, lakes, and rivers. The rest comes from plant transpiration.

The temperature of any substance is related to the average kinetic energy of its particles. Molecules in liquid water have a wide variety of speeds, moving about in all directions and bumping against one another. At any moment, some move at very high speeds while others barely move at all. In the next moment, the slowest molecule may become the fastest due to molecular collisions. Some gain kinetic energy while others lose kinetic energy. Molecules at the surface that gain kinetic energy by being bumped from below may have enough energy to break free from the liquid. They can leave the surface and escape into the space above the liquid. In this way, they become molecules of vapor.

The increased kinetic energy of molecules bumped hard enough to break free from the liquid comes from molecules remaining in the liquid. This is "billiard-ball physics": When balls bump into one another and some gain kinetic energy, others lose the same amount of kinetic energy. Molecules about to be propelled out of the liquid are the gainers, while the losers of energy remain in the liquid. Thus the average kinetic energy of the molecules remaining in the liquid is lowered—evaporation is a cooling process. Interestingly, the fast molecules that break free from the surface are slowed as they fly away due to their attraction to the surface. So although the water is cooled by evaporation, the air above is not correspondingly warmed by the process.

FIGURE 17.1
When wet, the cloth covering on the sides of the canteen promotes cooling.

The canteen shown in Figure 17.1 keeps cool because of evaporation when the cloth that covers the sides is kept wet. As the faster-moving water molecules break free from the cloth, the temperature of the cloth decreases. The cool wet cloth, in turn, cools the metal canteen by conduction, which, in turn, cools the water inside. So energy is transferred from the water in the canteen to the air outside. In this way, the water is cooled appreciably below the air temperature outside.

The cooling effect of evaporation is strikingly evident when some alcohol is applied to your body. The alcohol evaporates very rapidly, cooling the surface of the body quickly. The more rapid the evaporation, the faster the cooling.

When our bodies overheat, our sweat glands produce perspiration. This is part of nature's thermostat, for the evaporation of perspiration cools us and helps us to maintain a stable body temperature. Many animals have very few sweat glands or none at all and must cool themselves by other means (Figures 17.2 and 17.3).

FIGURE 17.2
Like other dogs, Tammy's dogs have no sweat glands (except between their toes). They cool by panting. In this way, evaporation occurs in the mouth and within the bronchial tract.

FIGURE 17.3
Pigs, having no sweat glands, wallow in the mud to cool themselves.

The rate of evaporation is greater at higher temperatures because there is a greater proportion of molecules having sufficient kinetic energy to escape the liquid. Water evaporates at lower temperatures, too, but at a lower rate. A puddle of water, for example, may slowly evaporate to dryness on a cool day.

Even frozen water "evaporates." This form of evaporation, in which molecules are bumped directly from a solid (ice or snow) to a gaseous phase bypassing the liquid phase, is called **sublimation.** Because water molecules are so tightly held in the solid phase, frozen water does not evaporate (sublime) as readily as liquid water. Sublimation, however, does account for the loss of significant portions of snow and ice, and it is especially high on sunny days in dry climates.

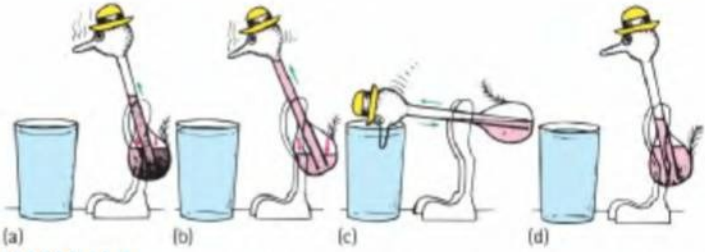


FIGURE 17.4
The toy drinking bird operates by the evaporation of ether inside its body and by the evaporation of water from the outer surface of its head. The lower body contains liquid ether, which evaporates rapidly at room temperature. As it (a) vaporizes, it (b) increases pressure (inside arrows), which pushes ether up the tube. Ether in the upper part does not vaporize because the head is cooled by the evaporation of water from the outer felt-covered beak and head. When the weight of ether in the head is sufficient, the bird (c) pivots forward, permitting the ether to flow back to the body. Each pivot wets the felt surface of the beak and head, and (d) the cycle is repeated.

CHECK POINT

Would evaporation be a cooling process if molecules of every speed had an equal chance to escape from the liquid surface?

Check Your Answer

No. If molecules of all speeds escaped equally easily from the surface, the molecules left behind would have the same range of speeds as before any escaped, and there would be no change of the liquid's temperature. When only the faster molecules can break free, those remaining are slower, and the liquid becomes cooler.

Condensation

The opposite of evaporation is **condensation**—the changing of a gas to a liquid. When gas molecules near the surface of a liquid are attracted to the liquid, they strike the surface with increased kinetic energy and become part of the liquid. In collisions with low-energy molecules in the liquid, excess kinetic energy is shared with the liquid, increasing the liquid temperature. Condensation is a warming process.

PhysicsPlace.com™
Video
Condensation Is a Warming Process

A dramatic example of the warming that results from condensation is the energy released by steam when it condenses—a painful experience if it condenses on you. That's why a steam burn is much more damaging than a burn from boiling water of the same temperature; the steam releases considerable energy when it condenses to a liquid and wets the skin. This energy release by condensation is utilized in steam-heating systems.

FIGURE 17.5

Internal energy is released by steam when it condenses inside the "radiator."

Steam is water vapor at a high temperature, usually 100°C or more. Cooler water vapor also releases energy when it condenses. In taking a shower, for example, you're warmed by condensation of vapor in the shower region—even vapor from a cold shower—if you remain in the moist shower area. You quickly sense the difference if you step outside. Away from the moisture, net evaporation takes place quickly and you feel chilly. But, if you remain in the shower stall, even with the water turned off, the warming effect of condensation counteracts the cooling effect of evaporation. If as much moisture condenses as evaporates, you feel no change in body temperature. If condensation exceeds evaporation, you are warmed. If evaporation exceeds condensation, you are cooled. So now you know why you can dry yourself with a towel much more comfortably if you remain in the shower stall. To dry yourself thoroughly, you can finish the job in a less moist area.

Spend a July afternoon in dry Tucson or Phoenix where evaporation is appreciably greater than condensation. The result of this pronounced evaporation is a much cooler feeling than you would experience in a same-temperature July afternoon in New York City or New Orleans. In these humid locations, condensation noticeably counteracts evaporation, and you feel the warming effect as vapor in the air condenses on your skin. You are literally being bombarded by the impact of H_2O molecules in the air slamming into you. Put more mildly, you are warmed by the condensation of vapor in the air upon your skin.

FIGURE 17.6

If you're chilly outside the shower stall, step back inside and be warmed by the condensation of the excess water vapor.

CHECK POINT

If the water level in a dish of water remains unchanged from one day to the next, can you conclude that no evaporation or condensation has occurred?

Check Your Answer

Not at all, for there is much activity taking place at the molecular level. Both evaporation and condensation occur continuously. The constant water level simply indicates equal rates of both, not that nothing's happening. When just as many molecules evaporate as condense, no *net* evaporation or condensation occurs. The two processes cancel each other.

CONDENSATION IN THE ATMOSPHERE

There is always some water vapor in the air. A measure of the amount of this water vapor is called *humidity* (mass of water per volume of air). Weather reports often use the term *relative humidity*—the ratio of the amount of water vapor currently in the air at a given temperature to the largest amount of water vapor the air can contain at that temperature.[1]

Air that contains as much vapor as it can is saturated. Saturation occurs when the air temperature drops and water-vapor molecules in the air begin condensing. Water molecules tend to stick together. Because of their normally high average speeds in air, however, most water molecules do not stick together when they collide. Instead, these fast-moving molecules bounce back when they collide and therefore remain in the

[1]Relative humidity is a good indicator of comfort. For most people, conditions are ideal when the temperature is about 20°C and the relative humidity is between 50% and 60%. When the relative humidity is higher, moist air feels "muggy" as condensation counteracts the evaporation of perspiration.

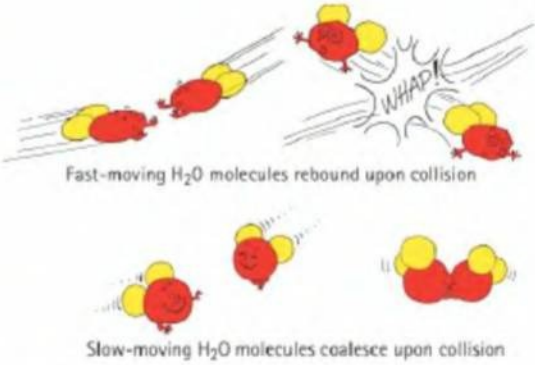


FIGURE 17.7
Condensation of water vapor.

fyi

- Does humidity make us feel warmer or colder—or both? If you're already cold, more humidity makes you feel colder. If you're already hot, more humidity makes you feel hotter. At pleasant temperatures, a little humidity makes us more comfortable.

gaseous phase. Some water molecules move more slowly than average, though, and these slow ones are more likely to stick to one another upon collision (Figure 17.7). (This can be understood by thinking of a fly making a grazing contact with sticky flypaper. At a high speed, the fly has enough momentum and energy to rebound from the flypaper into the air without sticking, but at a low speed, it is more likely to get stuck.) So slow-moving water molecules are the ones most likely to condense and to form droplets of water in saturated air. Because lower air temperatures are characterized by slower-moving molecules, saturation and condensation are more likely to occur in cool air than in warm air. Warm air can contain more water vapor than cold air.

CHECK POINT

Why does dew form on the surface of a cold soft-drink can?

Check Your Answer

Water vapor in the warm air is chilled when it makes contact with the cold can. What is the fate of chilled water molecules? They are slower when they collide, and they stick. This is condensation, which is why the surface of a cold can is wet.

Clouds are normally denser than air. So why don't clouds fall from the sky? The answer is, clouds *do* fall! A stable cloud falls as fast as the upwelling of air beneath it, so it remains stationary. If it falls anyway, we call it fog.

FIGURE 17.8
Why is it common for clouds to form where there are updrafts of warm moist air?

FOG AND CLOUDS

Warm air rises. As it rises, it expands. As it expands, it chills. As the air chills, water-vapor molecules too small to be visible are slowed. Lower-speed molecular collisions result in water molecules sticking together. Water molecules combine with tiny particles of dust, salt, and smoke in the air to form cloud droplets that grow and develop into clouds. If these particles are not present, we can stimulate cloud formation by "seeding" the air with appropriate particles or ions.

Warm breezes blow over the ocean and become moist. When the moist air moves from warmer to cooler waters or from warm water to cool land, it chills. As it chills, water-vapor molecules begin sticking rather than bouncing off one another. Condensation takes place near ground level, and we have fog. The difference between fog and a cloud is basically altitude. Fog is a cloud that forms near the ground. Flying through a cloud is much like driving through fog. Check the web for different kinds of fog.

Boiling

Under the right conditions, evaporation can take place beneath the surface of a liquid, forming bubbles of vapor that are buoyed to the surface, where they escape. This change of phase *throughout* a liquid rather than only at the

surface is called **boiling.** Bubbles in the liquid can form only when the pressure of the vapor within the bubbles is great enough to resist the pressure of the surrounding liquid. Unless the vapor pressure is great enough, the surrounding pressure will collapse any bubbles that tend to form. At temperatures below the boiling point, the vapor pressure in bubbles is not great enough, so bubbles do not form until the boiling point is reached. At this temperature—100°C for water at atmospheric pressure—molecules are energetic enough to exert a vapor pressure as great as the pressure of the surrounding water (which is due mainly to atmospheric pressure).

It is common to say that we boil water, meaning that we apply heat to it. Actually, the boiling process cools the water.

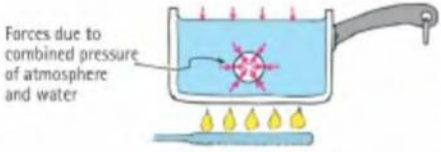


FIGURE 17.9
The motion of water-vapor molecules in the bubble of steam (much enlarged) creates a gas pressure (called the *vapor pressure*) that counteracts the atmospheric and water pressure against the bubble.

If pressure is increased, the molecules in the vapor must move faster to exert enough pressure to keep the bubble from collapsing. Extra pressure can be provided either by going deeper below the surface of the liquid (as in geysers, discussed below) or by increasing the air pressure above the liquid's surface—which is how a pressure cooker works. A pressure cooker has a tight-fitting lid that does not allow vapor to escape until it reaches a certain pressure greater than normal air pressure. As the evaporating vapor builds up inside the sealed pressure cooker, pressure on the surface of the liquid increases, which at first prevents boiling. Bubbles that would normally form are crushed. Continued heating increases the temperature beyond 100°C. Boiling does not occur until the vapor pressure within the bubbles overcomes the increased pressure on the water. The boiling point is raised. Conversely, lowered pressure (as at high altitudes) decreases the boiling point of the liquid. So we see that boiling depends not only on temperature but on pressure as well.

FIGURE 17.10
The tight lid of a pressure cooker holds pressurized water vapor above the water's surface, which inhibits boiling. Water therefore boils at a temperature greater than 100°C.

At high altitudes, water boils at a lower temperature. For example, in Denver, Colorado, the Mile-High City, water boils at 95°C instead of at the 100°C boiling temperature characteristic of sea level. If you try to cook food in boiling water of a lower temperature, you must wait a longer time for proper cooking. A 3-minute boiled egg in Denver is yucky. If the temperature of the boiling water is too low, food will not cook at all. It is important to note that it is the high temperature of the water that cooks the food, not the boiling process itself.

GEYSERS

A geyser is a periodically erupting natural pressure cooker. It consists of a long, narrow, vertical crevice into which underground streams seep (Figure 17.11). The column of water is heated by volcanic heat below to temperatures exceeding 100°C. This can happen because the relatively deep vertical column of water exerts pressure on the deeper water, thereby increasing the boiling point. The narrowness of the shaft shuts off convection currents, which allows the deeper portions to become considerably hotter than the water surface. Water at the surface is less than 100°C, but the water temperature below, where it is being heated, is more than 100°C, high enough to permit boiling before water at the top reaches the boiling point. Boiling therefore begins near the bottom, where the rising bubbles push out the column of water above, and the eruption starts. As the water gushes out, the pressure on the remaining water is reduced. It then boils rapidly and erupts with great force. When the eruption subsides, the crevices fill with new water and the cycle repeats.

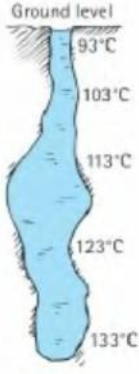


FIGURE 17.11
A geyser of the Old Faithful type.

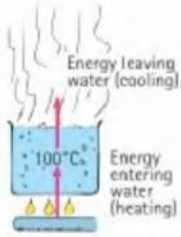


FIGURE 17.12
Heating warms the water, and boiling cools it.

Mountaineering pioneers in the 19th century, without altimeters, used the boiling point of water to determine their altitudes.

PhysicsPlace.com™
Video
Boiling Is a Cooling Process

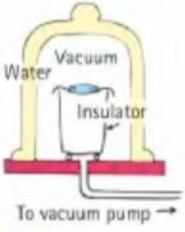


FIGURE 17.13
Apparatus to demonstrate that water will freeze and boil at the same time in a vacuum. A gram or two of water is placed in a dish that is insulated from the base by a polystyrene cup.

PhysicsPlace.com™
Video
Pressure Cooker: Boiling and Freezing at the Same Time

BOILING IS A COOLING PROCESS

Evaporation is a cooling process. So is boiling. At first thought, this may seem surprising—perhaps because we usually associate boiling with heating. But heating water is one thing; boiling is another. When 100°C water at atmospheric pressure is boiling, its temperature remains constant. That means it cools as fast as it warms. By what mechanism? By boiling. If cooling didn't take place, continued input of energy to a pot of boiling water would result in a continued increase in temperature. The reason a pressure cooker reaches higher temperatures is because it prevents normal boiling, which, in effect, prevents cooling.

CHECK POINT

Since boiling is a cooling process, would it be a good idea to cool your hot and sticky hands by dipping them into boiling water?

Check Your Answer

No, no, no! When we say boiling is a cooling process, we mean that the water (not your hands!) is being cooled relative to the higher temperature it would attain otherwise. Because of cooling, it remains at 100°C instead of getting hotter. A dip in 100°C water would be a big ouch!

BOILING AND FREEZING AT THE SAME TIME

We usually boil water by the application of heat. But we can boil water by the reduction of pressure. We can dramatically show the cooling effect of evaporation and boiling when room-temperature water is placed in a vacuum jar (Figure 17.13). If the pressure in the jar is slowly reduced by a vacuum pump, the water will start to boil. The boiling process removes heat from the water left in the dish, which cools to a lower temperature. As the pressure is further reduced, more and more of the molecules have enough speed to boil away. Continued boiling results in a lowering of temperature until the freezing point of approximately 0°C is reached. Continued cooling by boiling causes ice to form over the surface of the bubbling water. Boiling and freezing are taking place at the same time! This must be witnessed to be appreciated. Frozen bubbles of boiling water are a remarkable sight.[2]

If you spray some drops of coffee into a vacuum chamber, they, too, will boil until they freeze. Even after they are frozen, the water molecules will continue to evaporate into the vacuum until little crystals of coffee solids are left. This is how freeze-dried coffee is made. The low temperature of this process tends to keep the chemical structure of coffee solids from changing. When hot water is added, much of the original flavor of the coffee is restored. Boiling really is a cooling process!

Melting and Freezing

Suppose that you are holding hands with someone, and both of you start jumping around randomly. The more violently you jump, the more difficult holding hands would become. If you were to jump violently enough, holding hands would be impossible. Something like this happens to the molecules of a solid when it is heated. As heat is absorbed, the molecules vibrate more and more violently in a less ordered manner. If enough heat is absorbed, the attractive forces between the molecules will no longer be able to hold them together. The solid melts.

[2]"Water Freezer" is my favorite exhibit at the Exploratorium in San Francisco. Room-temperature water is placed in a vacuum chamber where it rapidly boils and turns to ice. The exhibit is featured in the opening photograph of this chapter.

Freezing is the reverse of this process. Substances freeze at exactly the same temperature as they melt. As energy is withdrawn from a liquid, molecular motion diminishes until finally the molecules, on the average, are moving slowly enough so that the attractive forces between them are able to cause cohesion. The molecules then vibrate about fixed positions and form a solid.

A pure substance has a definite melting or freezing point at any given pressure. The addition of any impurities will lower this temperature. Hence we can use the freezing or melting point as an indicator of the purity of a substance. For example, at atmospheric pressure, water freezes at 0°C—unless such substances as sugar or salt are dissolved in it. Then the freezing point is lower. In the case of salt in water, chlorine ions grab electrons from the hydrogen atoms in H_2O and impede crystal formation. The result of this interference by "foreign" ions is that slower motion is required for the formation of the six-sided ice-crystal structures. As ice crystals form, the interference is intensified because the proportion of "foreign" molecules or ions among nonfused water molecules increases. Connections become more and more difficult. Only when the water molecules move slowly enough for attractive forces to play an unusually large part in the process can freezing be completed. The ice first formed is almost always pure H_2O.

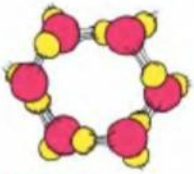


FIGURE 17.14
The open structure of pure ice crystals that normally fuse at 0°C. When impurities are introduced, crystal formation is interrupted, and the freezing temperature is lowered.

REGELATION

Because H_2O molecules form open structures in the solid phase (Figure 17.14), the application of pressure can cause ice to melt. The crystals are simply crushed to the liquid phase. (The temperature of the melting point is only slightly lowered, by 0.007°C for each additional atmosphere of added pressure.) When the pressure is removed, molecules crystallize and refreezing occurs. This phenomenon of melting under pressure and freezing again when the pressure is reduced is called **regelation.** It is one of the properties of water that distinguishes it from other materials.

Regelation is nicely illustrated in Figure 17.15 (and in the opening photo of this chapter). A fine copper wire with weights suspended from its ends is hung over a block of ice.[3] The wire will slowly cut through the ice, but its track will be left full of ice. So the wire and the weights will fall to the floor, leaving the ice a solid block.

Making snowballs is a good example of regelation. When we compress the snow with our hands, we cause a slight melting of the ice crystals; when pressure is removed, refreezing occurs and binds the snow together. Making snowballs is difficult in very cold weather because the pressure we can apply is not enough to melt the snow.

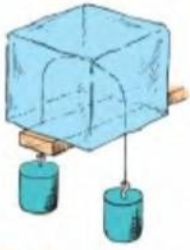


FIGURE 17.15
Regelation. The wire gradually passes through the ice without cutting it in half.

Energy and Changes of Phase

If we continually add heat to a solid or a liquid, the solid or liquid will eventually change phase. A solid will liquefy, and a liquid will vaporize. Energy input is required for both liquefaction of a solid and vaporization of a liquid. Conversely, energy must be extracted from a substance to change its phase in the direction from gas to liquid to solid (Figure 17.16).

The cooling cycle of a refrigerator nicely employs the concepts shown in Figure 17.16. A refrigerator is a **heat pump** that "pumps" heat from a cold environment to a warm one. This is accomplished by a liquid of low boiling point, the refrigerant, which is pumped into the cooling

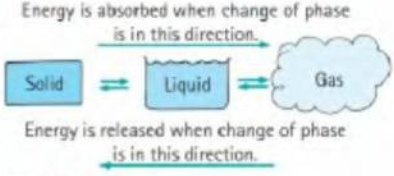


FIGURE 17.16
INTERACTIVE FIGURE
Energy changes with change of phase.

[3]Changes of phase are occurring as ice melts and the water refreezes. Energy is needed for these changes. When the water immediately above the wire refreezes, it gives up energy. How much? Sufficient to melt an equal amount of ice immediately under the wire. This energy must be conducted through the thickness of the wire. Hence, this demonstration requires that the wire be an excellent conductor of heat. String, for example, won't do.

unit, where it turns into a gas. When changing phase from liquid to gas, heat is drawn from the interior where the food is. The gas, with its added energy, is directed outside to condensation coils. At the coils, heat is released into the outside air as the gas condenses to the liquid phase again. A pump forces the refrigerant through the system, where it is made to undergo cyclic phase changes of vaporization and condensation. The next time you're near a refrigerator, place your hand near the condenser coils in the rear, or at the bottom, and you'll feel the air that has been warmed by the energy extracted from inside.

Heat pumps of various designs are increasingly being utilized to heat (and cool) homes. They typically use less energy than fossil fuel to heat a home. Heat pumps function like a standard refrigerator. Whereas a refrigerator unavoidably warms a room by removing heat from food inside and depositing it at its condensation coils, heat pumps warm a room *deliberately*. Instead of extracting heat from food, they can extract heat from water that is pumped in from nearby underground pipes.[5] Water underground is relatively warm. Subsoil temperatures depend on latitude. In the Midwest and the Central Plains, subsoil temperature below a meter deep is about 13°C (55°F) year-round—warmer than the air in wintertime. Underground pipes outside the home carry 13°C water to a heat pump inside the home. The vaporized refrigerant is then pumped to condensation coils, where it condenses and gives off heat to warm the home. The cooled water is returned to the ground outside, where it warms to ground temperature and repeats the cycle.

A refrigerator is a heat pump. It transfers heat out of a cold environment and into a warm environment. An air conditioner is also a heat pump, with the "cold" environment being indoors and the "warm" environment being outdoors. In both cases, external energy operates the device.

In summer, the process can be reversed, turning the heat pump into a cooler. An air conditioner is itself a heat pump. Employing the same principles, it simply pumps heat energy from the cooler inside of a home to the warmer outside on a summer day. In a crowded city, the effect of thousands of air conditioners operating at once can be to elevate the outdoor temperature somewhat.

So we see that a solid must absorb energy to melt, and a liquid must absorb energy to vaporize. Conversely, a gas must release energy to liquefy, and a liquid must release energy to solidify.

CHECK POINT

When H_2O in the vapor phase condenses, is the surrounding air warmed or cooled?

Check Your Answer

The change of phase is from vapor to liquid, which releases energy (Figure 17.16), so the surrounding air is warmed. Look ahead to Figure 17.7 for another way to see this. Removal of slower molecules from the air raises the average kinetic energy of remaining molecules—hence the warming. This goes hand in hand with water cooling when faster-moving molecules evaporate—where the ones remaining in the liquid phase have a lowered average kinetic energy.

Let's look, in particular, at the changes of phase that occur in H_2O. To make the numbers simple, consider a 1-g piece of ice at a temperature of −50°C in a closed container that is placed on a stove to heat. A thermometer in the container reveals a slow increase in temperature up to 0°C. Then an amazing thing happens. The temperature remains at 0°C even though heat input continues. Rather than getting warmer, the ice begins to melt. In order for the whole gram of ice to melt, 80 calories (335 joules) of energy is absorbed by the ice, not even raising its temperature a

Water's heat of vaporization is huge. The energy needed to vaporize a quantity of boiling water is nearly 7 times the energy needed to melt the same amount of ice.

[5]Depending on the amount of heat needed, about 200 to 500 meters of piping is normally placed outside the home in trenches about 1.0 to 1.8 meters beneath the ground surface. The configuration of the piping may be horizontal loops or deeper-reaching vertical U-shapes.

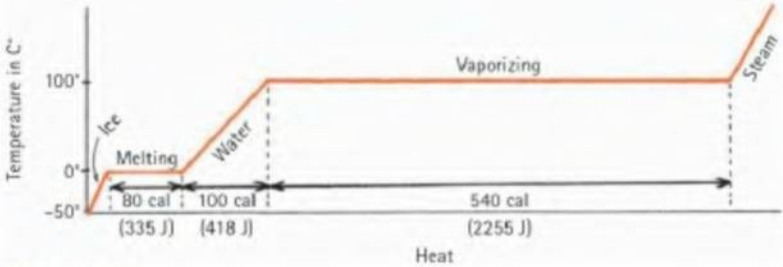


FIGURE 17.17

A graph showing the energy involved in the heating and the changes of phase of 1 g of H_2O.

fraction of a degree. Only when all the ice melts will each additional calorie (4.187 joules) absorbed by the water increase its temperature by 1°C until the boiling temperature, 100°C, is reached. Again, as energy is added, the temperature remains constant while more and more of the gram of water is boiled away and becomes steam. The water must absorb 540 calories (2260 joules) of heat energy to vaporize the whole gram. Finally, when all the water has become steam at 100°C, the temperature begins to rise once more. It will continue to rise as long as energy is added. This process is graphed in Figure 17.17.

The 540 calories (2260 joules) required to vaporize a gram of water is a large amount of energy—much more than is required to transform a gram of ice at absolute zero to boiling water at 100°C. Although the molecules in steam and boiling water at 100°C have the same average kinetic energy, steam has more potential energy because the molecules are relatively free of each other and are not bound together as in the liquid phase. Steam contains a vast amount of energy that can be released during condensation.

So we see that the energies required to melt ice (80 calories, or 335 joules, per gram) and to boil water (540 calories, or 2260 joules, per gram) are the same as the amounts released when the phase changes are in the opposite direction. The processes are reversible. The amount of energy required to change a unit mass of any substance from solid to liquid (and vice versa) is called the **latent heat of fusion** for the substance. (The word *latent* reminds us that this is thermal energy hidden from the thermometer.) For water, we have seen that this is 80 calories per gram (335 joules per gram). The amount of energy required to change any substance from liquid to gas (and vice versa) is called the **latent heat of vaporization** for the substance. For water, this is a whopping 540 calories per gram (2260 joules per gram).[6] It so happens that these relatively high values are due to the strong forces between water molecules—hydrogen bonds.

The large value of 540 calories per gram for the latent heat of vaporization of water explains why, under some conditions, hot water will freeze faster than warm water.[7] This phenomenon is evident when a thin layer of water is distributed over a large area—like when you wash a car with hot water on a cold winter day or flood a skating rink with hot water, which melts, smoothes out the rough spots, and refreezes quickly. The rate of cooling by rapid evaporation is very high because each evaporating gram of water draws at least 540 calories from the water left behind. This is an enormous amount of energy compared with the 1 calorie per Celsius

Heat of vaporization is either the energy required to separate molecules from the liquid phase or the energy released when gas condenses to the liquid phase.

FIGURE 17.18

On a cold day, hot water may freeze faster than warm water due to the energy that leaves the hot water during rapid evaporation.

Heat of fusion is either the energy needed to separate molecules from the solid phase or the energy released when bonds form in a liquid that change it to the solid phase.

[6]In SI units, the heat of vaporization of water is expressed as 2.260 megajoules per kilogram (MJ/kg), and the heat of fusion of water is 0.335 MJ/kg.

[7]Boiling-hot water will not freeze before cold water does, but it will freeze before moderately hot water does. For example, boiling-hot water will freeze before water warmer than about 60°C, but not before water cooler than 60°C. Try it and see.

FIGURE 17.19
Paul Ryan tests the hotness of molten lead by dragging his wetted finger through it.

FIGURE 17.20
Professor Dave Willey walks barefoot across red-hot wooden coals without harm.

degree that is drawn from each gram of water that cools by thermal conduction. Evaporation is truly a cooling process.

CHECK POINT

1. How much energy is transferred when 1 g of steam at 100°C condenses to water at 100°C?
2. How much energy is transferred when 1 g of boiling water at 100°C cools to ice water at 0°C?
3. How much energy is transferred when 1 g of ice water at 0°C freezes to ice at 0°C?
4. How much energy is transferred when 1 g of steam at 100°C turns to ice at 0°C?

Check Your Answers

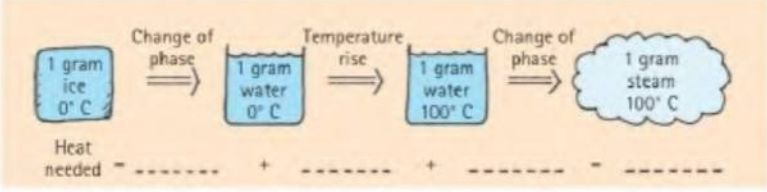
1. One gram of steam at 100°C transfers 540 calories of energy when it condenses to become water at the same temperature.
2. One gram of boiling water transfers 100 calories when it cools 100°C to become ice water.
3. One gram of ice water at 0°C transfers 80 calories to become ice at 0°C.
4. One gram of steam at 100°C transfers to the surroundings a grand total of the above values, 720 calories, to become ice at 0°C.

You dare not touch your dry finger to a hot skillet on a hot stove, but you can certainly do so without harm if you first wet your finger and touch the skillet very briefly. You can even touch it a few times in succession as long as your finger remains wet. This is because energy that ordinarily would go into burning your finger goes instead into changing the phase of the moisture on your finger. The energy converts the moisture to a vapor, which then provides an insulating layer between your finger and the skillet. Similarly, you are able to judge the hotness of a hot clothes iron if you touch it very briefly with a wet finger.

Former supervisor Paul Ryan of the Department of Public Works in Malden, Massachusetts, years ago used molten lead to seal pipes in certain plumbing operations. He startled onlookers by dragging his finger through molten lead to judge its hotness (Figure 17.19). He was sure that the lead was very hot and that his finger was thoroughly wet before doing this. (Do not try this on your own, for if the lead is not hot enough it will stick to your finger and you could be seriously burned!) Similarly, firewalkers walking barefoot on red-hot coals often prefer wet feet (others such as Dave Willey in Figure 17.20 prefer dry feet, claiming hot coals more readily stick to wet feet—OUCH!). The low conductivity of wooden coals, however (as discussed in the previous chapter), is the principal reason the feet of barefoot firewalkers are not burned.

Practicing Physics

Fill in the number of calories or joules at each step in changing the phase of 1 g of 0°C ice to 100°C steam.



CHECK POINT

Suppose that 4 g of boiling water is poured onto a cold surface and that 1 g rapidly evaporates. If evaporation takes 540 calories from the remaining 3 g of water and no other heat transfer takes place, what will be the temperature of the remaining 3 g?

Check Your Answer

The remaining 3 g will turn to 0°C ice. 540 calories from 3 g means each gram gives up 180 calories. 100 calories from a gram of boiling water reduces its temperature to 0°C, and removal of 80 more calories turns it to ice. This is why hot water so quickly turns to ice in a freezing-cold environment. (In practice, because of other heat transfer, more than 1 g of the original 4 g would need to evaporate to freeze the rest.)

SUMMARY OF TERMS

Evaporation The change of phase from liquid to gaseous.
Sublimation The change of phase from solid to gaseous, bypassing the liquid phase.
Condensation The change of phase from gaseous to liquid.
Boiling Rapid evaporation that takes place within a liquid as well as at its surface.
Regelation The process of melting under pressure and the subsequent refreezing when the pressure is removed.
Heat pump A device that transfers heat out of a cool environment and into a warm environment.
Latent heat of fusion The amount of energy required to change a unit mass of a substance from solid to liquid (and released in the reversed process).
Latent heat of vaporization The amount of energy required to change a unit mass of a substance from liquid to gas (and released in the reverse process).

REVIEW QUESTIONS

Phases of Matter

1. What are the four common phases of matter?

Evaporation

2. Do the molecules in a liquid all have about the same speed, or do they have a wide variety of speeds?
3. What is evaporation, and why is it a cooling process? Exactly what is it that cools?
4. Why does warmer water evaporate more readily than cold water?
5. What is sublimation?

Condensation

6. Distinguish between condensation and evaporation.
7. Why is a steam burn more damaging than a burn from boiling water of the same temperature?
8. Why do you feel uncomfortably warm on a hot and humid day?

Condensation in the Atmosphere

9. Distinguish between humidity and relative humidity.
10. Why does water vapor in the air condense when the air is chilled?

Fog and Clouds

11. Why does warm, moist air form clouds when it rises?
12. What is the basic difference between a cloud and fog?

Boiling

13. Distinguish between evaporation and boiling.
14. Does increased atmospheric pressure increase or decrease the boiling point of water? Why is this so?
15. Is it the boiling of water or the higher temperature of water that cooks food faster in a pressure cooker?

Geysers

16. Why will water at the bottom of a geyser not boil when it is at 100°C?
17. What happens to the water pressure at the bottom of a geyser when some of the water above gushes out?

Boiling Is a Cooling Process

18. The temperature of boiling water doesn't increase with continued energy input. Why is this evidence that boiling is a cooling process?

Boiling and Freezing at the Same Time

19. When will water boil at a temperature of less than 100°C?
20. What evidence can you cite for the claim that water can boil at a temperature of 0°C?

Melting and Freezing

21. Why does increasing the temperature of a solid make it melt?
22. Why does decreasing the temperature of a liquid make it freeze?

23. Why does freezing of water not occur at 0°C when foreign ions are present?

Regelation

24. What happens to the hexagonal open structure of ice when sufficient pressure is applied to it?
25. Why does a wire not simply cut a block of ice in two when it passes through the ice?

Energy and Changes of Phase

26. Does a liquid release energy or absorb energy when it changes into a gas?
27. Does a liquid release energy or absorb energy when it changes into a solid?
28. Is heat discharged at the back of a refrigerator and by a heat pump given off by vaporization of the refrigerating fluid or by condensation?
29. How many calories are needed to change the temperature of 1 g of water by 1°C? To melt 1 g of ice at 0°C? To vaporize 1 g of boiling water at 100°C?
30. Cite two reasons why firewalkers don't burn their wetted feet when walking barefoot on red-hot coals.

PROJECTS

1. Place a Pyrex funnel mouth-down in a saucepan full of water so that the narrow tube of the funnel protrudes above the water. Rest a part of the funnel on a nail or a coin so that water can get under it. Place the pan on a stove and watch the water as it begins to boil. Where do the bubbles form first? Why? As the bubbles rise, they expand rapidly and push water ahead of them. The funnel confines the water, which is forced up the tube and driven out at the top. Now do you know how a geyser and a coffee percolator work?

2. Watch the spout of a teakettle of boiling water. Notice that you cannot see the steam that issues from the spout. The cloud that you see farther away from the spout is not steam but condensed water droplets. Now hold the flame of a candle in the cloud of condensed steam. Can you explain your observations?
3. You can make rain in your kitchen. Put a cup of water in a Pyrex saucepan or a glass coffeemaker and heat it slowly over a low flame. When the water is warm, place a saucer filled with ice cubes on top of the container. As the water below is heated, droplets form at the bottom of the cold saucer and combine until they are large enough to fall, producing a steady "rainfall" as the water below is gently heated. How does this resemble, and how does it differ from, the way in which natural rain is formed?

4. Measure the temperature of boiling water and the temperature of a boiling solution of salt and water. How do they compare?
5. Do as Dean Baird demonstrates in the chapter-opener photo, or as the sketch shows, and suspend a heavy weight by copper wire over an ice cube. In a matter of minutes, the wire will be pulled through the ice. The ice will melt beneath the wire and refreeze above it, leaving a visible path if the ice is clear.

6. Place a tray of boiling-hot water and a tray of water from a hot-water tap to the same depth in a freezer. See which water will freeze first.
7. Write a letter to Grandma and tell her why bringing water to a boil when she's making tea is actually a process that *cools* the water. Explain how she could convince her teatime friends of this intriguing concept.

EXERCISES

1. Alcohol evaporates more quickly than water at the same temperature. Which produces more cooling—alcohol or the same amount of water on your skin?
2. You can determine wind direction by wetting your finger and holding it up in the air. Explain.
3. When you step out of a swimming pool on a hot, dry day in the Southwest, you feel quite chilly. Why?
4. Why is sweating an efficient mechanism for cooling off on a hot day?
5. Why does blowing over hot soup cool the soup?
6. Can you give two reasons why pouring a cup of hot coffee into a saucer results in faster cooling?
7. What happens to the temperature of a pan of water when evaporation exceeds condensation?
8. What is the source of energy that keeps the dunking bird in Figure 17.4 operating?
9. An inventor claims to have developed a new perfume that lasts a long time because it doesn't evaporate. Comment on this claim.
10. Pretend that all the molecules in a liquid have the same speed, not random speeds. Would evaporation of this liquid cause the remaining liquid to be cooled? Explain.
11. Does a common electric fan cool the air in a room? If not, then why is it used in an overly warm room?
12. Porous canvas bags filled with water are used by travelers in hot weather. When the bags are slung on the outside of a fast-moving car, the water inside is cooled considerably. Explain.
13. Why will wrapping a bottle in a wet cloth at a picnic often produce a cooler bottle than placing the bottle in a bucket of cold water?
14. The human body can maintain its customary temperature of 37°C on a day when the temperature is above 40°C. How is this done?
15. Double-pane windows have nitrogen gas or very dry air between the panes. Why is ordinary air a poor idea?
16. Why are icebergs often surrounded by fog?

17. How does Figure 17.7 help explain the moisture that forms on the inside of car windows when you're parking with your date on a cool night?
18. You know that the windows in your warm house get wet on a cold day. But can moisture form on the windows if the interior of your house is cold on a hot day? How is this different?
19. On freezing days, frost often forms on windows. Why is there usually more frost on the bottom portions of the windows?
20. Why do clouds often form above mountain peaks? (*Hint:* Consider the updrafts.)
21. Why will clouds tend to form above either a flat or a mountainous island in the middle of the ocean? (*Hint:* Compare the specific heat capacity of the land with that of the water and the subsequent convection currents in the air.)
22. A great amount of water vapor changes phase to become water in the clouds that form a thunderstorm. Does this release thermal energy or absorb it?
23. When can you add heat to something without raising its temperature?
24. When can you withdraw heat from something without lowering its temperature?
25. Why does the temperature of boiling water remain the same as long as the heating and boiling continue?
26. Why do vapor bubbles in a pot of boiling water increase in size as they rise in the water?
27. Why does the boiling temperature of water decrease when the water is under reduced pressure, such as when it is at a higher altitude?
28. Place a jar of water on a small stand within a saucepan of water so that the bottom of the jar is held above the bottom of the pan. When the pan is placed on a stove, the water in the pan will boil, but not the water in the jar. Why?
29. Hydrothermal vents are openings in the ocean floor that discharge very hot water. Water emerging at nearly 280°C from one such vent off the Oregon coast, some 2400 m beneath the surface, is not boiling. Provide an explanation.
30. Water will boil spontaneously in a vacuum—on the surface of the Moon, for example. Could you cook an egg in this boiling water? Explain.
31. Our inventor friend proposes a design for cookware that will allow boiling to occur at a temperature less than 100°C so that food can be cooked with less energy consumption. Comment on this idea.
32. What can go wrong if you grasp the handle of a hot skillet with a wet thin dishcloth?
33. How can water be brought to a boil without heating it?
34. If water that boils due to reduced pressure is not hot, then is ice formed by the reduced pressure not cold? Explain.
35. Your instructor hands you a closed flask partly filled with room-temperature water. When you hold it, the heat transfer between your bare hands and the flask causes the water to boil. Quite impressive! How is this accomplished?
36. When you boil potatoes, will your cooking time be reduced with vigorously boiling water instead of gently boiling water? (Directions for cooking spaghetti call for vigorously boiling water—not to lessen cooking time but to prevent something else. If you don't know what it is, ask a cook.)
37. Why does placing a lid over a pot of water on a stove shorten the time for the water to come to a boil, whereas, after the water is boiling, the use of a lid only slightly shortens the cooking time?
38. In the power plant of a nuclear submarine, the temperature of the water in the reactor is above 100°C. How is this possible?
39. Explain why the eruptions of many geysers repeat with notable regularity.
40. Why does the water in a car radiator sometimes boil explosively when the radiator cap is removed?
41. Can ice be colder than 0°C? What is the temperature of an ice–water mixture?
42. Why is very cold ice "sticky"?
43. How does the freezing point of a liquid compare with its melting point?
44. People who live where snowfall is common will tell you that air temperatures are higher when it's snowing than when it's clear. Some misinterpret this by stating that snowfall can't occur on very cold days. Explain this misinterpretation.
45. How might water be desalinized by freezing?
46. Would regelation occur if ice crystals did not have an open structure? Explain.
47. A piece of metal and an equal mass of wood are both removed from a hot oven at equal temperatures and are dropped onto blocks of ice. The metal has a lower specific heat capacity than the wood. Which will melt more ice before cooling to 0°C?
48. How does melting ice change the temperature of the surrounding air?
49. When you step inside a warm ski lodge on a cold day, you find your eyeglasses fog. Why does this occur?
50. What accounts for the bulged ends of a can of soda that has been frozen?
51. Why is half-frozen fruit punch always sweeter than completely melted fruit punch?
52. Air-conditioning units contain no water whatever, yet it is common to see water dripping from them when they're operating on a hot day. Explain.
53. Is it condensation or vaporization that occurs on the warm outside coils of an operating air conditioner?
54. Some old-timers found that when they wrapped newspaper around the ice in their iceboxes, melting was inhibited. Discuss the advisability of this practice.
55. When ice in a pond melts, what effect does this have on the temperature of the nearby air?
56. Why is it that a tub of water placed in a farmer's canning cellar helps prevent canned food from freezing in cold winters?
57. Why will spraying fruit trees with water before a frost help to protect the fruit from freezing?
58. How can devices that heat homes in winter also be used to cool homes in summer?
59. Why does a hot dog pant?
60. Make up a multiple-choice question about evaporation and condensation energy changes.

PROBLEMS

1. The quantity of heat Q that changes the temperature ΔT of a mass m of a substance is given by $Q = cm\Delta T$, where c is the specific heat capacity of the substance. For example, for H_2O, $c = 1$ cal/g°C. And for a change of phase, the quantity of heat Q that changes the phase of a mass m is $Q = mL$, where L is the heat of fusion or heat of vaporization of the substance. For example, for H_2O, the heat of fusion is 80 cal/g (or 80 kcal/kg) and the heat of vaporization is 540 cal/g (or 540 kcal/kg). Use these relationships to determine the number of calories to change (a) 1 kg of 0°C ice to 0°C ice water, (b) 1 kg of 0°C ice water to 1 kg of 100°C boiling water, (c) 1 kg of 100°C boiling water to 1 kg of 100°C steam, and (d) 1 kg of 0°C ice to 1 kg of 100°C steam.
2. The specific heat capacity of ice is about 0.5 cal/g°C. Supposing that it remains at that value all the way to absolute zero, calculate the number of calories it would take to change a 1-g ice cube at absolute zero (−273°C) to 1 g of boiling water. How does this number of calories compare with the number of calories required to change the same gram of 100°C boiling water to 100°C steam?
3. Find the mass of 0°C ice that 10 g of 100°C steam will completely melt.
4. Consider 50 g of hot water at 80°C poured into a cavity in a very large block of ice at 0°C. What will be the final temperature of the water in the cavity? Show that 50 g of ice must melt in order to cool the hot water down to this temperature.
5. A 50-g chunk of 80°C iron is dropped into a cavity in a very large block of ice at 0°C. Show that 5.5 g of ice will melt. (The specific heat capacity of iron is 0.11 cal/g°C.)
6. If you drop a piece of ice on a hard surface, the energy of impact will melt some of the ice. The higher it drops, the more ice will melt upon impact. Show that to completely melt a block of ice that falls without air drag, it should ideally be dropped from a height of 34 km. [*Hint:* Equate the joules of gravitational potential energy to the product of the mass of ice and its heat of fusion (in SI units, 335,000 J/kg). Do you see why the answer doesn't depend on mass?]
7. A 10-kg iron ball is dropped onto a pavement from a height of 100 m. If half of the heat generated goes into warming the ball, find the temperature increase of the ball. (In SI units, the specific heat capacity of iron is 450 J/kg°C.) Why is the answer the same for a ball of any mass?

• 8. The heat of vaporization of ethyl alcohol is about 200 cal/g. If 2 kg of this fluid were allowed to vaporize in a refrigerator, show that 5 kg of ice would be formed from 0°C water.

CHAPTER 17 ONLINE RESOURCES

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- 17.16

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- Condensation Is a Warming Process
- Boiling Is a Cooling Process
- Pressure Cooker: Boiling and Freezing at the Same Time

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18 Thermodynamics

1 After boiling a bit of water in the gallon-size can, then sealing the can when water vapor has driven out most of the air, Dan Johnson and his class watch the can slowly crumple. By way of student discussion, the class concludes that condensation of vapor inside the can leaves a partial vacuum inside, whereupon atmospheric pressure on the outside does its thing. 2 On a larger scale, P. O. Zetterberg uses a vacuum pump to reduce the air pressure inside a 50-times larger oil drum. 3 Barbara and Tomas Brage assist as atmospheric pressure on the outside does its thing—to the applause of the class!

Lord Kelvin, for whom the Kelvin temperature scale is named, published more than 600 scientific papers and filed a total of 70 patents. He began as William Thomson, born in 1824 in Belfast, Ireland. Educated at first by his father, young Thomson began studying at the children's division of Glasgow University at age 10 after his father moved to that Scottish city. He published his first scholarly paper when he was 16. After completing studies at Glasgow, he moved on to Cambridge University and graduated with honors in 1845, at age 21. The next year he was a full professor of natural philosophy at Glasgow University. No question about it—William Thomson was a smart guy.

Among the subjects Thomson studied was heat, and in 1847 he defined the absolute temperature scale, which was subsequently named after him. He was also a strong advocate of the metric system of measurement. And in 1856, he was the first to introduce the term *kinetic energy*. He introduced Bell's telephone into Britain and helped to plan the first transatlantic cable, devising a sensitive electric meter that led to rapid transmission of Morse code signals between Europe and North America. For this success, he was knighted. The government further expressed its appreciation in 1892 by making Thomson a baron. He thenceforth was Lord Kelvin, taking his title from the Kelvin River that ran through his estate in Glasgow.

Kelvin made an estimate of the age of the Earth, a controversial subject at the time. He began his calculations by assuming that the original temperature of Earth was the temperature of the Sun. From measurements of cooling rates in rock he calculated the time for a body of Earth's size to cool. He estimated Earth's age to be about 100 million years. What Kelvin didn't know about at the time was the phenomenon of radioactivity and its role in keeping the Earth's interior warm.

Even the greatest scientists make errors and some, even worse, defend them when evidence contradicts them. Kelvin stubbornly defended his 100-million-year calculation throughout his life and contested Darwin's conclusions on evolution as impossible in the 100-million-year time period. He also said that heavier-than-air aircraft would be an impossibility. In 1900 he stated, "There is nothing new to be discovered in physics now. All that remains is more and more precise measurement." Despite these serious misjudgments in his later years, his achievements in science and engineering were enormous. When he died in 1907, he was buried next to Isaac Newton in Westminster Abbey.

Thermodynamics

Kelvin was the first to coin the word **thermodynamics** (which stems from Greek words meaning "movement of heat"). The science of thermodynamics was developed in the early 19th century, before the atomic and molecular theory of matter was understood. Because the early workers in thermodynamics had only vague notions of atoms, and knew nothing about electrons and other microscopic particles, the models they used invoked macroscopic notions—such as mechanical work, pressure, and temperature—and their roles in energy transformations. The two foundation stones of thermodynamics are the conservation of energy and the fact that heat flows spontaneously from hot to cold and not the other way around. Thermodynamics provides the basic theory of heat engines, from steam turbines to nuclear reactors, and the basic theory of refrigerators and heat pumps. The laws of thermodynamics dashed the dreams of inventors and industrialists who believed in the possibility of a perpetual motion machine: a device that, upon receiving an initial input of energy, would continue to operate indefinitely without further input. We begin our study of thermodynamics with a look at one of its early concepts—a lower limit to temperature.

Absolute Zero

Absolute zero isn't the coldest you can reach. It's the coldest you can hope to approach. (Researchers have been within a billionth of a degree of it.)

In principle, there is no upper limit to temperature. As thermal motion increases, a solid object first melts and then vaporizes; as the temperature is further increased, molecules break up into atoms, and atoms lose some or all of their electrons, thereby forming a cloud of electrically charged particles—a plasma. This situation exists in stars, where the temperature is many millions of degrees Celsius.

In contrast, there is a definite limit at the other end of the temperature scale. Gases expand when heated and contract when cooled. Nineteenth-century experiments found that all gases, regardless of their initial pressures or volumes, change by 1/273 of their volume at 0°C for each degree Celsius change in temperature, provided the pressure is held constant. So, if a gas at 0°C were cooled down by 273°C, it would contract, according to this rule, by 273/273 of its volume and be reduced to zero volume. Clearly, we cannot have a substance with zero volume.

Scientists also found that the pressure of any gas in any container of fixed volume changes by 1/273 of its pressure at 0°C for each degree Celsius change in temperature. So a gas in a container of fixed volume cooled to 273°C below zero would have no pressure whatsoever. In practice, every gas liquefies before it gets this cold. Nevertheless, these decreases by 1/273 increments suggested the idea of a lowest temperature: −273°C. So there is a limit to coldness.

When atoms and molecules lose all available kinetic energy, they reach the **absolute zero** of temperature. At absolute zero, as briefly discussed in Chapter 15, no more energy can be extracted from a substance and no further lowering of its temperature is possible. This limiting temperature is actually 273.15° below zero on the Celsius scale (and 459.7° below zero on the Fahrenheit scale).

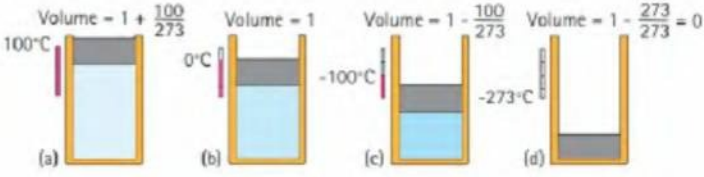

FIGURE 18.1

The gray piston in the vessel goes down as the volume of gas (blue) shrinks. The volume of gas changes its volume at 0°C by 1/273 with each 1°C change in temperature when the pressure is held constant. (a) At 100°C, the volume is 100/273 greater than it is at (b), when its temperature is 0°C. (c) When the temperature is reduced to −100°C, the volume is reduced by 100/273. (d) At −273°C, the volume of the gas would be reduced by 273/273 and so would ideally be zero.

The absolute temperature scale is called the Kelvin scale, after Lord Kelvin, who first suggested this thermodynamic temperature scale. Absolute zero is 0 K (short for "0 kelvin," rather than "0 degrees kelvin"). There are no negative numbers on the Kelvin scale. Degrees on the Kelvin scale are calibrated with the same-sized divisions as on the Celsius scale. Thus, the melting point of ice is 273.15 K, and the boiling point of water is 373.15 K.

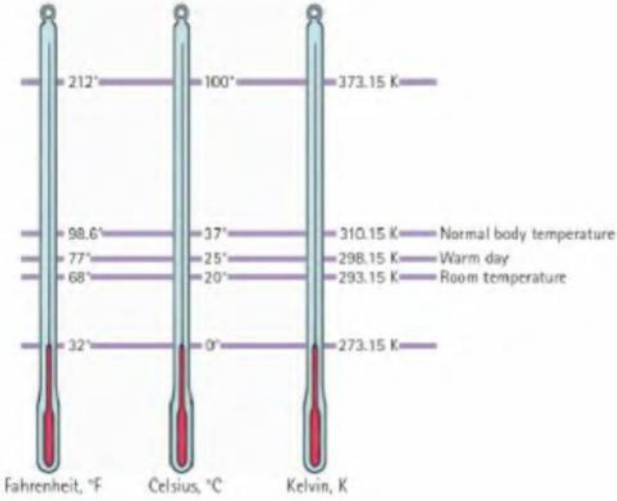

FIGURE 18.2
Familiar temperatures on different scales.

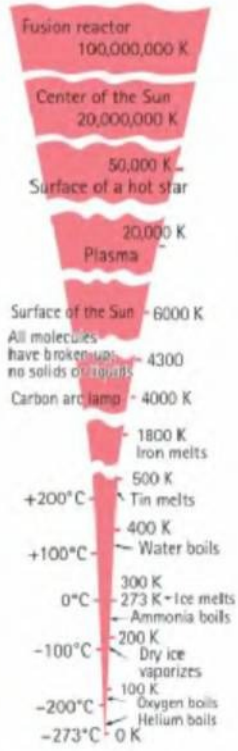

FIGURE 18.3
Some absolute temperatures.

CHECK POINT

1. Which is larger, a Celsius degree or a kelvin?
2. A flask of helium gas has a temperature of 0°C. If a second, identical flask containing an equal mass of helium is twice as hot (has twice the internal energy), what is its temperature in kelvins? In degrees Celsius?

Check Your Answers

1. Neither. They are equal.
2. A container of helium twice as hot has twice the absolute temperature, or 2 times 273 K, which is 546 K. This is 273°C. (Simply subtract 273 from the Kelvin temperature to convert to Celsius degrees. Can you see why?)

Internal Energy

As briefly discussed in Chapter 15, there is a vast amount of energy locked in all materials. In this book, for example, the paper is composed of molecules that are in constant motion. They have kinetic energy. Due to interactions with neighboring molecules, they also have potential energy. The pages can be easily burned, so we know they store chemical energy, which is really electric potential energy at the molecular level. We know there are vast amounts of energy associated with atomic nuclei. Then there is the "energy of being," described by the celebrated

equation $E = mc^2$ (mass energy). Energy at the particle level within a substance is found in these and other forms, which, when taken together, are called **internal energy.**[1] Although the internal energy in even the simplest substance can be quite complex, in our study of heat changes and heat flow we will be concerned only with the *changes* in the internal energy of a substance. Changes in temperature indicate these changes in internal energy.

First Law of Thermodynamics

Some 200 years ago, heat was thought to be an invisible fluid called *caloric,* which flowed like water from hot objects to cold objects. Caloric appeared to be conserved—that is, it seemed to flow from one place to another without being created or destroyed. This idea was the forerunner of the law of conservation of energy. By the middle of the 19th century, many years after Rumford showed that heat was not a substance locked up in matter, it was accepted that the flow of heat was nothing more than the flow of energy itself. The caloric theory of heat was gradually abandoned.[2] Today, we view heat as energy being transferred from one place to another, usually by molecular collisions. Heat is energy in transit.

When the law of energy conservation is broadened to include heat, we call it the **first law of thermodynamics.**[3] We state it generally in the following form:

When heat flows to or from a system, the system gains or loses an amount of energy equal to the amount of heat transferred.

Looking for a diet plan? Consume fewer calories than you burn. This is the only diet plan firmly based on the first law of thermodynamics.

By *system,* we mean a well-defined group of atoms, molecules, particles, or objects. The system may be the steam in a steam engine or it may be Earth's entire atmosphere. It can even be the body of a living creature. The important point is that we must be able to define what is contained *within* the system and what is *outside* it. If we add heat to the steam in a steam engine, to Earth's atmosphere, or to the body of a living creature, we are adding energy to the system. The system can "use" this heat to increase its own internal energy or to do work on its surroundings. So adding heat to a system does one or both of two things: (1) it increases the internal energy of the system, if it remains in the system, or (2) it does work on things external to the system, if it leaves the system. More specifically, the first law states:

Heat added to a system = increase in internal energy + external work done by the system.

The first law is an overall principle that is not concerned with the inner workings of the system itself. Whatever the details of molecular behavior in the system, the added heat either increases the internal energy of a system or enables the system to do external work (or both). Our ability to describe and predict the behavior of systems

[1]If this book were poised at the edge of a table and ready to fall, it would possess gravitational potential energy; if it were tossed into the air, it would possess kinetic energy. But these are not examples of internal energy, because they involve more than just the particles of which the book is composed. They include gravitational interactions with Earth and motion with respect to Earth. We distinguish between the internal energy in a book and forms of external energy that may also act on the book.

[2]Popular ideas, when proved wrong, are seldom suddenly discarded. People tend to identify with the ideas that characterize their time; hence, it is often the young who are more prone to discover and accept new ideas and to push the human adventure forward.

[3]There is also a zeroth law of thermodynamics (bearing this charming name because it was formulated *after* the first and second laws were formulated), which states that two systems, each in thermal equilibrium with a third system, are in equilibrium with each other. A third law states that no system can have its absolute temperature reduced to zero.

without the need to analyze complicated atomic and molecular processes is one of the beauties of thermodynamics. Thermodynamics bridges the microscopic and macroscopic worlds.

Consider a given amount of energy supplied to a steam engine, whether in a power plant or nuclear-powered ship. The amount of energy supplied will be evident in the increased internal energy of the steam and in the mechanical work done. The sum of the increase in internal energy and the work done will equal the energy input. In no way can energy output exceed energy input. The first law of thermodynamics is simply the thermal version of the law of conservation of energy.

Adding heat to a system so the system can do mechanical work is only one application of the first law of thermodynamics. If, instead of adding heat, we do mechanical work on the system, the first law tells us what we can expect: an increase in internal energy. Rub your palms together and they become warmer. Or rub two dry sticks together and they'll certainly become hotter. Or pump the handle of a bicycle pump and the pump becomes hot. Why? Because we are primarily doing mechanical work on the system and raising its internal energy. If the process happens so quickly that very little heat is conducted out of the system, then most of the work input goes into increasing the internal energy, and the temperature rises.

FIGURE 18.4

Paddle-wheel apparatus used to compare heat with mechanical energy. As the weights fall, they give up potential energy (mechanical), which is converted to heat that warms the water. This equivalence of mechanical and heat energy was first demonstrated by James Joule, for whom the unit of energy is named.

CHECK POINT

1. If 100 J of heat is added to a system that does no external work, by how much is the internal energy of that system raised?
2. If 100 J of heat is added to a system that does 40 J of external work, by how much is the internal energy of that system raised?

Check Your Answers

1. 100 J.
2. 60 J. We see from the first law that 100 J = 60 J + 40 J.

FIGURE 18.5

When you do work on the pump by pressing down on the piston, you compress the air inside. What happens to the temperature of the enclosed air? What happens to its temperature if it expands and pushes the piston outward?

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Video
Adiabatic Process

Adiabatic Processes

Compressing or expanding a gas while no heat enters or leaves the system is said to be an **adiabatic process** (from the Greek for "impassable"). Adiabatic conditions can be achieved by thermally insulating a system from its surroundings (with Styrofoam, for example) or by performing the process so rapidly that heat has no time to enter or leave. In an adiabatic process, therefore, because no heat enters or leaves the system, the "heat added" part of the first law of thermodynamics must be zero. Then, under adiabatic conditions, changes in internal energy are equal to the work done on or by the system.[4]

For example, if we do work *on* a system by compressing it, its internal energy increases: We raise its temperature. We notice this by the warmth of a bicycle pump when air is compressed. Conversely, if work is done *by* the system, its internal energy decreases: It cools. We note this by the coolness of a tire valve if air escapes and expands from it. Rapidly expanding gas cools.

You can demonstrate the cooling of air as it expands by repeating the personal experiment of blowing air on your hand, discussed in Chapter 16. Blow air on your hand—first with your mouth wide open, then with puckered lips so the air expands (Figure 16.6, Chapter 16). Your breath is noticeably cooler when the air expands!

As gas expands, it gives up some of its energy by doing work on its surroundings. Hence, the gas cools.

[4]ΔHeat = Δinternal energy + work. When there is no heat transfer, ΔHeat = 0. So 0 = Δinternal energy + work. Then we can say −Work = Δinternal energy.

Meteorology and the First Law

Thermodynamics is useful to meteorologists when analyzing weather. Meteorologists express the first law of thermodynamics in the following form:

Air temperature rises as heat is added or as pressure is increased.

The temperature of the air may be changed by adding or subtracting heat, by changing the pressure of the air (which involves work), or by both. Heat is added by solar radiation, by long-wave Earth radiation, by moisture condensation, or by contact with the warm ground. An increase in air temperature results. The atmosphere may lose heat by radiation to space, by evaporation of rain falling through dry air, or by contact with cold surfaces. The result is a drop in air temperature.

There are some atmospheric processes in which the amount of heat added or subtracted is very small—small enough so that the process is nearly adiabatic. Then we have the adiabatic form of the first law:

Air temperature rises (or falls) as pressure increases (or decreases).

Adiabatic processes in the atmosphere are characteristic of parts of the air, called *parcels*, which have dimensions on the order of tens of meters to kilometers. These parcels are large enough that outside air doesn't appreciably mix with the air inside them during the minutes to hours that they exist. They behave as if they are enclosed in giant, tissue-light garment bags. As a parcel flows up the side of a mountain, its pressure lessens, allowing it to expand and cool. The reduced pressure results in reduced temperature.[5]

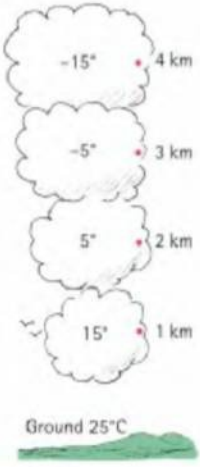


FIGURE 18.6
The temperature of a parcel of dry air that expands adiabatically decreases by about 10°C for each kilometer of elevation.

Measurements show that the temperature of a parcel of dry air will decrease by 10°C for a decrease in pressure that corresponds to an increase in altitude of 1 kilometer. So dry air cools 10°C for each kilometer it rises (Figure 18.6). Air flowing over tall mountains or rising in thunderstorms or cyclones may change elevation by several kilometers. Thus, if a parcel of dry air at ground level with a comfortable temperature of 25°C were lifted to 6 km, the temperature would be a frigid −35°C. On the other hand, if air at a typical temperature of −20°C at an altitude of 6 km descends to the ground, its temperature would be a whopping 40°C. A dramatic example of this adiabatic warming is the *chinook*—a wind that blows down from the Rocky Mountains across the Great Plains. Cold air moving down the slopes of the mountains is compressed into a smaller volume and is appreciably warmed (Figure 18.7). The effect of expansion or compression on gases is quite impressive.[6]

A rising parcel cools as it expands. But the surrounding air is cooler at increased elevations also. The parcel will continue to rise as long as it is warmer (and therefore less dense) than the surrounding air. If it gets cooler (denser) than its surroundings, it will sink. Under some conditions, large parcels of cold air sink and remain at a low level, with the result that the air above is warmer. When the upper regions of the atmosphere are warmer than the lower regions, we have a **temperature inversion.** If any rising warm air is denser than this upper layer of warm air, it will rise no farther. It is common to see evidence of this over a cold lake where visible gases and

[5]Recall that, in Chapter 16, we treated the cooling of expanding air at the microscopic level by considering the behavior of colliding molecules. With thermodynamics, we consider only the macroscopic measurements of temperature and pressure to come up with the same results. It's nice to analyze things from more than one point of view.

[6]Interestingly enough, when you're flying at high altitudes where outside air temperature is typically −35°C, you're quite comfortable in your warm cabin—but not because of heaters. The process of compressing outside air to a cabin pressure that approximates atmospheric pressure at sea level would normally heat the air to a roasting 55°C (131°F). So air conditioners must be used to extract heat from the pressurized air.

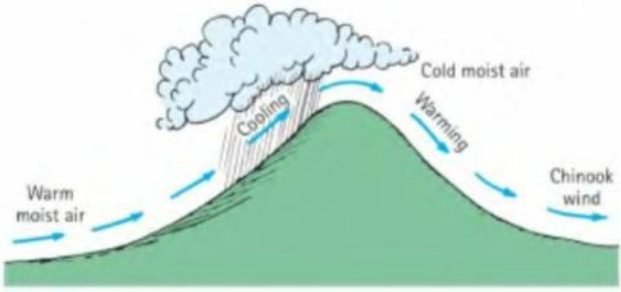


FIGURE 18.7
Chinooks, which are warm, dry winds, occur when high-altitude air descends and is adiabatically warmed.

FIGURE 18.8
A thunderhead is the result of the rapid adiabatic cooling of a rising mass of moist air. It derives energy from condensation of water vapor.

particles, such as smoke, spread out in a flat layer above the lake rather than rise and dissipate higher in the atmosphere (Figure 18.9). Temperature inversions trap smog and other thermal pollutants. The smog of Los Angeles is trapped by such an inversion, caused by low-level cold air from the ocean over which is a layer of hot air that has moved over the mountains from the hotter Mojave Desert. The mountains aid in holding the air trapped (Figure 18.10). The mountains on the edge of Denver play a similar role in trapping smog beneath a temperature inversion.[7]

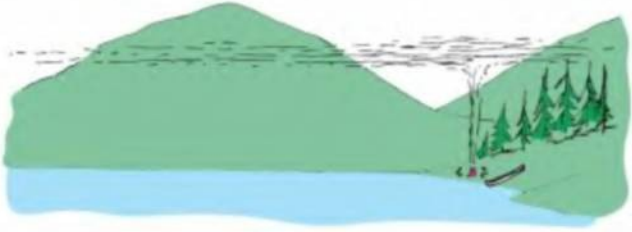


FIGURE 18.9
The layer of campfire smoke over the lake indicates a temperature inversion. The air above the smoke is warmer than the smoke, and the air below is cooler.

Adiabatic parcels are not restricted to the atmosphere, and changes in them do not necessarily happen quickly. Some deep ocean currents take thousands of years for circulation. The water masses are so huge and conductivities are so low that no appreciable quantities of heat are transferred to or from these parcels over these long periods of time. They are warmed or cooled adiabatically by changes in pressure.

FIGURE 18.10
Smog in Los Angeles is trapped by the mountains and a temperature inversion caused by warm air from the Mojave Desert overlying cool air from the Pacific Ocean.

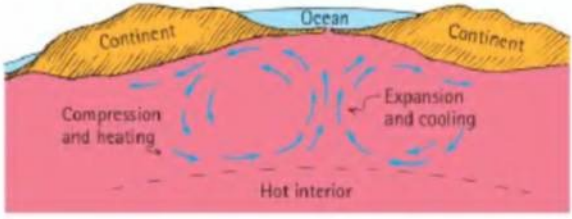
[7]Strictly speaking, meteorologists call any temperature profile that thwarts upward convection a temperature inversion—including instances in which the upper regions of air are cooler but not cool enough to allow continued upward convection.

Changes in adiabatic ocean convection, as evidenced by events such as the recurring El Niño, have a great effect on Earth's climate. Ocean convection is influenced by the temperature of the ocean floor, which, in turn, is influenced by convection currents in the molten material that lies beneath Earth's crust (Figure 18.11). Knowledge of the behavior of molten material in Earth's mantle is difficult to acquire. Once a parcel of hot liquid material deep within the mantle begins to rise, will it continue to rise to Earth's crust? Or will its rate of adiabatic cooling find it cooler and denser than its surroundings, at which point it will sink? Is convection self-perpetuating? Geophysical types are currently pondering these questions.

FIGURE 18.11

INTERACTIVE FIGURE

Do convection currents in the Earth's mantle drive the continents as they drift across the global surface? Do rising parcels of molten material cool faster or slower than the surrounding material? Do sinking parcels heat to temperatures above or below those of the surroundings? The answers to these questions are not known at this writing.



CHECK POINT

1. If a parcel of dry air initially at 0°C expands adiabatically while flowing upward alongside a mountain a vertical distance of 1 km, what will its temperature be? What will its temperature be when it has risen 5 km?
2. What happens to the air temperature in a valley when cold air blowing across the mountaintops descends into the valley?

Check Your Answers

1. At 1 km elevation, its temperature will be −10°C; at 5 km elevation, −50°C.
2. The air is adiabatically compressed and the temperature in the valley is increased. In this way, town residents of some valley towns in the Rocky Mountains, such as Salida, Colorado, experience "banana-belt" weather in midwinter.

fyi

- Mountaintop clouds created by forced adiabatic cooling, in effect a forced convection, is called *orographic lift* by meteorologists. These "lenticular clouds" have often been mistaken for UFOs.

Second Law of Thermodynamics

Suppose you place a hot brick next to a cold brick in a thermally insulated region. You know that the hot brick will cool as it gives heat to the cold brick, which will warm. They will arrive at a common temperature: thermal equilibrium. No energy will be lost, in accordance with the first law of thermodynamics. But pretend the hot brick extracts heat from the cold brick and becomes hotter. Would this violate the first law of thermodynamics? Not if the cold brick becomes correspondingly colder so that the combined energy of both bricks remains the same. If this were to happen, it would not violate the first law of thermodynamics.

But it would violate the **second law of thermodynamics.** The second law identifies the direction of energy transformation in natural processes. The second law of thermodynamics can be stated in many ways, but, put most simply, is

Heat of itself never flows from a cold object to a hot object.

In winter, heat flows from inside a warm, heated home to the cold air outside. In summer, heat flows from the hot air outside into the cooler interior. The direction of spontaneous heat flow is from hot to cold. Heat can be made to flow the other way from cooler to warmer, but only by doing work on the system or by adding

energy from another source—as occurs with heat pumps and air conditioners, both of which cause heat to flow from cooler to warmer places.

The huge amount of internal energy in the ocean cannot be used to light a single flashlight bulb without external effort. Energy will not of itself flow from the lower-temperature ocean to the higher-temperature bulb filament. Without external effort, the direction of heat flow is *from* hot *to* cold.

CHECK POINT

Can the internal energy of a huge iceberg be harnessed to do work?

Check Your Answer

According to the second law, it can do work on cooler things, but not on warmer things. Energy spontaneously flows from hot to cold, and not the other way around.

HEAT ENGINES

Machines were the focal point of the Industrial Revolution during the late 18th and early 19th centuries. With hopes dashed for perpetual motion machines, scientists and industrialists focused on the efficiency of actual machines and the engines that drove them.

A **heat engine** is any device that converts internal energy into mechanical work. The basic idea behind a heat engine—whether a steam engine, internal combustion engine, or jet engine—is that mechanical work can be obtained only when heat flows from a high temperature to a low temperature. In every heat engine, only some of the heat can be transformed into work. In considering heat engines, we talk about *reservoirs*. Heat flows out of a high-temperature reservoir and into a low-temperature one. Every heat engine (1) gains heat from a reservoir of higher temperature, increasing the engine's internal energy; (2) converts some of this energy into mechanical work; and (3) expels the remaining energy as heat to some lower-temperature reservoir, usually called a *sink* (Figure 18.12). In a gasoline engine, for example, (1) products of burning fuel in the combustion chamber provide the high-temperature reservoir, (2) hot gases do mechanical work on the piston, and (3) heat is expelled to the environment via the cooling system and exhaust (Figure 18.13).

The second law tells us that no heat engine can convert all the heat supplied into mechanical energy. Only *some* of the heat can be transformed into work, with the

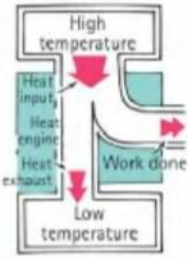


FIGURE 18.12

When heat in a heat engine flows from the high-temperature reservoir to the low-temperature sink, part of the heat can be turned into work. (If work is put into a heat engine, the flow of heat may be from the low-temperature sink to the high-temperature reservoir, as in a refrigerator or air conditioner.)

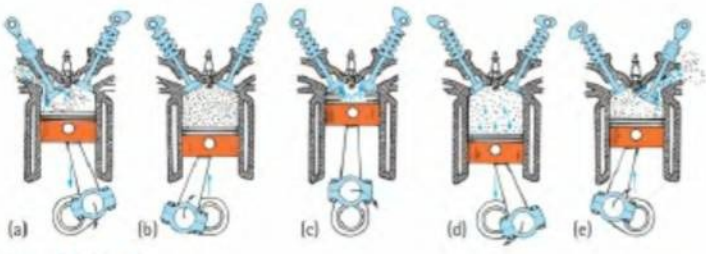


FIGURE 18.13

INTERACTIVE FIGURE

A four-cycle internal-combustion gasoline engine. (a) A fuel–air mixture fills the cylinder as the piston moves down. (b) The piston moves upward and compresses the mixture—adiabatically, because no appreciable heat is transferred in or out. (c) The spark plug fires, igniting the mixture, which raises it to a high temperature. (d) Adiabatic expansion pushes the piston downward, the power stroke. (e) The burned gases are pushed out the exhaust valve. Then the intake valve opens and the cycle repeats. These stages can be put differently: (a) suck, (b) squeeze, (c) bang, (d) push, and (e) blow.

An important source of water for a camel is not its hump but its oversized nose, which allows it to withdraw water from its own exhaled breath. Its inner nostrils are structured to recapture effectively most of the moisture contained in the warm water-saturated air moving out of its lungs.

remainder expelled in the process. Applied to heat engines, the second law may be stated:

When work is done by a heat engine operating between two temperatures, T_{hot} and T_{cold}, only some of the input heat at T_{hot} can be converted to work, and the rest is expelled at T_{cold}.

Every heat engine discards some heat, which may be desirable or undesirable. Hot air expelled in a laundry or a baking oven on a cold winter day may be quite desirable, while the same hot air on a hot summer day is something else. When expelled heat is undesirable, we call it *thermal pollution*.

Before scientists understood the second law, many people thought that a very low-friction heat engine could convert nearly all the input heat energy to useful work. But not so. In 1824, the French engineer Nicolas Léonard Sadi Carnot[8] analyzed the functioning of a heat engine and made a fundamental discovery. He showed that the greatest fraction of energy input that can be converted to useful work, even under ideal conditions, depends on the temperature difference between the hot reservoir and the cold sink. Carnot's equation is

$$\text{Ideal efficiency} = \frac{T_{hot} - T_{cold}}{T_{hot}}$$

where T_{hot} is the temperature of the hot reservoir and T_{cold} is the temperature of the cold sink.[9] Ideal efficiency depends only on the temperature difference between input and exhaust. Whenever ratios of temperatures are involved, the absolute temperature scale must be used, so T_{hot} and T_{cold} are expressed in kelvins. For example, when the hot reservoir in a steam turbine is 400 K (127°C) and the sink is 300 K (27°C), the ideal efficiency is

$$\frac{400 - 300}{400} = \frac{1}{4}$$

This means that, even under ideal conditions, only 25% of the heat provided by the steam can be converted into work, while the remaining 75% is expelled as waste. This is why steam is superheated to high temperatures in steam engines and power plants. The higher the steam temperature driving a motor or turbogenerator, the higher the possible efficiency of power production. For instance, if the operating temperature in the cited example is 600 K, rather than 400 K, the efficiency would be $(600 - 300)/600 = 1/2$, which is twice the efficiency at 400 K.

The body temperature of camels can rise several degrees above normal without causing heatstroke. Their excess heat is dissipated when air temperature drops at night.

We can see the role of temperature difference between heat reservoir and sink in the operation of the steam-turbine engine in Figure 18.14. The hot reservoir is steam from the boiler and the cold sink is the exhaust region in the condenser. The hot steam exerts pressure and does work on the blades when it pushes on their front sides. This is nice. But what if the same steam pressure were also exerted on the *back side* of the blades? This would be counterproductive and not so nice. It is vital that pressure on the back side of the blades be reduced. How is it done? The same way that pressure inside the can of steam is reduced in the Thermodynamics Dramatized! Box on page 325. If you condense the steam, the pressure on the blades' back sides is greatly reduced. We know that, with confined steam, temperature and pressure go hand in hand: Increase

[8]Carnot was the son of Lazare Nicolas Marguerite Carnot (pronounced car-no), who created the fourteen armies after the revolution that defended France against all of Europe. After his defeat at Waterloo, Napoleon said to Lazare, "Monsieur Carnot, I came to know you too late." A few years after producing his famous equation, Nicolas Léonard Sadi Carnot died tragically at the age of 36 during a cholera epidemic that swept through Paris.

[9]Efficiency = work output/heat input. From energy conservation, heat input = work output + heat that flows out at low temperature (see Figure 18.12). So work output = heat input − heat output. So efficiency = (heat input − heat output)/(heat input). In the ideal case, it can be shown that the ratio (heat out)/(heat in) = T_{cold}/T_{hot}. Then we can say ideal efficiency = $(T_{hot} - T_{cold})/T_{hot}$.

Thermodynamics Dramatized!

Put a small amount of water in an aluminum soda-pop can and heat it on a stove until steam issues from the opening. When this occurs, air has been driven out and replaced by steam. Then, with a pair of tongs, quickly invert the can into a pan of water. Crunch! The can is crushed by atmospheric pressure! Why? When the molecules of steam encounter water from the pan, condensation occurs, leaving a very low pressure in the can, whereupon the surrounding atmospheric pressure crunches the can. Here we see, dramatically, how pressure is reduced by condensation. Can you now better understand the role of condensation in the turbine of Figure 18.14?

temperature and you increase pressure; decrease temperature and you decrease pressure. So the pressure difference necessary for the operation of a heat engine is directly related to the temperature difference between source and sink. The greater the temperature difference, the greater the efficiency.[10]

Carnot's equation states the upper limit of efficiency for all heat engines, whether in an automobile, a nuclear-powered ship, or a jet aircraft. In practice, friction is always present in all engines, and efficiency is always less than ideal.[11] So, whereas friction is solely responsible for the inefficiencies of many devices, the overriding concept in the case of heat engines is the second law of thermodynamics: Only some of the heat input can be converted to work—even without friction.

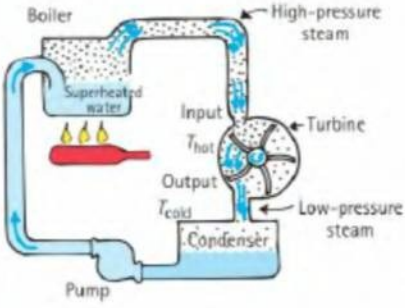


FIGURE 18.14

The steam cycle. The turbine turns because pressure exerted by high-temperature steam on the front side of the turbine blades is greater than that exerted by low-temperature steam on the back side of the blades. Without a pressure difference, the turbine would not rotate and deliver energy to an external load (such as an electric generator). The presence of steam pressure on the back side of the blades, even without friction, prevents the turbine from being a perfectly efficient engine.

[10] Physicist Victor Weisskopf tells the story of an engineer who is explaining the operation of a steam engine to a peasant. The engineer explains in detail the engine's steam cycle, whereupon the peasant asks, "Yes, I understand all that, but where's the horse?" It's difficult to abandon our way of looking at the world when a newer method comes along to replace established ways.

[11] The ideal efficiency of an automobile internal-combustion engine is more than 50%, but, in practice, the actual efficiency is about 25%. Engines of higher operating temperatures (compared to sink temperatures) would be more efficient, but the melting point of engine materials limits the upper temperatures at which they can operate. Higher efficiencies await engines made with new materials with higher melting points. Keep your eyes on ceramic engines!

FIGURE 18.15
The Transamerica Pyramid and some other buildings are heated by electric lighting, which is why the lights are on most of the time.

FIGURE 18.16
Molecules of perfume readily go from the bottle (a more ordered state) to the air (a less ordered state), and not vice versa.

FIGURE 18.17
If you push a crate full of auto parts across a rough floor, all your work goes into heating the floor and the crate. Work against friction produces heat, which cannot do any work on the crate. Ordered energy is transformed into disordered energy.

CHECK POINT

1. What would be the ideal efficiency of an engine if its hot reservoir and exhaust were the same temperature—say, 400 K?
2. What would be the ideal efficiency of a machine having a hot reservoir at 400 K and a cold reservoir somehow maintained at absolute zero?

Check Your Answers

1. Zero efficiency: (400 − 400)/400 = 0. So no work output is possible for any heat engine unless a temperature difference exists between the reservoir and the sink.
2. One: (400 − 0)/400 = 1. Only in this idealized case is an ideal efficiency of 100% possible.

Order Tends to Disorder

The first law of thermodynamics states that energy can neither be created nor destroyed. It speaks of the *quantity* of energy. The second law qualifies this by adding that the form energy takes in transformations "deteriorates" to less useful forms. It speaks of the *quality* of energy, as energy disperses and ultimately degenerates into waste. Another way to say this is that organized energy (concentrated, and therefore usable, high-quality energy) degrades into disorganized energy (nonusable, low-quality energy). For example, once water flows over a waterfall, it loses its potential for useful work. Similarly for gasoline, where organized energy degrades as it burns in a car engine. Useful energy degrades to nonuseful forms and is unavailable for doing the same work again, such as driving another car engine. Heat, dispersed into the environment as thermal energy, is the graveyard of useful energy.

The quality of energy is lowered with each transformation, as energy of an organized form tends to degrade into disorganized forms. With this broader perspective, the second law can be stated another way:

In natural processes, high-quality energy tends to transform into lower-quality energy—order tends toward disorder.

Consider a system consisting of a stack of pennies on a table, all heads up. Somebody walks by and accidentally bumps the table and the pennies topple to the floor, certainly not landing all heads up. Order becomes disorder. Molecules of gas all moving in harmony make up an orderly state—and also an unlikely state. On the other hand, molecules of gas moving in haphazard directions with a broad range of speeds make up a disorderly, chaotic (and more likely) state. If you remove the lid of a perfume bottle or open the oven door on a tray of baked chocolate cookies, molecules escape into the room and make up a more disorderly state. Relative order becomes disorder. You would not expect the reverse to happen by itself; that is, you would not expect the perfume or cookie molecules to spontaneously order themselves back into the bottle or tray and thereby return to the more ordered state.

Processes in which disorder returns to order without any external help don't occur in nature. Interestingly, time is given a direction via this thermodynamic rule. Time's arrow always points from order to disorder.[12]

Disordered energy can be changed to ordered energy only with organizational effort or work input. For example, water in a refrigerator freezes and becomes more

[12]Reversible systems look sensible when a movie film of them is run backward. Remember those old movies where a train comes to a stop inches away from a heroine tied to the tracks? How was this done without mishap? Simple. The train began at rest, inches away from the heroine, and went *backward*, gaining speed. When the film was reversed, the train was seen to move *toward* the heroine. Watch closely for the telltale smoke that *enters* the smokestack!

ordered because work is put into the refrigeration cycle; gas can be ordered into a small region if a compressor supplied with outside energy does work. Processes in which the net effect is an increase in order always require an external input of energy. But, for such processes, there is always an increase of disorder somewhere else to more than offset the increase of order.

Biological systems are enormously complex and, while living, never reach thermal equilibrium.

CHECK POINT

In your bedroom are probably some 10^{27} air molecules. If they were all to congregate on the opposite side of the room, you could suffocate. But this is unlikely. Is such a spontaneous congregation of molecules less likely, more likely, or of the same probability if there are fewer molecules in the room?

Check Your Answer

Fewer molecules mean a greater probability of their spontaneously congregating on the opposite side of your room. Exaggeration makes this credible: If there is only one molecule in the room, there's a 50% chance of it being in the other half of the room. If you have two molecules, the chances of both being on one side at the same time is 25%. If there are three molecules, the chance of your being breathless is one-eighth (12.5%). The greater the number of molecules, the greater the chances of there being nearly equal numbers of molecules on both sides of the room.

Sharks rely on a gel under their skin that detects extremely small changes in ocean temperature—less than a thousandth of a degree Celsius. This capability likely assists in detecting subtle temperature boundaries where their prey are found.

Entropy

Energy tends to disperse: Hot air in a hot oven disperses when an oven door is opened. Energy tends to degrade: Energy locked in chemical bonds of wood degrades when the wood is burned. **Entropy** is the term we use to describe the natural dispersing or degrading of energy. Entropy can be measured by the *amount of disorder* in a system.[13] More entropy means more dispersal or more degradation of energy. Since energy tends to disperse and degrade with time, the total amount of entropy in any system tends to increase with time. Whenever a physical system is allowed to distribute its energy freely, it always does so in a manner such that entropy increases while the energy of the system remaining available for doing work decreases.

The net entropy in the universe is continually increasing (continually running "downhill"). We say *net* because there are some regions in which energy is actually being organized and concentrated. This occurs in living organisms, which survive by concentrating and organizing energy from food sources. All living organisms, from bacteria to trees to human beings, extract energy from their surroundings and use it to increase their own organization (growth and repair). In living organisms, entropy decreases. But the order in life forms is maintained by increasing entropy elsewhere, resulting in a net increase in entropy. Energy must be transformed into the living system to support life. When it isn't, the organism soon dies and tends toward disorder.[14]

The first law of thermodynamics is a universal law of nature to which no exceptions have been observed. The second law, however, is a probabilistic statement.

FIGURE 18.18
Entropy.

[13]Entropy can be expressed mathematically. The increase in entropy ΔS of a thermodynamic system is equal to the amount of heat added to the system ΔQ divided by the temperature T at which the heat is added: $\Delta S = \Delta Q/T$.

[14]Interestingly enough, the American writer Ralph Waldo Emerson, who lived during the time the second law of thermodynamics was the new science topic of the day, philosophically speculated that not everything becomes more disordered with time and cited the example of human thought. Ideas about the nature of things grow increasingly refined and better organized as they pass through the minds of succeeding generations. Human thought is evolving toward more order.

Old riddle: "How do you unscramble an egg?" Answer: "Feed it to a chicken." But even then you won't get your original egg back. Making eggs takes energy and increases entropy.

Given enough time, even the most improbable states may occur; entropy may sometimes decrease. For example, the haphazard motions of air molecules could momentarily become harmonious in a corner of the room, just as a tall stack of pennies spilled on the floor could all come up heads. These situations are possible, but they are not probable. The second law tells us the most probable course of events, not the only possible one.

The laws of thermodynamics are often stated this way: You can't win (because you can't get any more energy out of a system than you put into it), you can't break even (because you can't get as much useful energy out as you put in), and you can't get out of the game (entropy in the universe is always increasing).

FIGURE 18.19
Why is the motto of this contractor—"Increasing entropy is our business"—so appropriate?

SUMMARY OF TERMS

Thermodynamics The study of heat and its transformation to different forms of energy.

Absolute zero The lowest possible temperature that a substance may have; the temperature at which particles of a substance have their minimum kinetic energy.

Internal energy The total energy (kinetic plus potential) of the submicroscopic particles that make up a substance. *Changes* in internal energy are of principal concern in thermodynamics.

First law of thermodynamics A restatement of the law of energy conservation, applied to systems in which energy is transferred by heat and/or work. The heat added to a system equals its increase in internal energy plus the external work it does on its environment.

Adiabatic process A process, often of fast expansion or compression, wherein no heat enters or leaves a system.

Temperature inversion A condition in which upward convection of air ceases, often because an upper region of the atmosphere is warmer than the region below it.

Second law of thermodynamics Thermal energy never spontaneously flows from a cold object to a hot object. Also, no machine can be completely efficient in converting heat to work; some of the heat supplied to the machine at high temperature is dissipated as waste heat at lower temperature. And finally, all systems tend to become more and more disordered as time goes by.

Heat engine A device that uses heat as input and supplies mechanical work as output, or that uses work as input and moves heat "uphill" from a cooler to a warmer place.

Entropy A measure of the disorder of a system. Whenever energy freely transforms from one form to another, the direction of transformation is toward a state of greater disorder and therefore toward one of greater entropy.

REVIEW QUESTIONS

Thermodynamics

1. What is the origin and meaning of the word *thermodynamics?*
2. Is the study of thermodynamics concerned primarily with microscopic processes or with macroscopic ones?

Absolute Zero

3. By how much does the volume of gas at 0°C contract for each decrease in temperature of 1 Celsius degree when the pressure is held constant?

4. By how much does the pressure of gas at 0°C decrease for each decrease in temperature of 1 Celsius degree when the volume is held constant?
5. If we assume the gas does not condense to a liquid, what volume is approached for a gas at 0°C cooled by 273 Celsius degrees?
6. What is the lowest possible temperature on the Celsius scale? On the Kelvin scale?

Internal Energy

7. What else besides molecular kinetic energy contributes to the internal energy of a substance?
8. Is the principal concern in the study of thermodynamics the *amount* of internal energy in a system or the *changes* in internal energy in a substance?

First Law of Thermodynamics

9. How does the law of the conservation of energy relate to the first law of thermodynamics?
10. What is the relationship between heat added to a system, change in its internal energy, and external work done by the system?
11. What happens to the internal energy of a system when mechanical work is done on it? What happens to its temperature?

Adiabatic Processes

12. What condition is necessary for a process to be adiabatic?
13. If work is done *on* a system, does the internal energy of the system increase or decrease? If work is done *by* a system, does the internal energy of the system increase or decrease?

Meteorology and the First Law

14. How do meteorologists express the first law of thermodynamics?
15. What is the adiabatic form of the first law?
16. What generally happens to the temperature of rising air? Of sinking air?
17. What is a temperature inversion?
18. Do adiabatic processes apply only to gases? Defend your answer.

Second Law of Thermodynamics

19. How does the second law of thermodynamics relate to the direction of heat flow?

Heat Engines

20. What three processes occur in every heat engine?
21. What exactly is thermal pollution?
22. How does the second law relate to heat engines?
23. Why is the condensation part of the cycle in a steam turbine so essential?

Order Tends to Disorder

24. Distinguish between high-quality energy and low-quality energy in terms of organized and disorganized energy. Give an example of each.
25. How can the second law be stated with regard to high-quality and lower-quality energy?
26. With respect to orderly and disorderly states, what do natural systems tend to do? Can a disorderly state ever transform to an orderly state? Explain.

Entropy

27. What is the physicist's term for *measure of amount of disorder?*
28. Distinguish between the first and second laws of thermodynamics in terms of whether or not exceptions occur.

EXERCISES

1. A friend said the temperature inside a particular oven is 500 and the temperature inside a particular star is 50,000. You're unsure whether your friend meant Celsius degrees or kelvins. How much difference does it make in each case?
2. The temperature of the Sun's interior is about 10^7 degrees. Does it matter whether this is degrees Celsius or kelvins? Explain.
3. When heat flows from a warm object in contact with a cool object, do both objects undergo the same amount of temperature change?
4. Heat always flows spontaneously from an object with a higher temperature to an object with a lower temperature. Is this the same thing as saying that heat always flows from an object with a greater internal energy to one with a lower internal energy? Explain.
5. Consider a jar of helium with a temperature of 0°C. What will be its temperature if it is twice as hot (has twice the internal energy)?
6. If you vigorously shake a can of chicken broth back and forth for more than a minute, will the temperature of the broth increase? (Try it and see.)
7. When air is quickly compressed, why does its temperature increase?
8. Suppose you do 100 J of work in compressing a gas. If 80 J of heat escapes in the process, what is the change in internal energy of the gas?
9. Why does the bottom of a tire pump feel hot when you pump air in the tire, but when air is released, the valve stem feels cool?
10. When you blow up a balloon, do you slightly warm the balloon? When air is allowed to rush out of it, how, if at all, does the temperature of that expanding air change?
11. What happens to the gas pressure within a sealed gallon can when it is heated? When it is cooled? Why?
12. Is it possible to wholly convert a given amount of mechanical energy into thermal energy? Is it possible to wholly convert a given amount of thermal energy into mechanical energy? Cite examples to illustrate your answers.
13. Why does cold mountain air become warm when it descends into a valley?
14. Everybody knows that warm air rises. So it might seem that the air temperature should be higher at the tops of

mountains than down below. But the opposite is most often the case. Why?

15. What is the ultimate source of energy in coal, oil, and wood? Why do we call energy from wood renewable but energy from coal and oil nonrenewable?

16. What is the ultimate source of energy in a hydroelectric power plant?

17. The combined molecular kinetic energies of molecules in a cool lake are greater than the combined molecular kinetic energies of molecules in a cup of hot tea. Pretend you partially immerse the teacup in the lake and that the tea *absorbs* 10 calories from the water and becomes hotter, while the water that gives up 10 calories becomes cooler. Would this energy transfer violate the first law of thermodynamics? The second law of thermodynamics? Defend your answers.

18. Why is thermal pollution a relative term?

19. The box "Thermodynamics Dramatized" shows the crushing of an inverted steam-filled can placed in a pan of water. Would the water need to be cold? Would crushing occur if the water were hot but not boiling? Would it crush in boiling water? (Try it and see!)

20. Why is it advantageous to use steam that is as hot as possible in a steam-driven turbine?

21. How does the ideal efficiency of an automobile relate to the temperature of the engine and the temperature of the environment in which it operates? Be specific.

22. What happens to the efficiency of a heat engine when the temperature of the reservoir into which thermal energy is transferred is lowered?

23. Under what conditions would a heat engine be 100% efficient?

24. To increase the efficiency of a heat engine, would it be preferable to produce the same temperature increment by increasing the temperature of the reservoir while maintaining the temperature of the sink constant, or to decrease the temperature of the sink while maintaining the temperature of the reservoir constant? Explain.

25. Could you cool a kitchen by leaving the refrigerator door open and closing the kitchen door and windows? Explain.

26. Could you warm a kitchen by leaving the door of a hot oven open? Explain.

27. An electric fan not only doesn't decrease the temperature of air, but it actually increases air temperature. How, then, are you cooled by a fan on a hot day?

28. Strictly speaking, why will a refrigerator containing a fixed amount of food consume more energy in a warm room than in a cold room?

29. A refrigerator moves heat from cold to warm. Why does this not violate the second law of thermodynamics?

30. What happens to the density of a quantity of gas when its temperature is decreased and its pressure is held constant?

31. If you squeeze an air-filled balloon and no heat escapes, what happens to the internal energy of the gas in the balloon?

32. In buildings that are being electrically heated, is it at all wasteful to turn all the lights on? Is turning all the lights on wasteful if the building is being cooled by air-conditioning?

33. Why can the drinking bird in Figure 17.4 in the previous chapter be considered a heat engine?

34. Defend the statement that 100% of the electrical energy that goes into lighting a lamp is converted to thermal energy. Are the first and the second laws of thermodynamics violated?

35. Molecules in the combustion chamber of a rocket engine are in a high state of random motion. When the molecules are expelled through a nozzle in a more ordered state, will their temperature be more, less, or the same as their initial temperature in the chamber before being exhausted?

36. Is the total energy of the universe becoming more unavailable with time? Explain.

37. According to the second law of thermodynamics, is the universe moving to a more ordered state or to a more disordered state?

38. Do adiabatic parcels occur in the atmosphere, in the ocean, or in both?

39. The ocean possesses enormous numbers of molecules, all with kinetic energy. Can this energy be extracted and used as a power source? Defend your answer.

40. Why do we say a substance in a liquid phase is more disordered than the same substance in a solid phase?

41. Comment on this statement: The second law of thermodynamics is one of the most fundamental laws of nature, yet it is not an exact law at all.

42. Water evaporates from a salt solution and leaves behind salt crystals that have a higher degree of molecular order than the more randomly moving molecules in the saltwater. Has the entropy principle been violated? Why or why not?

43. Water put into the freezer compartment of your refrigerator goes to a state of less molecular disorder when it freezes. Is this an exception to the entropy principle? Explain.

44. As a chicken develops from an egg, it becomes more ordered with time. Does this violate the principle of entropy? Explain.

45. The United States Patent and Trademark Office rejects claims for perpetual motion machines (in which energy output is as great or greater than energy input) without even investigating them. Why is this?

46. It is generally assumed that perpetual motion machines are impossible to construct. Is it inconsistent to say that molecules are in perpetual motion?

47. A classmate says that all this stuff about no perpetual motion is bunk; that atoms, planets, stars, and everything are in perpetual motion. What distinction is being missed here?

48. (a) If you spent 10 minutes repeatedly shaking and throwing down a pair of coins, would you expect to see two heads come up at least once? (b) If you spent an hour shaking a handful of 10 coins and thtowing them down, would you expect to see all 10 come up heads at least once? (c) If you stirred a box of 10,000 coins and tossed them repeatedly on the floor all day long, would you expect to see all 10,000 appear as heads at least once?

PROBLEMS

1. What is the ideal efficiency of an automobile engine in which fuel is heated to 2700 K and the outdoor air is 270 K?
2. Consider an ocean thermal energy conversion (OTEC) power plant that operates on a temperature difference between deep 4°C water and 25°C surface water. Show that the Carnot efficiency of this plant is 7%.
3. On a chilly 10°C day, your friend who loves cold weather says she wishes it were twice as cold. Taking this literally, show that the temperature she wishes for would be −131.5°C.
4. Imagine a giant dry-cleaner's bag full of air at a temperature of −35°C floating like a balloon with a string hanging from it 10 km above the ground. Estimate what its temperature would be if you were able to yank it suddenly back to Earth's surface.
5. Calculate the ideal efficiency of an engine wherein fuel is heated to 2700 K and the surrounding air is 300 K.
6. Wally Whacko claims to have invented a heat engine that will revolutionize industry. It runs between a hot source at 300°C and a cold sink at 25°C. He claims that his engine is 92% efficient.
   (a) What error did he make in his choice of temperature scales?
   (b) What is the actual maximum efficiency of his engine?
7. A power station with an efficiency of 0.4 generates 10^8 W of electric power and dissipates 1.5×10^8 J of heat energy each second to the cooling water that flows through it, which increases its temperature by 3 Celsius degrees. Knowing that the specific heat of water in SI units is 4184 J/kg·°C, show that 12,000 kg of warmed water flows through the plant each second.
• 8. Construct a table of all the possible combinations of numbers that can come up when you throw two dice. Your friend says, "Yes, I know that 7 is the most likely total number when two dice are thrown. But *why* 7?" Based on your table, answer your friend, and explain that, in thermodynamics, the situations that are likely to be observed are those that can be formed in the greatest number of ways.

CHAPTER 18 ONLINE RESOURCES

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- 18.11, 18.13

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- Adiabatic Process

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PART THREE MULTIPLE-CHOICE PRACTICE EXAM

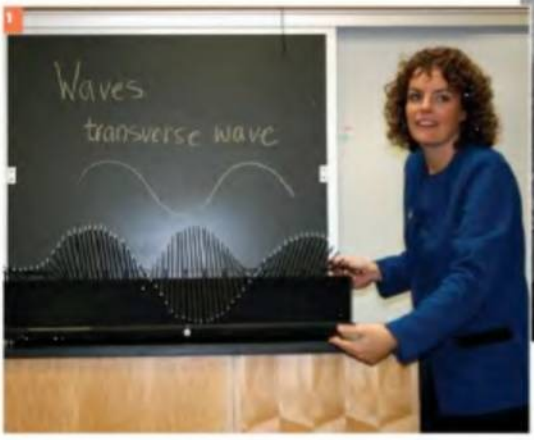
Choose the BEST answer to the following.

1. Temperature is generally proportional to a substance's
   (a) thermal energy.
   (b) vibrational kinetic energy.
   (c) average translational kinetic energy.
   (d) rotational kinetic energy.
2. Heat is simply another word for
   (a) temperature.
   (b) internal energy.
   (c) internal energy that flows from hot to cold.
   (d) radiant energy.
3. Which of these temperatures is likely when a container of water at 20°C is mixed with water at 28°C?
   (a) 19°C. (c) 30°C.
   (b) 22°C. (d) More than 30°C.
4. The amount of heat transferred to a system can be measured in
   (a) calories. (c) Either.
   (b) joules. (d) Neither.
5. Hot sand cools off faster at night than vegetation. Compared with vegetation, sand's specific heat capacity is
   (a) less. (c) about the same.
   (b) greater. (d) Can't say.
6. When the temperature of a strip of iron is increased, the length of the strip
   (a) also increases.
   (b) actually decreases.
   (c) may increase and may decrease.
   (d) decreases in width as it gets longer.
7. Microscopic slush in water tends to make the water
   (a) more dense. (c) more slippery.
   (b) less dense. (d) warmer.
8. The principal source of Earth's internal energy is
   (a) tidal friction. (c) radioactivity.
   (b) gravitational pressure. (d) geothermal heat.
9. The surface of planet Earth loses energy to outer space due mostly to
   (a) conduction. (c) radiation.
   (b) convection. (d) radioactivity.
10. The greenhouse gases that contribute to global warming are
    (a) water vapor. (c) Both.
    (b) carbon dioxide. (d) Neither.
11. In a mixture of hydrogen, oxygen, and nitrogen gases at a given temperature, the fastest molecules on average are those of
    (a) hydrogen. (c) nitrogen.
    (b) oxygen. (d) All have same average speed.
12. Thermal conduction mainly involves
    (a) electrons. (c) neutrons.
    (b) protons. (d) ions.
13. Thermal convection mainly involves
    (a) radiant energy. (c) insulators.
    (b) fluids. (d) All of these.
14. Heat comes from the Sun to Earth by the process of
    (a) conduction.
    (b) convection.
    (c) radiation.
    (d) All of these, though radiation is greater.
15. A high-temperature source radiates relatively
    (a) short wavelengths. (c) low frequencies of radiation.
    (b) long wavelengths. (d) None of these.
16. An object that absorbs energy well also
    (a) conducts well. (c) radiates well.
    (b) convects well. (d) None of these.
17. Newton's law of cooling applies to objects that
    (a) cool. (c) Both.
    (b) warm up. (d) Neither.
18. Compared with radiation from the Sun, terrestrial radiation has a lower
    (a) wavelength. (c) Both.
    (b) frequency. (d) Neither.
19. When relatively slow-moving molecules condense from the air, the temperature of the remaining air tends to
    (a) remain unchanged. (c) increase.
    (b) decrease. (d) spread out uniformly.
20. Put a saucer of water on your table. A process that then occurs is
    (a) evaporation. (c) Both.
    (b) condensation. (d) Neither.
21. The process of boiling water tends to
    (a) warm the water. (c) Both.
    (b) cool the water. (d) Neither.
22. Boiling and freezing occur when water is subjected to
    (a) decreased temperatures.
    (b) decreased atmospheric pressure.
    (c) increased temperatures.
    (d) increased atmospheric pressure.
23. Regelation occurs due to water's
    (a) high specific heat.
    (b) open-structured ice crystals.
    (c) high rate of expansion.
    (d) slight tendency to freeze when temperature is lowered.
24. When water changes to steam, energy is
    (a) absorbed by the water.
    (b) released by the water.
    (c) conserved as the phase change occurs.
    (d) changed to a different form.
25. The lowest possible temperature is absolute zero, at
    (a) 0 kelvin. (c) Both are the same.
    (b) −273°C. (d) None of these.
26. When you breathe on your hand, the temperature of the exhaled air reaching your hand
    (a) increases. (c) remains unchanged.
    (b) decreases. (d) depends on how you blow.
27. The second law of thermodynamics tells us that heat doesn't flow from
    (a) hot to cold ever.
    (b) cold to hot ever.
    (c) hot to cold without external energy.
    (d) cold to hot without external energy.
28. Heat engines, such as a jet engine, are more efficient when run at
    (a) high temperatures.
    (b) constant temperatures.
    (c) low temperatures.
    (d) a constant rate.
29. The direction of natural processes is from states of
    (a) higher order to lower order.
    (b) lower order to higher order.
    (c) disorganization to organization.
    (d) disorder to equilibrium.
30. As entropy in a system increases, energy in the system
    (a) becomes more ordered.
    (b) becomes less ordered.
    (c) reaches equilibrium.
    (d) moves toward destruction.

After you have made thoughtful choices, and discussed them with your friends, find the answers on page 681.

Part Four
Sound

19 Vibrations and Waves



1 Diane Reindeau shows her class how waves are generated by vibrations in a classroom wave demonstrator. 2 Frank Oppenheimer at the San Francisco Exploratorium shows a straight-line trace when a swinging pendulum bob leaks sand on a stationary conveyor belt. 3 When the conveyor belt moves in uniform motion, a sine curve is traced.

The Exploratorium in San Francisco is not only a world-class museum of science and technology, it is also perhaps the best place on planet Earth to teach a physics class. I was honored to do so in the years 1982–2000. The Exploratorium is special because of its founder, Frank Oppenheimer, the younger brother of more famous J. Robert Oppenheimer, the director of the Los Alamos lab during World War II. Frank's passion for doing physics was surpassed only by his passion for teaching it. I was enormously privileged to share my classroom with him when vibrations, waves, and musical sounds were the topic. I remember after one of his brilliant presentations he quietly asked me how he did. Almost tearfully I responded, "You were great." For it was true. In addition to his explanations of physics being great, he himself exuded a personal greatness—with his insistence on excellence, a lack of pretentiousness, and a respect for invention and play, and for his students. Frank was the most-loved teacher in my experience.

Frank Oppenheimer suffered in the political witch hunts of the 1950s when he admitted membership in the American Communist Party back in the depths of the Depression, along with many idealistic citizens who were sensitive to the nation's high unemployment at the time. Frank told me that after he refused to give the names of other members to the House Un-American Activities Committee, he was hounded by the FBI. Despite high accomplishments in physics, and despite international awards in physics, he was barred from practicing physics. He was, however, allowed to be a cattle farmer and teach general science at Pagosa Springs High School in Colorado. Frank went on to say that adding insult to injury, his neighbors were warned by government agents to keep a wary eye on his potential "un-American activities." Frank devoted the rest of his life to exposing the general public to the wonders of science, which culminated in the Exploratorium in San Francisco.

I dedicated the Fifth Edition of my *Conceptual Physics* to him. Before Frank died in 1985, he contributed this paragraph, which I used as the book's opening paragraph:

"By trying to understand the natural world around us, we gain confidence in our ability to determine whom to trust and what to believe about other matters as well. Without this confidence, our decisions about social, political, and economic matters are inevitably based entirely on the most appealing lie that someone else dishes out to us. Our appreciation of the noticings and discoveries of both scientists and artists therefore serves, not only to delight us, but also to help us make more satisfactory and valid decisions and to find better solutions for our individual and societal problems."

Frank's main motive for founding the Exploratorium was to lift people by encouraging them to do for themselves, and think for themselves—a way of teaching that is now widespread.

Good Vibrations

In a general sense, anything that moves back and forth, to and fro, side to side, in and out, or up and down is vibrating. A *vibration* is a periodic wiggle in time. A periodic wiggle in both space and time is a *wave*. A wave extends from one place to another. Light and sound are both vibrations that propagate throughout space as waves, but two very different kinds of waves. Sound is a mechanical wave, the propagation of vibrations through a material medium—a solid, liquid, or gas. If there is no medium to vibrate, then no sound is possible. Sound cannot travel in a vacuum. But light can, for, as we shall learn in later chapters, light is a vibration of electric and magnetic fields—an electromagnetic wave of pure energy. Although light can pass through many materials, it needs none. This is evident when it propagates through the vacuum between the Sun and Earth. The source of all waves—mechanical or electromagnetic—is something that is vibrating. We shall begin our study of vibrations and waves by considering the motion of a simple pendulum.

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Tutorial
Waves and Vibrations

Vibration of a Pendulum

If we suspend a stone at the end of a piece of string, we have a simple pendulum. Likewise for a sand-filled container suspended at the end of a vertical pole that swings to and fro. In the opening photos of this chapter, Frank Oppenheimer shows how sand leaking from such a pendulum traces a straight line on a stationary conveyor belt, and then, when the belt moves at constant speed, produces a special curve known as a **sine curve.** A sine curve is a pictorial representation of a wave produced by simple harmonic motion.[1]

Pendulums swing to and fro with such regularity that, for a long time, they were used to control the motion of most clocks. They can still be found in grandfather clocks and cuckoo clocks. Galileo discovered that the time a pendulum takes to swing to and fro through small distances depends only on the *length of the pendulum.*[2] The

In 1848, Jean Foucault devised a very long pendulum, that when swinging appears to be changing directions during the day. Actually, Earth revolves underneath the pendulum.

[1]The condition for simple harmonic motion is that the restoring force is proportional to the displacement from equilibrium. This condition is met, at least approximately, for most vibrations. The component of weight that restores a displaced pendulum to its equilibrium position is directly proportional to the pendulum's displacement (for small angles)—likewise for a bob attached to a spring. Recall from Chapter 12, Hooke's law for a spring: $F = k\Delta x$, where the force to stretch (or compress) a spring is directly proportional to the distance stretched (or compressed).

[2]The equation for the period of a simple pendulum for small arcs is $T = 2\pi\sqrt{\frac{L}{g}}$, where T is the period, L is the length of the pendulum, and g is the acceleration of gravity.

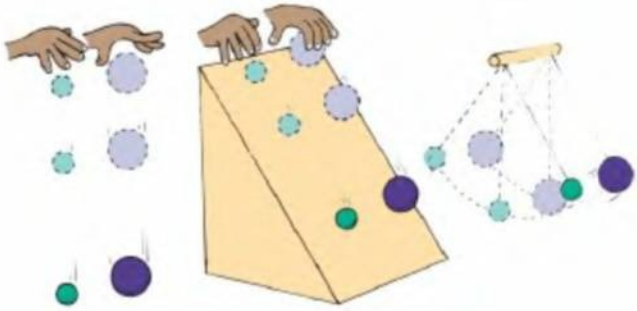

FIGURE 19.1
If you drop two balls of different mass, they accelerate at g. Let them slide without friction down the incline, and they slide together at the same fraction of g. Tie them to strings of the same length so they are pendulums, and they swing to and fro in unison. In all cases, the motions are independent of mass.

time of a to-and-fro swing, called the **period,** does not depend on the mass of the pendulum or on the size of the arc through which it swings.

A long pendulum has a longer period than a short pendulum; that is, it swings to and fro less frequently than a short pendulum. A grandfather clock's pendulum with a length of about 1 meter, for example, swings with a leisurely period of 2 seconds, while the much shorter pendulum of a cuckoo clock swings with a period that is less than a second. In addition to length, the period of a pendulum depends on the acceleration of gravity. Oil and mineral prospectors use very sensitive pendulums to detect slight differences in this acceleration, which is affected by the densities of underlying formations.

Wave Description

A sine curve can also be traced by a bob attached to a spring undergoing vertical simple harmonic motion (Figure 19.2). As previously mentioned, a sine curve is a pictorial representation of a wave. As for a water wave, the high points of a sine wave are called *crests* and the low points are called *troughs.* The straight dashed line represents the "home" position, or midpoint of the vibration. The term **amplitude** refers to the distance from the midpoint to the crest (or trough) of the wave. So the amplitude equals the maximum displacement from equilibrium.

The **wavelength** of a wave is the distance from the top of one crest to the top of the next crest. Or, equivalently, the wavelength is the distance between any successive identical parts of the wave. The wavelengths of waves at the beach are measured in meters, the wavelengths of ripples in a pond are measured in centimeters, and the wavelengths of light are measured in billionths of a meter (nanometers).

How frequently a vibration occurs is described by its **frequency.** The frequency of a vibrating pendulum, or of an object on a spring, specifies the number of to-and-fro vibrations it makes in a given time (usually 1 second). A complete to-and-fro oscillation is one vibration. If it occurs in 1 second, the frequency is one vibration per second. If two vibrations occur in 1 second, the frequency is two vibrations per second.

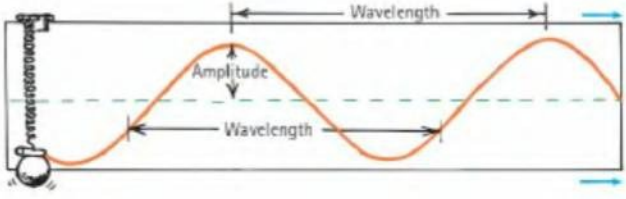

FIGURE 19.2
INTERACTIVE FIGURE
When the bob vibrates up and down, a marking pen traces a sine curve on paper that is moved horizontally at constant speed.

The unit of frequency is called the **hertz** (Hz), after Heinrich Hertz, who demonstrated radio waves in 1886. One vibration per second is 1 hertz; two vibrations per second is 2 hertz, and so on. Higher frequencies are measured in kilohertz (kHz, thousands of hertz), and still higher frequencies in megahertz (MHz, millions of hertz) or gigahertz (GHz, billions of hertz). AM radio waves are measured in kilohertz, and FM radio waves are measured in megahertz; radar and microwave ovens operate at gigahertz frequencies. A station at 960 kHz on the AM radio dial, for example, broadcasts radio waves that have a frequency of 960,000 vibrations per second. A station at 101.7 MHz on the FM dial broadcasts radio waves with a frequency of 101,700,000 hertz. These radio-wave frequencies are the frequencies at which electrons are forced to vibrate in the antenna of a radio station's transmitting tower. So we see that the source of all waves is something that vibrates. The frequency of the vibrating source and the frequency of the wave it produces are the same.

FIGURE 19.3
Electrons in the transmitting antenna vibrate 940,000 times each second and produce 940-kHz radio waves.

The **period** of a vibration or wave is the time for one complete vibration. If an object's frequency is known, its period can be calculated, and vice versa. Suppose, for example, that a pendulum makes two vibrations in 1 second. Its frequency is 2 Hz. The time needed to complete one vibration—that is, the period of vibration—is 1/2 second. Or, if the vibration frequency is 3 Hz, then the period is 1/3 second. The frequency and period are the inverse of each other:

$$\text{Frequency} = \frac{1}{\text{period}}$$

or, vice versa,

$$\text{Period} = \frac{1}{\text{frequency}}$$

The frequency of a "classical" wave—such as a sound wave, water wave, or radio wave—matches the frequency of its vibrating source. (In the quantum world of atoms and photons, the rules are different.)

CHECK POINT

1. An electric toothbrush completes 90 cycles every second. What is (a) its frequency? (b) its period?
2. Gusts of wind make the Willis Tower in Chicago sway back and forth, completing a cycle in 10 s. What is (a) its frequency? (b) its period?

Check Your Answers

1. (a) 90 cycles per second is 90 Hz; (b) 1/90 s.
2. (a) 1/10 Hz; (b) 10 s.

Wave Motion

Most information about our surroundings arrives in some form of waves. It is through wave motion that sounds are transported to our ears, light to our eyes, and electromagnetic signals to our radios and wireless phones. Through *wave motion*, energy can be transferred from a source to a receiver without the transfer of matter between the two points.

Wave motion can be most easily understood by first considering the simple case of a horizontally stretched rope. If one end of such a rope is shaken up and down, a rhythmic disturbance travels along the rope. Each particle of the rope moves up and down, while, at the same time, the disturbance moves along the length of the rope. The medium, rope or whatever, returns to its initial condition after the disturbance has passed. What is propagated is the disturbance, not the medium itself.

Numerous fans at a concert or stadium "do the wave" by rising from their seats, swinging their arms high, then sitting back in their seats—all in appropriate sequence.

Perhaps a more familiar example of wave motion is provided by a water wave. If a stone is dropped into a quiet pond, waves will travel outward in expanding circles, the centers of which are at the source of the disturbance. In this case, we might think that water is being transported with the waves, since water is splashed onto previously dry ground when the waves meet the shore. We should realize, however, that, barring obstacles, the water will flow back into the pond, and things will be much as they were in the beginning. The surface of the water will have been disturbed, but the water itself will have gone nowhere. A leaf on the surface will bob up and down as the waves pass, but will end up where it started. Again, the medium returns to its initial condition after the disturbance has passed—even in the extreme case of a tsunami.

Mechanical waves require a medium. A Slinky needs its coils; ocean waves need water; sound from a bugle needs air; "doing the wave" in a stadium needs exuberant fans.

Let us consider another example of a wave to illustrate that what is transported from one location to another is a disturbance in a medium, not the medium itself. If you view a field of tall grass from an elevated position on a gusty day, you will see waves travel across the grass. The individual stems of grass do not leave their places; instead, they swing to and fro. Furthermore, if you stand in a narrow footpath, the grass that blows over the edge of the path, brushing against your legs, is very much like the water that doused the shore in our earlier example. While wave motion continues, the tall grass swings back and forth, vibrating between definite limits but going nowhere. When the wave motion stops, the grass returns to its initial position.

Wave Speed

The speed of periodic wave motion is related to the frequency and wavelength of the waves. We can understand this by considering the simple case of water waves (Figures 19.4 and 19.5). Imagine that we fix our eyes on a stationary point on the surface of water and observe the waves passing by this point. We can measure how much time passes between the arrival of one crest and the arrival of the next one (the period) and also observe the distance between crests (the wavelength). We know that speed is defined as distance divided by time. In this case, the distance is one wavelength and the time is one period, so **wave speed** = wavelength/period.

For example, if the wavelength is 10 m and the time between crests at a point on the surface is 0.5 s, the wave moves 10 m in 0.5 s and its speed is 10 m divided by 0.5 s, or 20 m/s.

Since period is the inverse of frequency, the formula wave speed = wavelength/period can also be written

$$\text{Wave speed} = \text{frequency} \times \text{wavelength}$$

This relationship holds true for all kinds of waves, whether they are water waves, sound waves, or light waves.

FIGURE 19.4
Water waves.

FIGURE 19.5
A top view of water waves.

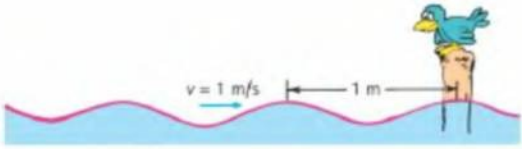

FIGURE 19.6
INTERACTIVE FIGURE
If the wavelength is 1 m, and one wavelength per second passes the pole, then the speed of the wave is 1 m/s.

CHECK POINT

1. If a train of freight cars, each 10 m long, rolls by you at the rate of three cars each second, what is the speed of the train?
2. If a water wave oscillates up and down three times each second and the distance between wave crests is 2 m, what is its frequency? What is its wavelength? What is its wave speed?

Check Your Answers

1. 30 m/s. We can see this in two ways. (a) According to the speed definition from Chapter 2, $v = d/t = (3 \times 10\ \text{m})/1\ \text{s} = 30\ \text{m/s}$, since 30 m of train passes you in 1 s. (b) If we compare our train to wave motion, where wavelength corresponds to 10 m and frequency is 3 Hz, then speed = frequency × wavelength = 3 Hz × 10 m = 3/s × 10 m = 30 m/s.
2. The frequency of the wave is 3 Hz, its wavelength is 2 m, and its wave speed = frequency × wavelength = 3/s × 2 m = 6 m/s.

The speed v of a wave can be expressed by the equation $v = f\lambda$, where f is the wave frequency and λ (the Greek letter lambda) is the wavelength of the wave.

Transverse Waves

Fasten one end of a rope to a wall and hold the free end in your hand. If you suddenly shake the free end up and then down, a pulse will travel along the rope and back (Figure 19.7). In this case, the motion of the rope (up and down arrows) is at right angles to the direction of wave speed. The right-angled, or sideways, motion is called *transverse motion.* Now shake the rope with a regular, continuing up-and-down motion, and the series of pulses will produce a wave. Since the motion of the medium (the rope, in this case) is transverse to the direction the wave travels, this type of wave is called a **transverse wave.**

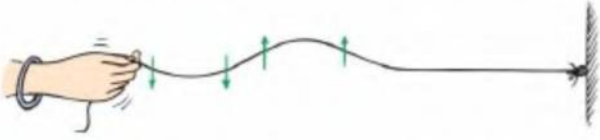

FIGURE 19.7
A transverse wave.

Waves in the stretched strings of musical instruments and on the surfaces of liquids are transverse. We will see later that electromagnetic waves, which make up radio waves and light, are also transverse.

Practicing Physics

Here we have a sine curve that represents a transverse wave. With a ruler, measure the wavelength and amplitude of the wave.

Wavelength _____
Amplitude _____

Longitudinal Waves

Sound requires a medium. It can't travel in a vacuum because there's nothing to compress and stretch.

Not all waves are transverse. Sometimes parts that make up a medium move to and fro in the same direction in which the wave travels. Motion is *along* the direction of the wave rather than at right angles to it. This produces a **longitudinal wave.**

Both a transverse wave and a longitudinal wave can be demonstrated with a spring or a Slinky stretched out on the floor, as shown in Figure 19.8. A transverse wave is demonstrated by shaking the end of a Slinky from side to side in a direction perpendicular to the Slinky. A longitudinal wave is demonstrated by rapidly pulling and pushing the end of the Slinky toward and away from you in a direction parallel to the Slinky. In this case, we see that the medium vibrates parallel to the direction of energy transfer. Part of the Slinky is compressed, and a wave of *compression* travels along the spring. In between successive compressions is a stretched region, called a *rarefaction*. Both compressions and rarefactions travel in the same direction along the Slinky. Sound waves are longitudinal waves.

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Video
Longitudinal vs. Transverse Waves

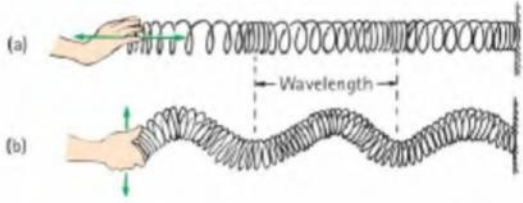

FIGURE 19.8
INTERACTIVE FIGURE
Both waves transfer energy from left to right. (a) When the end of the Slinky is pushed and pulled rapidly along its length, a longitudinal wave is produced. (b) When it's shaken from side to side, a transverse wave is produced.

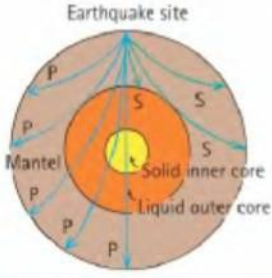

FIGURE 19.9
P and S waves generated by an earthquake.

Waves that have been generated by earthquakes and that travel in the ground are of two main types: longitudinal P waves and transverse S waves. (Geology students often remember P waves as "push–pull" waves, and S waves as "side-to-side" waves.) S waves cannot travel through liquid matter, but P waves can travel through both molten and solid parts of Earth's interior. Study of these waves reveals much about Earth's interior.

The wavelength of a longitudinal wave is the distance between successive compressions or, equivalently, the distance between successive rarefactions. The most common example of longitudinal waves is sound in air. Elements of air vibrate to and fro about some equilibrium position as the waves move by. We will treat sound waves in detail in Chapter 20.

Wave Interference

Whereas a material object such as a rock will not share its space with another rock, more than one vibration or wave can exist at the same time in the same space. If we drop two rocks in water, the waves produced by each can meet and produce **wave interference.** The overlapping of waves can form an **interference pattern.** Within the pattern, wave effects may be increased, decreased, or neutralized.

When more than one wave occupies the same space at the same time, the displacements add at every point. This is the *superposition principle*. So, when the crest of one wave overlaps the crest of another, their individual effects add together to produce a wave of increased amplitude. This is called *constructive interference*

(Figure 19.10). When the crest of one wave overlaps the trough of another, their individual effects are reduced. The high part of one wave simply fills in the low part of another. This is called *destructive interference*.

FIGURE 19.10
Constructive and destructive interference in a transverse wave.

Wave interference is easiest to see in water. In Figure 19.11 we see the interference pattern made when two vibrating objects touch the surface of water. We can see the regions where a crest of one wave overlaps the trough of another to produce regions of zero amplitude. At points along these regions, the waves arrive out of step. We say they are *out of phase* with each other.

Interference is characteristic of all wave motion, whether the waves are water waves, sound waves, or light waves. We will treat the interference of sound in the next chapter and the interference of light in Chapter 29.

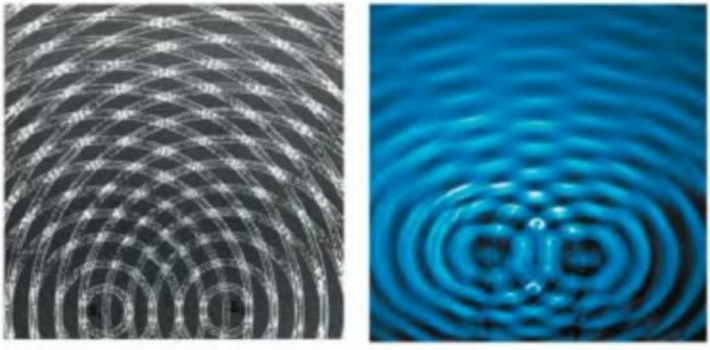

FIGURE 19.11
Two sets of overlapping water waves produce an interference pattern. The left image is an idealized drawing of the expanding waves from the two sources. The right image is a photograph of an actual interference pattern.

Standing Waves

If we tie a rope to a wall and shake the free end up and down, we produce a train of waves in the rope. The wall is too rigid to shake, so the waves are reflected back along the rope. By shaking the rope just right, we can cause the incident and reflected waves to form a **standing wave,** where parts of the rope, called the *nodes,* appear to be standing still. Nodes are the regions of minimal or zero displacement, with minimal or zero energy. *Antinodes* (not labeled in Figure 19.12), on the other hand, are the regions of maximum displacement and maximum energy. You can hold your fingers just over and under the nodes and the rope doesn't touch them. Other parts of the rope, especially the antinodes, would make contact with your fingers. Antinodes occur halfway between nodes.

Standing waves are the result of interference (and, as we will see in Chapter 20, *resonance*). When two sets of waves of equal amplitude and wavelength pass through each other in opposite directions, the waves are steadily in and out of phase with each other. This occurs for a wave that reflects upon itself. Stable regions of constructive and destructive interference are produced.

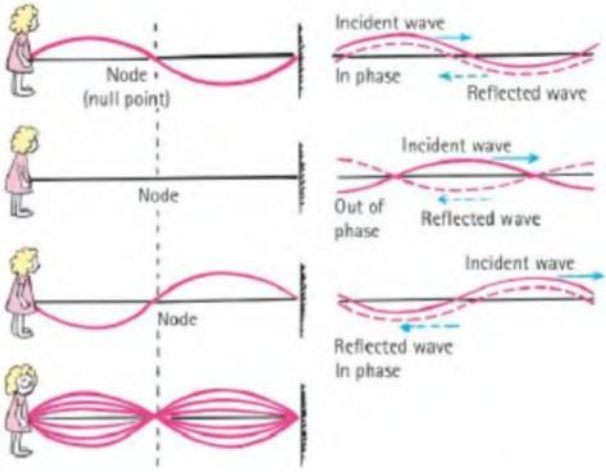

FIGURE 19.12
INTERACTIVE FIGURE

The incident and reflected waves interfere to produce a standing wave.

It is easy to make standing waves yourself. Tie a rope—or better, a rubber tube—to a firm support. Shake the tube from side to side with your hand. If you shake the tube with the right frequency, you will set up a standing wave, as shown in Figure 19.13a. Shake the tube with twice the frequency, and a standing wave of half the previous wavelength, having two loops, will result (Figure 19.13b). (The distance between successive nodes is a half wavelength; two loops constitute a full wavelength.) If you triple the frequency, a standing wave with one-third the original wavelength, having three loops, will result (Figure 19.13c); and so forth.

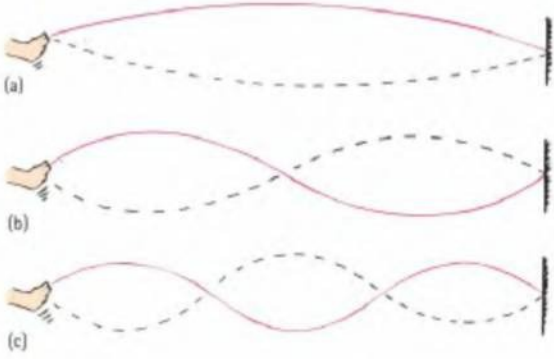

FIGURE 19.13
INTERACTIVE FIGURE

(a) Shake the rope until you set up a standing wave of one segment (1/2 wavelength).
(b) Shake with twice the frequency and produce a wave with two segments (1 wavelength).
(c) Shake with three times the frequency and produce three segments (1 1/2 wavelengths).

An organ pipe or flute makes sound by standing waves of air in a column of air.

Standing waves are set up in the strings of musical instruments when plucked, bowed, or struck. They are set up in the air in an organ pipe, a trumpet, or a clarinet and the air of a soda-pop bottle when air is blown over the top. Standing waves can be set up in a tub of water or in a cup of coffee by sloshing the tub or cup back and forth with the right frequency. Standing waves can be produced with either transverse or longitudinal vibrations.

CHECK POINT

1. Is it possible for one wave to cancel another wave so that no amplitude remains at certain points?
2. Suppose you set up a standing wave of three segments, as shown in Figure 19.13c. If you shake with twice as much frequency, how many wave segments will occur in your new standing wave? How many wavelengths?

Check Your Answers

1. Yes. This is called destructive interference. In a standing wave in a rope, for example, parts of the rope have no amplitude—the nodes.
2. If you impart twice the frequency to the rope, you'll produce a standing wave with twice as many segments. You'll have six segments. Since a full wavelength has two segments, you'll have three complete wavelengths in your standing wave.

FIGURE 19.14
Satchmo produces standing waves of sound in his trumpet.

Doppler Effect

A pattern of water waves produced by a bug jiggling its legs and bobbing up and down in the middle of a quiet puddle is shown in Figure 19.15. The bug is not going anywhere but is merely treading water in a fixed position. The waves it makes are concentric circles, because wave speed is the same in all directions. If the bug bobs in the water at a constant frequency, the distance between wave crests (the wavelength) is the same in all directions. Waves encounter point A as frequently as they encounter point B. This means that the frequency of wave motion is the same at points A and B, or anywhere in the vicinity of the bug. This wave frequency is the same as the bobbing frequency of the bug.

FIGURE 19.15
Top view of water waves formed by a stationary bug jiggling in still water.

Suppose the jiggling bug moves across the water at a speed less than the wave speed. In effect, the bug chases part of the waves it has produced. The wave pattern is distorted and is no longer made of concentric circles (Figure 19.16). The center of the outer wave was made when the bug was at the center of that circle. The center of the next smaller wave was made when the bug was at the center of that circle, and so forth. The centers of the circular waves move in the direction of the swimming bug. Although the bug maintains the same bobbing frequency as before, an observer at B would see the waves coming more often. The observer would measure a higher frequency. This is because each successive wave has a shorter distance to travel and therefore arrives at B more frequently than if the bug weren't moving toward B. An observer at A, on the other hand, would measure a *lower* frequency because of the longer time between wave-crest arrivals. This is because, in order to reach A, each crest has to travel farther than the one ahead of it due to the bug's motion. This change in frequency due to the motion of the source (or receiver) is called the **Doppler effect** (after the Austrian scientist Christian Doppler, 1803–1853).

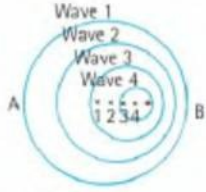

FIGURE 19.16
INTERACTIVE FIGURE
Water waves formed by a bug swimming in still water toward point B.

Water waves spread over the flat surface of the water. Sound and light waves, on the other hand, travel in three-dimensional space in all directions like an expanding balloon. Just as circular waves are closer together in front of the swimming bug, spherical sound or light waves ahead of a moving source are closer together and reach a receiver more frequently.

The Doppler effect is evident when you hear the changing pitch of an ambulance siren as it passes you. When the vehicle approaches, the pitch is higher than normal (like a higher note on a musical scale). This is because the crests of the sound waves encounter your ear more frequently. And when the vehicle passes and moves away, you hear a drop in pitch because the crests of the waves are hitting your ear less frequently.

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Tutorial
Doppler Effect
Video
Doppler Effect

Be clear about the distinction between *frequency* and *speed*. How frequently a wave vibrates is altogether different from how fast it moves from one location to another.

The Doppler effect also occurs for light. When a light source approaches, there is an increase in its measured frequency; and when it recedes, there is a decrease in its frequency. An increase in frequency is called a *blue shift*, because the increase is toward the high-frequency (or blue) end of the color spectrum. A decrease in frequency is called a *red shift*, referring to a shift toward the lower-frequency (or red) end of the color spectrum. Distant galaxies, for example, show a red shift in the light they emit. A measurement of this shift permits a calculation of their speeds of recession. A rapidly spinning star shows red-shifted light from the side turning away from us and blue-shifted light from the side turning toward us. This enables astronomers to calculate the star's spin rate.

FIGURE 19.17
INTERACTIVE FIGURE
The pitch (frequency) of sound is higher when a source is moving toward you, and lower when the source is moving away.

CHECK POINT

While you're at rest, a sound source moves toward you. Do you measure the speed of its sound wave to be greater or less than if the source were stationary?

Check Your Answer

Neither! It is the *frequency* of a wave that undergoes a change where there is motion of the source, not the *wave speed*. Be clear about the distinction between frequency and speed.

Bow Waves

When the speed of a source is as great as the speed of the waves it produces, something interesting occurs. The waves pile up in front of the source. Consider the bug in our previous example when it swims as fast as the wave speed. Can you see that the bug will keep up with the waves it produces? Instead of the waves moving ahead of the bug, they superimpose and hump up on one another directly in front of the bug (Figure 19.18). The bug moves right along with the leading edge of the waves it is producing.

FIGURE 19.18
Wave pattern created by a bug swimming at wave speed.

A similar thing happens when an aircraft travels at the speed of sound. In the early days of jet aircraft, it was believed that this pile-up of sound waves in front of the airplane imposed a "sound barrier" and that in order to go faster than the speed of sound, the plane would have to "break the sound barrier." What actually happens is that the overlapping wave crests disrupt the flow of air over the wings, making it more difficult to control the aircraft. But the barrier is not real. Just as a boat can easily travel faster than the waves it produces, an aircraft with sufficient power easily travels faster than the speed of sound. Then we say that it is *supersonic*. A supersonic airplane flies into smooth, undisturbed air because no sound wave can propagate out in front of it. Similarly, a bug swimming faster than the speed of water waves finds itself always entering into water with a smooth, unrippled surface.

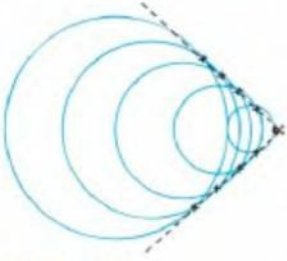


FIGURE 19.19
A bow wave, the pattern produced by a bug swimming faster than wave speed. The points at which adjacent waves overlap (×) produce the V shape.

When the bug swims faster than wave speed, ideally it produces a wave pattern, as shown in Figure 19.19. It outruns the waves it produces. The waves overlap at the edges and produce a V shape, called a **bow wave,** which appears to be dragging behind the bug. The familiar bow wave generated by a speedboat knifing through

the water is not a typical oscillatory wave. It is a disturbance produced by the overlapping of many circular waves.

Some wave patterns made by sources moving at various speeds are shown in Figure 19.20. Note that after the speed of the source exceeds wave speed, increased speed of the source produces a narrower V shape.[3]

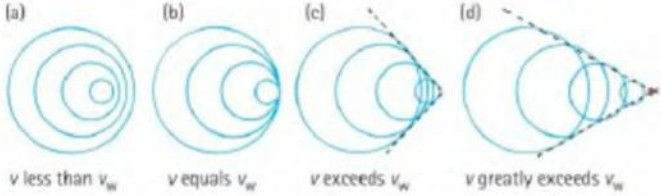


FIGURE 19.20
Patterns produced by a bug swimming at successively greater speeds. Overlapping at the edges occurs only when the bug swims faster than wave speed.

Shock Waves

A speedboat knifing through the water generates a two-dimensional bow wave. A supersonic aircraft similarly generates a three-dimensional **shock wave.** Just as a bow wave is produced by overlapping circles that form a V, a shock wave is produced by overlapping spheres that form a cone. And, just as the bow wave of a speedboat spreads until it reaches the shore of a lake, the conical wave generated by a supersonic craft spreads until it reaches the ground.

The bow wave of a speedboat that passes by can splash and douse you if you are at the water's edge. In a sense, you can say that you are hit by a "water boom." In the same way, when the conical shell of compressed air that sweeps behind a supersonic aircraft reaches listeners on the ground below, the sharp crack they hear is described as a **sonic boom.**

FIGURE 19.21
This aircraft is producing a cloud of water vapor that has just condensed out of the rapidly expanding air in the rarefied region behind the wall of compressed air.

We don't hear a sonic boom from slower-than-sound, or subsonic, aircraft because the sound waves reaching our ears are perceived as one continuous tone. Only when the aircraft moves faster than sound do the waves overlap to reach the listener in a single burst. The sudden increase in pressure is much the same in effect as the sudden expansion of air produced by an explosion. Both processes direct a burst of high-pressure air to the listener. The ear is hard pressed to distinguish between the high pressure from an explosion and the high pressure from many overlapping waves.

A water skier is familiar with the fact that next to the high crest of the V-shaped bow wave is a V-shaped depression. The same is true of a shock wave, which usually consists of two cones: a high-pressure cone generated at the bow of the supersonic aircraft and a low-pressure cone that follows at the tail of the aircraft.[4] The edges of these cones are visible in the photograph of the supersonic bullet in Figure 19.22. Between these two cones, the air pressure rises sharply to above atmospheric pressure, then falls below atmospheric pressure before sharply returning to normal beyond the inner tail cone (Figure 19.23). This overpressure suddenly followed by underpressure intensifies the sonic boom.

FIGURE 19.22
Shock wave of a bullet piercing a sheet of Plexiglas. Light deflecting as the bullet passes through the compressed air makes the shock visible. Look carefully and see the second shock wave originating at the tail of the bullet.

A common misconception is that sonic booms are produced when an aircraft flies through the "sound barrier"—that is, just as the aircraft surpasses the speed of sound. This is the same as saying that a boat produces a bow wave when it first overtakes its own waves. This is not so. The fact is that a shock wave and its

[3]Bow waves generated by boats in water are more complex than is indicated here. Our idealized treatment serves as an analogy for the production of the less complex shock waves in air.

[4]Shock waves are often more complex and involve multiple cones.

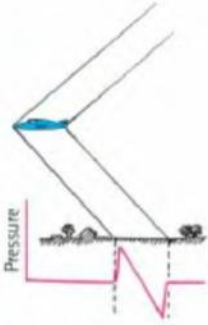


FIGURE 19.23

The shock wave is actually made up of two cones—a high-pressure cone with the apex at the bow of the aircraft and a low-pressure cone with the apex at the tail. A graph of the air pressure at ground level between the cones takes the shape of the letter N.

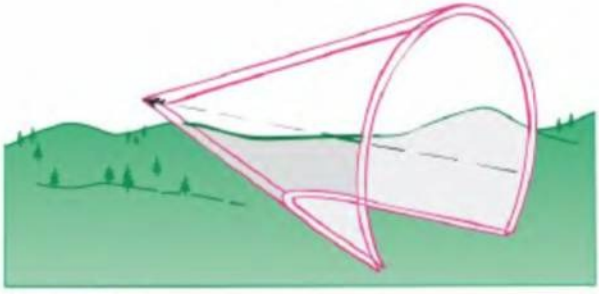


FIGURE 19.24

A shock wave.

resulting sonic boom are swept continuously behind and below an aircraft traveling faster than sound, just as a bow wave is swept continuously behind a speedboat. In Figure 19.25, listener B is in the process of hearing a sonic boom. Listener C has already heard it, and listener A will hear it shortly. The aircraft that generated this shock wave may have broken through the sound barrier many minutes ago!

FIGURE 19.25

The shock wave has not yet reached listener A, but it is now reaching listener B and has already reached listener C.

It is not necessary that the moving source be "noisy" to produce a shock wave. Once an object is moving faster than the speed of sound, it will *make* sound. A supersonic bullet passing overhead produces a crack, which is a small sonic boom. If the bullet were larger and disturbed more air in its path, the crack would be more boom-like. When a lion tamer cracks a circus whip, the cracking sound is actually a sonic boom produced by the tip of the whip when it travels faster than the speed of sound. Both the bullet and the whip are not in themselves sound sources, but, when traveling at supersonic speeds, they produce their own sound as they generate shock waves.

SUMMARY OF TERMS

Sine curve The waveform traced by simple harmonic motion, which can be made visible on a moving conveyor belt by a pendulum swinging at right angles above the moving belt.

Amplitude For a wave or vibration, the maximum displacement on either side of the equilibrium (midpoint) position.

Wavelength The distance between successive crests, troughs, or identical parts of a wave.

Frequency For a vibrating body or medium, the number of vibrations per unit time. For a wave, the number of crests that pass a particular point per unit time.

Hertz The SI unit of frequency. One hertz (symbol Hz) equals one vibration per second.

Period The time in which a vibration is completed. The period of a wave equals the period of the source and is equal to 1/frequency.

Wave speed The speed with which waves pass a particular point:

$$\text{Wave speed} = \text{frequency} \times \text{wavelength}$$

Transverse wave A wave in which the medium vibrates in a direction perpendicular (transverse) to the direction in which the wave travels. Light waves and water waves are transverse.

Longitudinal wave A wave in which the medium vibrates in a direction parallel (longitudinal) to the direction in which the wave travels. Sound waves are longitudinal.

Wave interference Phenomenon that occurs when two waves meet while traveling along the same medium.

Interference pattern The pattern formed by superposition of different sets of waves that produces reinforcement in some places and cancellation in others.

Standing wave A stationary wave pattern formed in a medium when two sets of identical waves pass through the medium in opposite directions.

Doppler effect The shift in received frequency due to motion of a vibrating source toward or away from a receiver.

Bow wave The V-shaped disturbance created by an object moving across a liquid surface at a speed greater than the wave speed.

Shock wave The cone-shaped disturbance created by an object moving at supersonic speed through a fluid.

Sonic boom The loud sound resulting from the incidence of a shock wave.

SUMMARY OF EQUATIONS

$$\text{Frequency} = \frac{1}{\text{period}}$$

$$\text{Period} = \frac{1}{\text{frequency}}$$

$$\text{Wave speed} = \frac{\text{wavelength}}{\text{period}} \text{ or frequency} \times \text{wavelength}$$

REVIEW QUESTIONS

Good Vibrations

1. What is a *wiggle in time* called? What do you call a *wiggle in space* and time?
2. What is the source of all waves?

Vibration of a Pendulum

3. What is meant by the *period* of a pendulum?
4. Which has the longer period, a short or a long pendulum?

Wave Description

5. How is a sine curve related to a wave?
6. Distinguish between these different aspects of a wave: period, amplitude, wavelength, and frequency.
7. How many vibrations per second are represented in a radio wave of 101.7 MHz?
8. How do *frequency* and *period* relate to each other?

Wave Motion

9. In one word, what is it that moves from source to receiver in wave motion?
10. Does the medium in which a wave travels move with the wave? Give examples to support your answer.

Wave Speed

11. What is the relationship among frequency, wavelength, and wave speed?

Transverse Waves

12. In what direction are the vibrations relative to the direction of wave travel in a transverse wave?

Longitudinal Waves

13. In what direction are the vibrations relative to the direction of wave travel in a longitudinal wave?
14. The wavelength of a transverse wave is the distance between successive crests (or troughs). What is the wavelength of a longitudinal wave?

Wave Interference

15. What is meant by the *superposition principle?*
16. Distinguish between *constructive interference* and *destructive interference*.
17. What kinds of waves can show interference?

Standing Waves

18. What is a *node*? What is an *antinode?*
19. Are standing waves a property of transverse waves, of longitudinal waves, or of both?

Doppler Effect

20. In the Doppler effect, does frequency change? Does wavelength change? Does wave speed change?
21. Can the Doppler effect be observed with longitudinal waves, with transverse waves, or with both?
22. What is meant by a blue shift and a red shift for light?

Bow Waves

23. How fast must a bug swim to keep up with the waves it produces? How fast must it move to produce a bow wave?
24. How fast does a supersonic aircraft fly compared with the speed of sound?
25. How does the V shape of a bow wave depend on the speed of the source?

Shock Waves

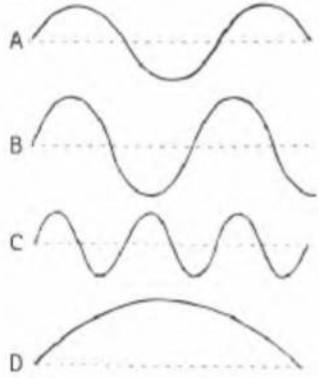
26. A bow wave on the surface of water is two-dimensional. How about a shock wave in air?
27. True or false: A sonic boom occurs only when an aircraft is breaking through the sound barrier. Defend your answer.
28. True or false: In order for an object to produce a sonic boom, it must be "noisy." Give two examples to support your answer.

PROJECTS

1. Tie a rubber tube, a spring, or a rope to a fixed support and produce standing waves. See how many nodes you can produce.
2. Wet your finger and rub it slowly around the rim of a thin-rimmed, stemmed wine glass while you hold the base of the glass firmly to a tabletop with your other hand. The friction of your finger will excite standing waves in the glass, much like the wave made on the strings of a violin by the friction from a violin bow. Try it with a metal bowl.
3. Write a letter to Grandma and tell her how waves can cancel one another, as well as what some of the applications of this physical phenomenon are these days.

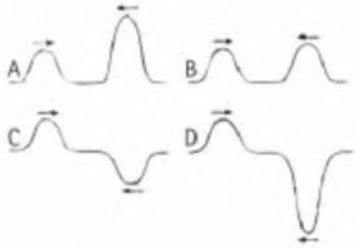
RANKING

1. All the waves shown have the same speed in the same medium. Use a ruler and rank these waves from most to least for

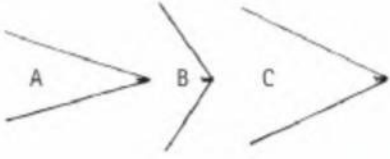


a. amplitude.
b. wavelength.
c. frequency.
d. period.

2. Shown above right are four different pairs of transverse wave pulses that move toward each other. At some point in time, the pulses meet and interact (interfere) with each other. Rank the four cases, from most to least, on the basis of the height of the peak that results when the centers of the pulses coincide.



3. The siren of a fire engine is heard in situations A, B, and C. Rank the pitch heard, from greatest to least, when the fire engine is traveling
   a. toward the listener at 30 km/h.
   b. toward the listener at 50 km/h.
   c. away from the listener at 20 km/h.
4. The shock waves A, B, C are produced by supersonic aircraft. Rank their speeds from greatest to least.



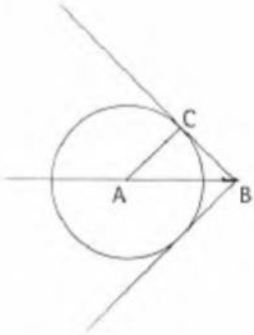
EXERCISES

1. Does the period of a pendulum depend on the mass of the bob? On the length of the string?
2. A heavy person and a light person swing to and fro on swings of the same length. Who has the longer period?
3. If a pendulum is shortened, does its frequency increase or decrease? What about its period?
4. A grandfather pendulum clock keeps perfect time. Then it is relocated to a summer home high in the mountains. Does it run faster, slower, or the same? Explain.
5. You pick up an empty briefcase and let it swing to and fro at its natural frequency. If the case were filled with books, would the natural frequency be lower, greater, or the same as before?
6. Is the time required to swing to and fro (the period) on a playground swing longer or shorter when you stand rather than sit? Explain.
7. What happens to the period of a wave when the frequency decreases?
8. Does it make sense that the mass of a bob in a simple pendulum doesn't affect the frequency of the pendulum? Defend your answer.
9. What happens to the wavelength of a wave when the frequency decreases?
10. If the speed of a wave doubles while the frequency remains the same, what happens to the wavelength?
11. If the speed of a wave doubles while the wavelength remains the same, what happens to the frequency?

12. You use a vice to firmly clamp one end of a hacksaw blade. You twang the free end and it vibrates. If you do the same, but first place a wad of clay on the free end, how, if at all, will the frequency of vibration differ? Would it make a difference if the wad of clay were stuck to the middle? Explain. (Why could this question have been asked back in Chapter 8?)
13. The needle of a sewing machine moves up and down in simple harmonic motion. Its driving force comes from a rotating wheel that is powered by an electric motor. How do you suppose the period of the up-and-down needle compares with the period of the rotating wheel?
14. If you shake the end of a spring to produce a wave, how does the frequency of the wave compare with the frequency of your shaking hand? Does your answer depend on whether you're producing a transverse wave or a longitudinal wave? Defend your answer.
15. What kind of motion should you impart to the nozzle of a garden hose so that the resulting stream of water approximates a sine curve?
16. What kind of motion should you impart to a stretched coiled spring (or Slinky) to provide a transverse wave? To provide a longitudinal wave?
17. What kind of wave is each of the following? (a) An ocean wave rolling toward Waikiki Beach. (b) The sound of one whale calling another whale under water. (c) A pulse sent down a stretched rope by snapping one end of it.
18. If a gas tap is turned on for a few seconds, someone a couple of meters away will hear the gas escaping long before she smells it. What does this indicate about the speed of sound and the speed at which molecules diffuse through the sound-carrying medium?
19. If we double the frequency of a vibrating object or the wave it produces, what happens to the period?
20. Do the two terms *wave speed* and *wave frequency* refer to the same thing? Defend your answer.
21. Red light has a longer wavelength than violet light. Which has the greater frequency?
22. What is the frequency of the second hand of a clock? The minute hand? The hour hand?
23. Consider a wave traveling along a thick rope tied to a thin rope. Which of these three wave characteristics does *not* undergo change—speed, frequency, or wavelength?
24. If you dip your finger repeatedly into a puddle of water, it creates waves. What happens to the wavelength if you dip your finger more frequently?
25. How does the frequency of vibration of a small object floating in water compare with the number of waves passing it each second?
26. In terms of wavelength, show how far a wave travels in one period.
27. What is the source of mechanical waves and of electromagnetic waves?
28. How many nodes, not including the endpoints, are there in a standing wave that is two wavelengths long? Three wavelengths long?
29. A rock is dropped in water, and waves spread over the flat surface of the water. What becomes of the energy in these waves when they die out?
30. The wave patterns seen in Figures 19.4 and 19.5 are composed of circles. What does this tell you about the speed of waves moving in different directions?
31. Why is lightning seen before thunder is heard?
32. A banjo player plucks the middle of a string pinned down at both ends. Where are the nodes of the standing wave in the string? What is the wavelength of the vibrating string?
33. Violinists sometimes bow a string to produce maximum vibration (antinodes) at one-quarter and three-quarters of the string length rather than at the middle of the string. Then the string vibrates with a wavelength equal to the string length rather than twice the string length. (See Figures 19.13a and b). What is the effect on frequency when this occurs?
34. A bat chirps as it flies toward a wall. Is the frequency of the echoed chirps it receives higher, lower, or the same as the emitted ones?
35. A railroad locomotive is at rest with its whistle shrieking, then starts moving toward you. (a) Does the frequency of sound that you hear increase, decrease, or stay the same? (b) How about the wavelength reaching your ear? (c) How about the speed of sound in the air between you and the locomotive?
36. Why is there a Doppler effect when the source of sound is stationary and the listener is in motion? In which direction should the listener move to hear a higher frequency? A lower frequency?
37. When you blow your horn while driving toward a stationary listener, the listener hears an increase in frequency of the horn. Would the listener hear an increase in horn frequency if he or she were also in a car traveling at the same speed in the same direction as you are? Explain.
38. Is there an appreciable Doppler effect when the motion of the source is at right angles to a listener? Explain.
39. How does the Doppler effect aid police in detecting speeding motorists?
40. Astronomers find that light emitted by a particular element at one edge of the Sun has a slightly higher frequency than light from that element at the opposite edge. What do these measurements tell us about the Sun's motion?
41. Would it be correct to say that the Doppler effect is the apparent change in the speed of a wave due to motion of the source? (Why is this question a test of reading comprehension as well as a test of physics knowledge?)
42. How does the phenomenon of interference play a role in the production of bow waves or shock waves?
43. What can you say about the speed of a boat that makes a bow wave?
44. Does the conical angle of a shock wave open wider, narrow down, or remain constant as a supersonic aircraft increases its speed?
45. If the sound of an airplane does not come from the part of the sky where the plane is seen, does this imply that the airplane is traveling faster than the speed of sound? Explain.
46. Does a sonic boom occur at the moment when an aircraft exceeds the speed of sound? Explain.
47. Why is it that a subsonic aircraft, no matter how loud it may be, cannot produce a sonic boom?
48. Imagine a superfast fish that is able to swim faster than the speed of sound in water. Would such a fish produce a "sonic boom"?
49. Make up a multiple-choice question that would check a classmate's understanding of the distinction between a transverse wave and a longitudinal wave.
50. Make up two multiple-choice questions that would check a classmate's understanding of any of the terms that describe a wave.

PROBLEMS

1. What is the frequency, in hertz, that corresponds to each of the following periods?
   (a) 0.10 s
   (b) 5 s
   (c) 1/60 s
2. What is the period, in seconds, that corresponds to each of the following frequencies?
   (a) 10 Hz
   (b) 0.2 Hz
   (c) 60 Hz
3. A skipper on a boat notices wave crests passing his anchor chain every 5 s. He estimates the distance between wave crests to be 15 m. He also correctly estimates the speed of the waves. Show that this speed is 3 m/s.
4. A weight suspended from a spring is seen to bob up and down over a distance of 20 cm twice each second. What is its frequency? Its period? Its amplitude?
5. A mosquito flaps its wings 600 vibrations per second, which produces the annoying 600-Hz buzz. Given that the speed of sound is 340 m/s, how far does the sound travel between wing beats? In other words, find the wavelength of the mosquito's sound.
6. On a keyboard, you strike middle C, whose frequency is 256 Hz.
   (a) What is the period of one vibration of this tone?
   (b) As the sound leaves the instrument at a speed of 340 m/s, what is its wavelength in air?
7. As shown in the drawing, the half-angle of the shock wave cone generated by a supersonic airplane is 45°. What is the speed of the plane relative to the speed of sound?



• 8. An astronaut on the Moon attaches a small brass ball to a 1.00-m length of string and makes a simple pendulum. She times 15 complete swings in a time of 75 seconds. From this measurement she calculates the acceleration due to gravity on the Moon. What is her result?

CHAPTER 19 ONLINE RESOURCES

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- 19.2, 19.6, 19.8, 19.12, 19.13, 19.16, 19.17

Tutorials

- Waves and Vibrations
- Doppler Effect

Videos

- Longitudinal vs. Transverse Waves
- Doppler Effect

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Links

20 Sound

1 Ken Ford was one of the first to wear noise-canceling earphones when towing gliders in quiet comfort. 2 Chris Chiaverina, former president of the American Association of Physics Teachers, and Tom Rossing, recipient of the Acoustics Gold Medal by the Acoustical Society of America, produce sounds on a hang, a new hand-played steel instrument. 3 Singer, composer, and chemistry professor John Suchocki produces pleasing sounds with his voice and guitar.

One of the world's great combinations of physicist, author, and physics educator is Kenneth W. Ford, who was a University of California professor, a college president, and head of the American Institute of Physics before he became a classroom teacher in grades 9 through 12 at Germantown Academy in Pennsylvania. An expert and author of books on quantum physics, his passions also include teaching, flying small airplanes and gliders, and his wife Joanne. He is also a dear friend and rides "shotgun" in the writing of my physics books. *Conceptual Physics* is a beneficiary of Ken's deep and extensive knowledge of physics. I am grateful that he tweaks most all my writing before it goes to press, so that there is a higher likelihood that the physics is correct.

When I first wrote *Conceptual Physics*, Ken's textbook *Basic Physics* was an inspiration to me, as were the three volumes of *Feynman's Lectures on Physics* and *Physics for the Inquiring Mind* by Eric Rogers. Ken was one of the first to write a review of *Conceptual Physics*. He gave it much praise, adopted it for his own classes, and alerted me to some of its errors, which I quickly corrected. It is said that if you want to learn physics, teach it. I add, if you want to learn more about physics, write a textbook on it. I continually learn, much more due to the input of Ken Ford.

Ken Ford

Years ago, as seen in his photo above, Ken was a user of noise-canceling earphones when flying noisy aircraft. More recently, his book *In Love With Flying* emphasizes his greater passion for motorless flight—soaring. In Ken's portrait, notice Planck's constant on the license plate of his hybrid and a Diamond Soaring Badge on his lapel.

Let's learn a bit of the physics that Ken Ford loves.

Nature of Sound

If a tree fell in the middle of a deep forest hundreds of kilometers away from any living being, would there be a sound? Different people will answer this question in different ways. "No," some will say, "sound is subjective and requires a listener. If there is no listener, there will be no sound." "Yes," others will say, "a sound is not something in a listener's head. A sound is an objective thing." Discussions like this one often are beyond agreement because the participants fail to realize that they are arguing not about the nature of sound, but about the definition of the word. Either side is correct, depending on the definition taken, but investigation can proceed only when a definition has been agreed upon. Scientists, such as the four shown on the previous page, take the objective position and define sound as a form of energy that exists whether or not it is heard, and they go on from there to investigate its nature.

Origin of Sound

Most sounds are waves produced by the vibrations of matter. In a piano, a violin, and a guitar, the sound is produced by the vibrating strings; in a saxophone, by a vibrating reed; in a flute, by a fluttering column of air at the mouthpiece. Your voice results from the vibration of your vocal chords. Sounds in the air are caused by a wide variety of vibrations.

In each of these cases, the original vibration stimulates the vibration of something larger or more massive, such as the sounding board of a stringed instrument, the air column within a reed or wind instrument, or the air in the throat and mouth of a singer. This vibrating material then sends a disturbance through the surrounding medium, usually air, in the form of longitudinal waves. Under ordinary conditions, the frequencies of the vibrating source and sound waves are the same. We describe our subjective impression about the frequency of sound by the word **pitch.** Frequency corresponds to pitch: A high-pitched sound from a piccolo has a high frequency of vibration, and a low-pitched sound from a foghorn has a low frequency of vibration.

Elephants communicate with one another with infrasonic waves. Their large ears help them to detect these low-frequency sound waves.

The ear of a young person can normally hear pitches corresponding to the range of frequencies between about 20 and 20,000 hertz. As we grow older, the limits of this human hearing range shrink, especially at the high-frequency end. Sound waves with frequencies below 20 hertz are **infrasonic,** and those with frequencies above 20,000 hertz are called **ultrasonic.** We cannot hear infrasonic and ultrasonic sound waves. Infrasonic: frequency too low for human hearing. Ultrasonic: frequency too high for human hearing.

CHECK POINT

What is the wave frequency of sound produced by a 220-hertz tuning fork?

Check Your Answer

220 Hz.

Sound in Air

When we clap our hands, the sound produced is nonperiodic. It consists of a wave *pulse* that travels outward in all directions. To better understand how a pulse in air moves, consider a long room, as shown in Figure Figure 20.1a. At one

end is an open window with a curtain over it. At the other end is a door. When we open the door, we can imagine the door pushing the molecules next to it away from their initial positions and into their neighbors. The neighboring molecules, in turn, push into their neighbors, and so on, like a compression traveling along a spring, until the curtain flaps out the window. A pulse of compressed air has moved from the door to the curtain. This pulse of compressed air is called a **compression.**

When we close the door (Figure 20.1b), the door pushes some air molecules out of the room. This produces an area of low pressure behind the door. Neighboring molecules then move into it, leaving a zone of lower pressure behind them. We say this zone of lower-pressure air is *rarefied.* Other molecules farther away from the door, in turn, move into these rarefied regions, and a disturbance again travels across the room. This is evidenced by the curtain, which flaps inward. This time the disturbance is a **rarefaction.**

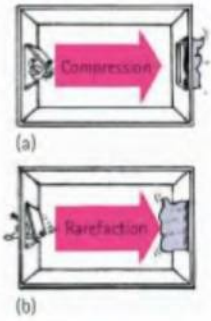

FIGURE 20.1

(a) When the door is opened, a compression travels across the room. (b) When the door is closed, a rarefaction travels across the room.

As with all wave motion, it is not the medium itself that travels across the room but the energy-carrying pulse. In both compression and rarefaction, the pulse travels from the door to the curtain. We know this because, in both cases, the curtain moves after the door is opened or closed. If you continually swing the door open and closed in periodic fashion, you can set up a wave of periodic compressions and rarefactions that will cause the curtain to swing in and out of the window. On a much smaller but more rapid scale, this is what happens when a tuning fork is struck. The periodic vibrations of the tuning fork and the waves produced are considerably higher in frequency and lower in amplitude than those caused by the swinging door. You don't notice the effect of sound waves on the curtain, but you are well aware of them when they meet your sensitive eardrums.

Consider sound waves in the tube shown in Figure 20.2. For simplicity, only the waves that travel in the tube are depicted. When the prong of the tuning fork next to the tube moves toward the tube, a compression enters the tube. When the prong swings away in the opposite direction, a rarefaction follows the compression. It's like a Ping-Pong paddle moving to and fro in a room packed with Ping-Pong balls. As the source vibrates, a periodic series of compressions and rarefactions is produced. The frequency of the vibrating source and the frequency of the wave it produces are the same.

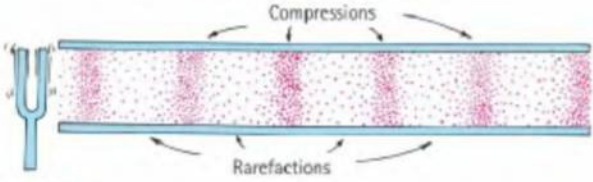

FIGURE 20.2

Compressions and rarefactions travel (both at the same speed in the same direction) from the tuning fork through the air in the tube.

FIGURE 20.3

A Ping-Pong paddle vibrating in the midst of Ping-Pong balls produces vibration of the balls.

Pause to reflect on the physics of sound while you are listening to your radio sometime. The radio loudspeaker is a paper cone that vibrates in rhythm with an electrical signal. Air molecules next to the vibrating cone of the speaker are themselves set into vibration. This air, in turn, vibrates against neighboring particles, which, in turn, do the same, and so on. As a result, rhythmic patterns of compressed and

FIGURE 20.4

Waves of compressed and rarefied air, produced by the vibrating cone of the loudspeaker, make up the pleasing sound of music.

Loudspeaker

The loudspeaker of your radio or other sound-producing systems changes electrical signals into sound waves. The electrical signals pass through a coil wound around the neck of a paper cone. This coil, which acts as an electromagnet, is located near a permanent magnet. When current flows one way, magnetic force pushes the electromagnet toward the permanent magnet, pulling the cone inward. When current flows in the opposite direction, the cone is pushed outward. Vibrations in the electric signal cause the cone to vibrate. Vibrations of the cone then produce sound waves in the air. The physics of large loudspeakers applies to small ones, even those that fit in your ear.

rarefied air emanate from the loudspeaker, showering the whole room with undulating motions. The same process occurs with the bud earphones used with your iPod or other device wherein the speaker is small enough to fit in your ear. The resulting vibrating air sets your eardrum into vibration, which, in turn, sends cascades of rhythmic electrical impulses along the cochlea nerve canal and into the brain. And you listen to the sound of music.

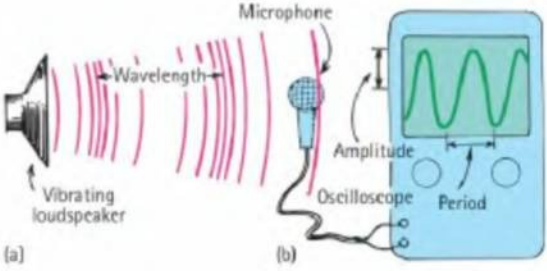

FIGURE 20.5
(a) Vibrations of the radio loudspeaker set up similar vibrations in the microphone, which are displayed on an oscilloscope.
(b) The shape of the waveform on the oscilloscope screen reveals information about the sound.

Media That Transmit Sound

Most sounds that we hear are transmitted through the air. However, any elastic substance—whether solid, liquid, gas, or plasma—can transmit sound. Elasticity is the property of a material that has changed shape in response to an applied force to resume its initial shape once the distorting force is removed. Steel is an elastic substance. In contrast, putty is inelastic.[1] In elastic liquids and solids, the atoms are relatively close together, respond quickly to one another's motions, and transmit energy with little loss. Sound travels about 4 times faster in water than in air and about 15 times faster in steel than in air.

Atoms and molecules in a medium tremble as they transmit sound. Sound cannot travel in a vacuum because there's nothing to do the trembling.

Relative to solids and liquids, air is a poor conductor of sound. You can hear the sound of a distant train more clearly if your ear is placed against the rail. Similarly, a ticking watch placed on a table beyond hearing distance can be heard if you place your ear to the table. Or click some rocks together under water while your ear is submerged. You'll hear the clicking sound very clearly. If you've ever been swimming

[1]Elasticity is not "stretchiness," like a rubber band. Some very stiff materials are elastic—like steel.

Practicing Physics

Suspend the wire grille from a refrigerator or an oven from a string, holding the ends of the string to your ears. Let a friend gently stroke the grille with pieces of broom straw and with other objects. The effect is best appreciated when you are in a relaxed condition with your eyes closed. Be sure to try this!

in the presence of motorized boats, you probably noticed that you can hear the boats' motors much more clearly under water than above water. Liquids and crystalline solids are generally excellent conductors of sound—much better than air. The speed of sound is generally greater in solids than in liquids, and greater in liquids than in gases. Sound won't travel in a vacuum because there is nothing to compress and expand.

Speed of Sound in Air

If we watch a person at a distance chopping wood, or see a far-away baseball player hit a ball, we can easily see that the blow takes place an appreciable time before its sound reaches our ears. Likewise, thunder is heard after we see a flash of lightning. These common experiences show that sound requires a recognizable time to travel from one place to another. The speed of sound depends on wind conditions, temperature, and humidity. It does not depend on the loudness or the frequency of the sound; all sounds in the same medium travel at the same speed. The speed of sound in dry air at 0°C is about 330 meters per second, nearly 1200 kilometers per hour (a little more than one-millionth the speed of light). Water vapor in the air increases this speed slightly. Sound travels faster through warm air than cold air. This is to be expected because the faster-moving molecules in warm air bump into one another more often and therefore can transmit a pulse in less time.[2] For each degree rise in temperature above 0°C, the speed of sound in air increases by 0.6 meter per second. So, in air at a normal room temperature of about 20°C, sound travels at about 340 meters per second.

Your two ears are so sensitive to the differences in sound reaching them that you can tell from what direction a sound is coming with almost pinpoint accuracy. With only one ear, you would have no idea (and, in an emergency, might not know which way to jump).

CHECK POINT

1. Do compressions and rarefactions in a sound wave travel in the same direction or in opposite directions from one another?
2. What is the approximate distance of a thunderstorm when you note a 3-s delay between the flash of lightning and the sound of thunder?

Check Your Answers

1. They travel in the same direction.
2. Assuming that the speed of sound in air is about 340 m/s, in 3 s it will travel (340 m × 3 s) = 1020 m. There is no appreciable delay for the flash, so the storm is slightly more than 1 km away.

[2]The speed of sound in a gas is about 3/4 the average speed of the gas molecules.

FIGURE 20.6
The angle of incident sound is equal to the angle of reflected sound.

Reflection of Sound

We call the reflection of sound an *echo*. The fraction of energy carried by the reflected sound wave can be large if the surface is rigid and smooth, and less if the surface is soft and irregular. Sound energy not carried by the reflected sound wave is carried by the "transmitted" (absorbed) wave.

Sound reflects from a smooth surface the same way that light does—the angle of incidence is equal to the angle of reflection (Figure 20.6). Sometimes, when sound reflects from the walls, ceiling, and floor of a room, the reflecting surfaces are too reflective and the sound becomes garbled. When sound undergoes multiple reflections and persists after the source has ceased emitting, we hear **reverberations.**

FIGURE 20.7
Special spongy walls absorb rather than reflect sound in this acoustical quiet room.

On the other hand, if the reflective surfaces are too absorbent, the sound level will be low and the hall will sound dull and lifeless. Reflection of sound in a room makes it sound lively and full, as you have probably discovered while singing in the shower. In the design of an auditorium or concert hall, a balance must be achieved between reverberation and absorption. The study of sound properties is called *acoustics*.

Bats hunt moths in darkness by echo location. Some moths are protected by a thick covering of fuzzy scales that deaden the echoes.

It is often advantageous to place highly reflective surfaces behind the stage to direct sound out to an audience. Reflecting surfaces are suspended above the stage in some concert halls. Most often they are large, shiny, plastic surfaces that also reflect light (Figure 20.8). A listener can look up at these reflectors and see the reflected images of the members of the orchestra. The plastic reflectors are somewhat curved, which increases the field of view. Both sound and light obey the same law of reflection, so if a reflector is oriented so that you can see a particular musical instrument, rest assured that you will hear it also. Sound from the instrument will follow the line of sight to the reflector and then to you.

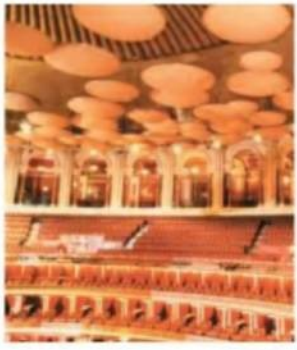

FIGURE 20.8
The plastic plates above the orchestra reflect both light and sound. Adjusting them is quite simple: What you see is what you hear.

Refraction of Sound

When sound waves continue through a medium and bend, they undergo **refraction.** Sound waves bend when parts of the wave fronts travel at different speeds. This may happen in uneven winds or when sound is traveling through air of uneven temperatures. On a warm day, the air near the ground may be appreciably warmer than the rest of the air, so the speed of sound near the ground increases (Figure 20.9). Sound waves therefore tend to bend away from the ground, resulting in sound that does not seem to travel well. Refraction of sound is caused by differences in the speed of sound.

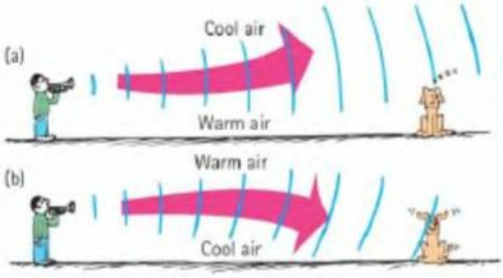

FIGURE 20.9
Sound waves are bent in air of uneven temperatures.

We hear thunder when the lightning is reasonably close, but we often fail to hear the thunder for distant lightning because of refraction. The sound travels slower at higher altitudes and bends away from the ground, so you may not hear it. The opposite often occurs on a cold day or at night when the layer of air near the ground is colder than the air above. Then the speed of sound near the ground is reduced. The higher speed of the wave fronts above causes a bending of the sound toward the ground, resulting in sound that can be heard over considerably longer distances. Sound refraction explains why you can clearly hear conversations over a campfire far across a lake at night. Sound does not always travel in straight-line paths.

Note in Figure 20.9 that the directions of the sound waves are always at right angles to the wave fronts.

The refraction of sound occurs under water, where the speed of sound varies with temperature. This poses a problem for surface vessels that bounce ultrasonic waves off the bottom of the ocean to chart the sea bottom's features. Refraction is a blessing to submarines that wish to escape detection. Because of thermal gradients and layers of water at different temperatures, the refraction of sound leaves gaps or "blind spots" in the water. This is where submarines hide. If it weren't for refraction, submarines would be easier to detect.

The multiple reflections and refractions of ultrasonic waves are used by physicians in a technique for harmlessly viewing inside the body without the use of X-rays. When high-frequency sound (ultrasound) enters the body, it is reflected more strongly from the outside of an organ than from its interior, and an image of the outline of the organ is obtained. When ultrasound is incident upon a moving object, the reflected sound has a slightly different frequency. Using this Doppler effect, a physician can "see" the beating heart of a fetus as early as 11 weeks after conception (Figure 20.10).

FIGURE 20.10
A human fetus is clearly displayed on a viewing screen by ultrasound.

Ultrasound is used in medicine to produce images of internal body organs and babies in the womb and in industry to detect flaws in metal. Although the ultrasound echo technique may be relatively new to humans, it is old stuff to creatures such as bats and dolphins. Bats, for example, emit ultrasonic squeaks and locate objects by their echoes. Dolphins do this and more.[3] Whereas sound is a passive sense for us, it is an active sense for the dolphin who sends out sounds and then perceives its surroundings on the basis of their echoes. Sensing ultrasonic waves enables a dolphin to "see" through the bodies of other animals and people. Skin, muscle, and fat are almost transparent to dolphins, so they "see" only a thin outline of the body—but the bones,

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Refraction of Sound

[3]The primary sense of the dolphin is acoustic, for vision is not a very useful sense in the often murky and dark depths of the ocean. What's more interesting, the dolphin can reproduce the sonic signals that paint the mental image of its surroundings; thus the dolphin probably communicates its experience to other dolphins by communicating the full acoustic image of what is "seen," placing it directly in the minds of other dolphins. It needs no word or symbol for "fish," for example, but communicates an image of the real thing—perhaps with emphasis highlighted by selective filtering, as we similarly communicate a musical concert to others via various means of sound reproduction. Small wonder that the language of the dolphin is very unlike our own!

FIGURE 20.11
A dolphin emits ultra-high-frequency sound to locate and identify objects in its environment. Distance is sensed by the time delay between sending sound and receiving its echo, and direction is sensed by differences in time for the echo to reach its two ears. A dolphin's main diet is fish and since hearing in fish is limited to fairly low frequencies, they are not alerted to the fact they are being hunted.

teeth, and gas-filled cavities are clearly apparent. Physical evidence of cancers, tumors, heart attacks, and even emotional state can all be "seen" by the dolphin—as humans have only recently been able to accomplish with ultrasound.

CHECK POINT

An oceanic depth-sounding vessel surveys the ocean bottom with ultrasonic sound that travels an average 1530 m/s in seawater. How deep is the water if the time delay of the echo from the ocean floor is 2 s?

Check Your Answer

1530 m (1 s down and 1 s up).

Energy in Sound Waves

Wave motion of all kinds possesses energy of varying degrees. Electromagnetic waves from the Sun, for instance, bring us the enormous quantities of energy that sustain life on Earth. By comparison, the energy in sound is extremely small. That's because producing sound requires only a small amount of energy. For example, 10,000,000 people talking at the same time would produce sound energy equal only to the energy needed to operate a common flashlight. Hearing is possible only because of our remarkably sensitive ears. Only the most sensitive microphone can detect sound that is softer than what we can hear.

Sound energy dissipates to thermal energy while sound travels in air. For waves of higher frequency, the sound energy is transformed into internal energy more rapidly than for waves of lower frequencies. As a result, sound of low frequencies will travel farther through air than sound of higher frequencies. That's why the foghorns of ships are of a low frequency.

Forced Vibrations

If we strike an unmounted tuning fork, the sound from it may be rather faint. If we hold the same tuning fork against a table after striking it, the sound is louder. This is because the table is forced to vibrate, and, with its larger surface, the table will set more air in motion. The table can be made to vibrate by a fork of any frequency—a case of **forced vibration.** The mechanism in a music box is mounted on a sounding board. Without the sounding board, the sound produced by the music-box mechanism is barely audible. Sounding boards are important in all stringed musical instruments.

Natural Frequency

When someone drops a wrench on a concrete floor, we are not likely to mistake its sound for that of a baseball bat hitting the floor. This is because the two objects vibrate differently when they are struck. Tap a wrench and the vibrations it makes are different from the vibrations of a baseball bat, or of anything else. Any object composed of an elastic material when disturbed will vibrate at its own special set of frequencies, which together form its special sound. We speak of an object's **natural frequency,** which depends on such factors as the elasticity and shape of the object. Bells and tuning forks, of course, vibrate at their own characteristic frequencies. And, interestingly enough, most things from planets to atoms and almost everything else in between have a springiness to them and vibrate at one or more natural frequencies.

FIGURE 20.12
The natural frequency of the smaller bell is higher than that of the larger bell, and it rings at a higher pitch.

Resonance

When the frequency of forced vibrations on an object matches the object's natural frequency, a dramatic increase in amplitude occurs. This phenomenon is called **resonance.** Literally, *resonance* means "resounding," or "sounding again." Putty doesn't resonate because it isn't elastic, and a dropped handkerchief is too limp. In order for something to resonate, it needs a force to pull it back to its starting position and enough energy to keep it vibrating.

A common experience illustrating resonance occurs on a swing. When pumping a swing, we pump in rhythm with the natural frequency of the swing. More important than the force with which we pump is the timing. Even small pumps or small pushes from someone else, if delivered in rhythm with the frequency of the swinging motion, produce large amplitudes. A common classroom demonstration of resonance is illustrated with a pair of tuning forks adjusted to the same frequency and spaced a meter or so apart. When one of the forks is struck, it sets the other fork into vibration (Figure 20.13). This is a small-scale version of pushing a friend on a swing—it's the timing that's important. When a series of sound waves impinge on the fork, each compression gives the prong of the fork a tiny push. Since the frequency of these pushes corresponds to the natural frequency of the fork, the pushes will successively increase the amplitude of vibration. This is because the pushes occur at the appropriate time and repeatedly occur in the same direction as the instantaneous motion of the fork. The motion of the second fork is often called a *sympathetic vibration.*

If the forks are not adjusted for matched frequencies, the timing of pushes is off, and resonance will not occur. When you tune a radio, you are similarly adjusting the natural frequency of the electronics to match one of the many surrounding signals. The set then resonates to one station at a time instead of playing all stations at once.

FIGURE 20.13
When Ryan strikes one of the matched-frequency tuning forks, the other is set into resonance.

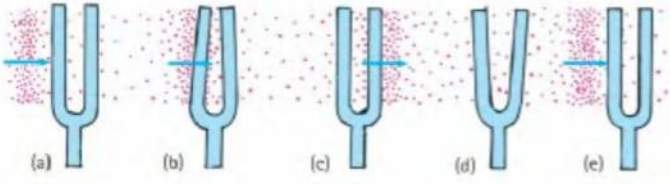

FIGURE 20.14
Stages of resonance (blue arrows indicate sound waves traveling to the right). (a) The first compression meets the tuning fork and gives it a tiny and momentary push. (b) The fork bends and then (c) returns to its initial position just at the time a rarefaction arrives and (d) overshoots in the opposite direction. Just when the fork returns to its initial position (e), the next compression arrives to repeat the cycle. Now it bends farther because it is moving.

FIGURE 20.15

In 1940, four months after being completed, the Tacoma Narrows Bridge in Washington State was destroyed by wind-generated resonance. A mild gale produced an irregular force in resonance with the natural frequency of the bridge, steadily increasing the amplitude of vibration until the bridge collapsed.

FIGURE 20.16

INTERACTIVE FIGURE

Pumping a swing in rhythm with its natural frequency produces a large amplitude.

Resonance is not restricted to wave motion. It occurs whenever successive impulses are applied to a vibrating object in rhythm with its natural frequency. Cavalry troops marching across a footbridge near Manchester, England, in 1831 inadvertently caused the bridge to collapse when they marched in rhythm with the bridge's natural frequency. Since then, it is customary to order troops to "break step" when crossing bridges in order to prevent resonance. A century later another major bridge disaster was caused by wind-generated resonance (Figure 20.15).

The effects of resonance are all about us. Resonance underscores not only the sound of music but the color of autumn leaves, the height of ocean tides, the operation of lasers, and a vast multitude of phenomena that add to the beauty of the world.

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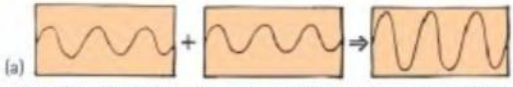
Videos

Resonance

Resonance and Bridges

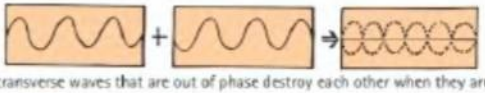
Interference

Sound waves, like any waves, can be made to exhibit **interference.** Recall that wave interference was discussed in the previous chapter. A comparison of interference for transverse waves and longitudinal waves is shown in Figure 20.17. In either case, when the crests of one wave overlap the crests of another wave,



(a) The superposition of two identical transverse waves in phase produces a wave of increased amplitude.

(b) The superposition of two identical longitudinal waves in phase produces a wave of increased intensity.



(c) Two identical transverse waves that are out of phase destroy each other when they are superimposed.

(d) Two identical longitudina waves that are out of phase destroy each other when they are superimposed.

FIGURE 20.17

INTERACTIVE FIGURE

Constructive (a, b) and destructive (c, d) wave interference in transverse and longitudinal waves.

increased amplitude results. Or, when the crest of one wave overlaps the trough of another wave, decreased amplitude results. In the case of sound, the crest of a wave corresponds to a compression and the trough of a wave corresponds to a rarefaction. Interference occurs for all waves, both transverse and longitudinal.

An interesting case of sound interference is illustrated in Figure 20.18. If you are an equal distance from two sound speakers that emit identical tones of fixed frequency, the sound is louder because the effects of the two speakers add. The compressions and rarefactions of the tones arrive in step, or in *phase*. However, if you move to the side so that the paths from the speakers to you differ by a half wavelength, then the rarefactions from one speaker will be filled in by the compressions from the other speaker. This is destructive interference. It is just as if the crest of one water wave exactly filled in the trough of another water wave, canceling both. If the region is devoid of any reflecting surfaces, little or no sound will be heard!

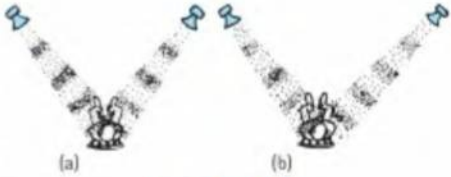


FIGURE 20.18
INTERACTIVE FIGURE

Interference of sound waves.
(a) Waves arrive in phase and interfere constructively when the path lengths from the speakers are the same.
(b) Waves arrive out of phase and interfere destructively when the path lengths differ by half a wavelength (or 3/2, 5/2, etc.).

If the speakers emit a whole range of sounds with different frequencies, only some waves destructively interfere for a given difference in path lengths. So interference of this type is usually not a problem, because there is usually enough reflection of sound to fill in canceled spots. Nevertheless, "dead spots" are sometimes evident in poorly designed theaters or music halls, where sound waves reflect off walls and interfere with nonreflected waves to produce zones of low amplitude. When you move your head a few centimeters in either direction, you may hear a noticeable difference.

Sound interference is dramatically illustrated when monaural sound is played by stereo speakers that are out of phase. Speakers are out of phase when the input wires to one speaker are interchanged (positive and negative wire inputs reversed). For a monaural signal, this means that when one speaker is sending a compression of sound, the other is sending a rarefaction. The sound produced is not as full and not as loud as from speakers properly connected in phase because the longer waves are being canceled by interference. This is dramatically illustrated in Figure 20.19. Shorter waves are canceled as the speakers are brought closer together, and when the pair of speakers is brought face to face against each other, very little sound is heard! Only the sound waves having the highest frequencies survive cancellation. You must try this to appreciate it.

FIGURE 20.19

If the positive and negative wire inputs to one of the stereo speakers are switched, the speakers are out of phase. When the speakers are far apart, monaural sound is not as loud as from properly phased speakers. When brought face to face, very little sound is heard. Interference is nearly complete as the compressions of one speaker fill in the rarefactions of the other!

Destructive sound interference is a useful property in *antinoise technology*. Such noisy devices as jackhammers are being equipped with microphones that send the sound of the device to electronic microchips, which create mirror-image wave patterns of the sound signals. For the jackhammer, this mirror-image sound signal is fed to earphones worn by the operator. Sound compressions (or rarefactions) from the hammer are canceled by mirror-image rarefactions (or compressions) in the earphones. The combination of signals cancels the jackhammer noise. Noise-canceling earphones are already common for pilots (as worn by Ken, pictured at the outset of this chapter). The cabins of some airplanes are now quieted with antinoise technology. When they're not, that's when you should wear your noise-canceling earphones.

CHECK POINT

In the demonstration of Figure 20.19, why is it important that monaural sound be used?

Check Your Answer

You can cancel signals if they're identical, not the different signals fed to stereo speakers. Identical signals fed to both speakers produce monaural sound—just what you need for maximum destructive interference when you switch the phases of monaural signals.

FIGURE 20.20

When a mirror image of a sound signal combines with the sound itself, the sound is canceled.

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Video
Interference and Beats

Beats

When two tones of slightly different frequency are sounded together, a fluctuation in the loudness of the combined sounds is heard; the sound is loud, then faint, then loud, then faint, and so on. This periodic variation in the loudness of sound is called **beats** and is due to interference. Strike two slightly mismatched tuning forks and, because one fork vibrates at a different frequency than the other, the vibrations of the forks will be momentarily in step, then out of step, then in again, and so on. When the combined waves reach our ears in step—say, when a compression from one fork overlaps a compression from the other—the sound is a maximum. A moment later, when the forks are out of step, a compression from one fork is met with a rarefaction from the other, resulting in a minimum. The sound that reaches our ears throbs between maximum and minimum loudness and produces a tremolo effect.

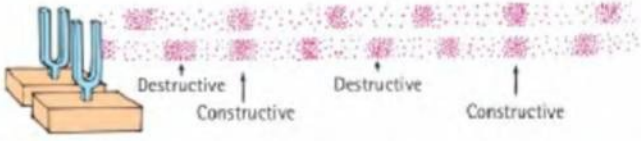


FIGURE 20.21
The interference of two sound sources of slightly different frequencies produces beats.

Why does Hollywood persist in playing engine noises whenever a spacecraft in outer space passes by? Wouldn't seeing them float by silently be far more dramatic?

We can understand beats by considering the analogous case of a tall person and short person walking side by side with different strides. At some moment they will be in step, a little later out of step, then in step again, and so on. Imagine that the tall person with longer legs takes exactly 70 steps in 1 minute, and the shorter person takes 72 steps in the same time. The shorter person gains 2 steps per minute on the taller person. A little thought will show that they will both be momentarily in step twice each minute. In general, if two people with different strides walk together, the number of times they are in step in each unit of time is equal to the difference in the frequencies of the steps. This applies also to the pair of tuning forks. If one fork undergoes 264 vibrations each second and the other fork vibrates 262 times per second, they will be in step twice each second. A beat frequency of 2 hertz will be heard. The overall tone will correspond to the average frequency, 263 hertz.

If we overlap two combs with different teeth spacing, we'll see a moiré pattern that is related to beats (Figure 20.22). The number of beats per length will equal the difference in the number of teeth per length for the two combs.

FIGURE 20.22
The unequal spacings of the combs produce a moiré pattern that is similar to beats.

Beats can occur with any kind of wave and can provide a practical way to compare frequencies. To tune a piano, for example, a piano tuner listens for beats produced between a standard frequency and the frequency of a particular string on the piano. When the frequencies are identical, the beats disappear. Beats can help you tune a variety of musical instruments. Simply listen for beats between the tone of your instrument and a standard tone produced by a piano or some other instrument.

Beats are utilized by dolphins in surveying the motions of things around them. When a dolphin sends out sound signals, beats may be produced when the echoes it receives interfere with the sound it sends. When there is no relative motion between the dolphin and the object returning the sound, the sending and receiving frequencies are the same and no beats occur. But when there is relative motion, the echo has a different frequency due to the Doppler effect, and beats are produced when the

echo and emitted sound combine. The same principle is applied by the radar guns used by police officers. The beats between the signal that is sent and the one that is reflected are used to determine the speed of a car.

An intriguing and life-saving application of beats is used in detecting dangerous gases in mines. The air in some mines contains poisonous methane. There's a slight difference in the speed of sound in pure air and in air that contains methane. When a pair of small identical pipes are blown together, one by pure air from a reservoir and the other by the air in the mine, beats are heard if the air contains methane. If you work in a mine, do so in one where beats are not heard when this procedure is done!

CHECK POINT

What is the beat frequency when a 262-Hz tuning fork and a 266-Hz tuning fork are sounded together? A 262-Hz fork and a 272-Hz fork?

Check Your Answers

For the 262-Hz and 266-Hz forks, the ear will hear 264 Hz, which will beat at 4 Hz (266 Hz − 262 Hz). For the 272-Hz and 262-Hz forks, 267 Hz will be heard, and some people will hear it throb 10 times each second (272 Hz − 262 Hz). Beat frequencies greater than 10 Hz are normally too rapid to be heard.

Radio Broadcasts

A radio receiver turns electromagnetic waves, which we cannot hear, into sound waves that we can hear. Every radio station has an assigned frequency at which it broadcasts. The electromagnetic wave transmitted at this frequency is the *carrier wave*. The relatively low-frequency sound signal to be communicated is superimposed on the much higher-frequency carrier wave in two principal ways: by slight variations in amplitude that match the audio frequency or by slight variations in frequency. This impression of the sound wave on the higher-frequency radio wave is *modulation*. When the *amplitude* of the carrier wave is modulated, we call it AM, or *amplitude modulation*. AM stations broadcast in the range of 535 to 1605 kilohertz. When the *frequency* of the carrier wave is modulated, we call it FM, or *frequency modulation*. FM stations broadcast in the higher-frequency range of 88 to 108 megahertz. Amplitude modulation is similar to rapidly changing the brightness of a constant-color lightbulb. Frequency modulation is similar to rapidly changing the color of a constant-intensity lightbulb.

Turning the knob of a radio receiver to select a particular station is like adjusting movable masses on the prongs of a tuning fork to make it resonate to the sound produced by another fork. In choosing a radio station, you adjust the frequency of an electrical circuit inside the radio receiver to match and resonate with the frequency of the desired station. You sort out one carrier wave from many. Then the impressed sound signal is separated from the carrier wave, amplified, and fed to the loudspeaker. It's nice to hear only one station at a time!

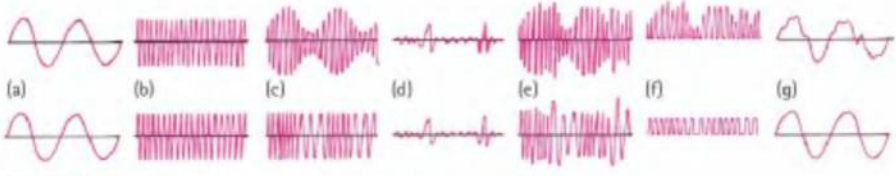


FIGURE 20.23

AM and FM radio signals. (a) Sound waves that enter a microphone. (b) Radio-frequency carrier wave produced by a transmitter without a sound signal. (c) Carrier wave modulated by signal. (d) Static interference. (e) Carrier wave and signal affected by static. (f) Radio receiver cuts out negative half of carrier wave. (g) Signal remaining is rough for AM because of static but is smooth for FM because the tips of the waveform are clipped without loss to the signal.

CHECK POINT

Is it correct to say that, in every case, without exception, any radio wave travels faster than any sound wave?

Check Your Answer

Yes, because any radio wave is an electromagnetic wave and travels at the speed of light. A sound wave, on the other hand, is a mechanical wave that travels in air about 340 m/s, about one-millionth the speed of a radio wave. So any radio wave travels appreciably faster than any sound wave.

SUMMARY OF TERMS

Pitch The highness or lowness of a tone related to wave frequency.
Infrasonic Describes a sound that has a frequency too low to be heard by the normal human ear.
Ultrasonic Describes a sound that has a frequency too high to be heard by the normal human ear.
Compression Condensed region of the medium through which a longitudinal wave travels.
Rarefaction Rarefied region (of reduced pressure) of the medium through which a longitudinal wave travels.
Reverberation Persistence of sound, as in an echo, due to multiple reflections.
Refraction Bending of sound or any wave caused by a difference in wave speeds.
Forced vibration The setting up of vibrations in an object by a vibrating force.
Natural frequency A frequency at which an elastic object naturally tends to vibrate if it is disturbed and the disturbing force is removed.
Resonance The response of a body when a forcing frequency matches its natural frequency.
Interference A result of superposing different waves, often of the same wavelength. Constructive interference results from crest-to-crest reinforcement; destructive interference results from crest-to-trough cancellation.
Beats A series of alternate reinforcements and cancellations produced by the interference of two waves of slightly different frequencies, heard as a throbbing effect in sound waves.

REVIEW QUESTIONS

Nature of Sound

1. How does a physicist usually define sound?

Origin of Sound

2. What is the relationship between *frequency* and *pitch*?
3. What is the average range of a young person's hearing?
4. Distinguish between *infrasonic* and *ultrasonic* sound waves.

Sound in Air

5. Distinguish between a *compression* and a *rarefaction*.
6. Cite evidence to support the fact that compressions and rarefactions travel in the same direction in a wave.

Media That Transmit Sound

7. Relative to solids and liquids, how does air rank as a conductor of sound?
8. Why will sound not travel in a vacuum?

Speed of Sound in Air

9. What factors does the speed of sound depend upon? What are some factors that it does *not* depend upon?
10. What is the speed of sound in dry air at 0°C?
11. Does sound travel faster in warm air than in cold air? Defend your answer.

Reflection of Sound

12. What is an *echo*?
13. What is a *reverberation*?

Refraction of Sound

14. What is the cause of refraction?
15. Does sound tend to bend upward or downward when its speed is less near the ground?
16. Why does sound sometimes refract under water?

Energy in Sound Waves

17. Which is normally greater, the energy in ordinary sound or the energy in ordinary light?
18. What ultimately becomes of the energy of sound in the air?

Forced Vibrations

19. Why will a struck tuning fork sound louder when it is held against a table?

Natural Frequency

20. Give at least two factors that determine the natural frequency of an object.

Resonance

21. How do forced *vibrations* relate to *resonance*?
22. When you listen to a radio, why do you hear only one station at a time rather than hearing all stations at once?
23. How did wind-generated resonance affect the Tacoma Narrows Bridge in the state of Washington in 1940?

Interference

24. When is it possible for one wave to cancel another?
25. What kind of waves can exhibit interference?

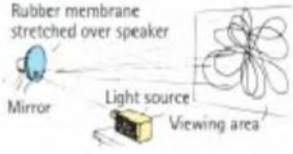
Beats

26. What physical phenomenon underlies the production of beats?
27. What beat frequency will occur when a 370-Hz and a 374-Hz sound source are sounded together?
28. How does a radio wave differ from a sound wave?

PROJECTS

1. In the bathtub, submerge your head and listen to the sound you make when clicking your fingernails together or tapping the tub beneath the water surface. Compare the sound by doing the same when both the source and your ears are above the water. At the risk of getting the floor wet, slide back and forth in the tub at different frequencies and see how the amplitude of the sloshing waves quickly builds up when you slide in rhythm with the waves. (The latter of these projects is most effective when you are alone in the tub.)

2. Stretch a piece of balloon rubber not too tightly over a radio loudspeaker. Glue a small, very lightweight piece of mirror, aluminum foil, or polished metal near one edge. Project a narrow beam of light on the mirror while your favorite music is playing and observe the beautiful patterns that are reflected on a screen or wall.



RANKING

1. Rank the speed of sound through the following from greatest to least:
a. Air
b. Steel
c. Water

2. Rank the beat frequency from highest to lowest for the following pairs of sounds:
a. 132 Hz, 136 Hz
b. 264 Hz, 258 Hz
c. 528 Hz, 531 Hz
d. 1056 Hz, 1058 Hz

EXERCISES

1. Why do you not hear the sound of distant fireworks until after you see them?
2. If the Moon blew up, why would we not hear it?
3. Why would it be futile to attempt to detect sounds from other planets, even given the very best in audio detectors?
4. If you toss a stone in still water, concentric circles are formed. What form will waves have if a stone is tossed into smoothly flowing water?
5. Why do flying bees buzz?
6. A cat can hear sound frequencies up to 70,000 Hz. Bats send and receive ultra-high-frequency squeaks up to 120,000 Hz. Which hears sound of shorter wavelengths, cats or bats?
7. What does it mean to say that a radio station is "at 101.1 on your FM dial"?
8. Suppose a sound wave and an electromagnetic wave have the same frequency. Which has the longer wavelength?
9. Sound from source A has twice the frequency of sound from source B. Compare the wavelengths of sound from the two sources.
10. What happens to the wavelength of sound as the frequency increases?
11. In the stands of a racetrack, you notice smoke from the starter's gun before you hear it fire. Explain.
12. In Olympic competition, a microphone detects the sound of the starter's gun and sends it electrically to speakers at every runner's starting block. Why?
13. When a sound wave moves past a point in air, are there changes in the density of air at this point? Explain.

14. At the instant that a high-pressure region is created just outside the prongs of a vibrating tuning fork, what is being created inside between the prongs?
15. Why is it so quiet after a snowfall?
16. If a bell is ringing inside a bell jar, we can no longer hear it when the air is evacuated, but we can still see it. What differences in the properties of sound and light does this indicate?
17. Why is the Moon described as a "silent planet"?
18. As you pour water into a glass, you repeatedly tap the glass with a spoon. As the tapped glass is being filled, does the pitch of the sound increase or decrease? (What should you do to answer this question?)
19. If the speed of sound were dependent on its frequency, would you enjoy a concert sitting in the second balcony? Explain.
20. If the frequency of sound is doubled, what change will occur in its speed? In its wavelength?
21. Why does sound travel slower in cold air?
22. Why does sound travel faster in moist air? (*Hint:* At the same temperature, water vapor molecules have the same average kinetic energy as the heavier nitrogen and oxygen molecules in the air. How, then, do the average speeds of H_2O molecules compare with those of N_2 and O_2 molecules?)
23. Would the refraction of sound be possible if the speed of sound were unaffected by wind, temperature, and other conditions? Defend your answer.
24. Why can the tremor of the ground from a distant explosion be felt before the sound of the explosion can be heard?
25. What kinds of wind conditions would make sound more easily heard at long distances? Less easily heard at long distances?
26. Ultrasonic waves have many applications in technology and medicine. One advantage is that large intensities can be used without danger to the ear. Cite another advantage of their short wavelength. (*Hint:* Why do microscopists use blue light rather than white light to see detail?)
27. If the distance from a bugle is tripled, by what factor does the sound intensity decrease? Assume that no reflections affect the sound.
28. Why is an echo weaker than the original sound?
29. What two physics mistakes occur in a science fiction movie that shows a distant explosion in outer space, where you see and hear the explosion at the same time?
30. A rule of thumb for estimating the distance in kilometers between an observer and a lightning stroke is to divide the number of seconds in the interval between the flash and the sound by 3. Is this rule correct? Defend your answer.
31. If a single disturbance at an unknown distance emits both transverse and longitudinal waves that travel with distinctly different speeds in the medium, such as in the ground during an earthquake, how can the distance to the disturbance be determined?
32. Why will marchers at the end of a long parade following a band be out of step with marchers near the front?
33. Why is it a sensible procedure for soldiers to break step when marching over a bridge?
34. Why is the sound of a harp soft in comparison with the sound of a piano?
35. Your classmate says that the speed of sound and the frequency of sound depend on the medium in which it travels. What part of this statement do you disagree with?
36. Apartment dwellers will testify that bass notes are more distinctly heard from music played in nearby apartments. Why do you suppose lower-frequency sounds travel through walls, floors, and ceilings more easily?
37. The sitar, an Indian musical instrument, has a set of strings that vibrate and produce music, even though they are never plucked by the player. These "sympathetic strings" are identical to the plucked strings and are mounted below them. What is your explanation?
38. Why does a dance floor heave only when certain kinds of dance steps are being performed?
39. A pair of loudspeakers on two sides of a stage are emitting identical pure tones (tones of a fixed frequency and fixed wavelength in air). When you stand in the center aisle, equally distant from the two speakers, you hear the sound loud and clear. Why does the intensity of the sound diminish considerably when you step to one side? (*Suggestion:* Use a diagram to make your point.)
40. A special device can transmit out-of-phase sound from a noisy jackhammer to its operator using earphones. Over the noise of the jackhammer, the operator can easily hear your voice while you are unable to hear his. Explain.
41. When two out-of-phase speakers are brought together as shown in Figure 20.19, which waves are most canceled, long waves or short waves? Why?
42. An object resonates when the frequency of a vibrating force either matches its natural frequency or is a submultiple of its natural frequency. Why will it not resonate to multiples of its natural frequency? (*Hint:* Think of pushing a child in a swing.)
43. How can a certain note sung by a singer cause a crystal glass to shatter?
44. Are beats the result of interference or of the Doppler effect, or of both?
45. Can it correctly be said that beats of sound are much the same thing as the rhythmic "beat" of music? Defend your answer.
46. Two sound waves of the same frequency can interfere, but, in order to produce beats, the two sound waves must be of different frequencies. Why?
47. Walking beside you, your friend takes 50 strides per minute while you take 48 strides per minute. If you start in step, you'll soon be out of step. When will you be in step again?
48. Suppose a piano tuner hears 3 beats per second when listening to the combined sound from a tuning fork and the piano wire being tuned. After slightly tightening the string, 5 beats per second are heard. Should the string be loosened or tightened?
49. A piano tuner using a 264-Hz tuning fork hears 4 beats per second. What are two possible frequencies of vibration of the piano wire?
50. A human cannot hear sound at a frequency of 100 kHz or sound at 102 kHz. But if you walk into a room in which two sources are emitting sound waves, one at 100 kHz and the other at 102 kHz, you'll hear sound. Explain.

PROBLEMS

1. What is the wavelength of a 340-Hz tone in air? What is the wavelength of a 34,000-Hz ultrasonic wave in air?
2. For years, marine scientists were mystified by sound waves detected by underwater microphones in the Pacific Ocean. These so-called T-waves were among the purest sounds in nature. Eventually they traced the source to underwater volcanoes, whose rising columns of bubbles resonated like organ pipes. What is the wavelength of a typical T-wave whose frequency is 7 Hz? (The speed of sound in seawater is 1530 m/s.)
3. An oceanic depth-sounding vessel surveys the ocean bottom with ultrasonic waves that travel 1530 m/s in seawater. The time delay of the echo to the ocean floor and back is 6 s. Show that the depth of the water directly below the vessel is 4590 m.
4. A bat flying in a cave emits a sound and receives its echo 0.1 s later. Show that its distance from the cave wall is 19 m.
5. You watch distant Sally Homemaker driving nails into a front porch at a regular rate of 1 stroke per second. You hear the sound of the blows exactly synchronized with the blows you see. And then you hear one more blow after you see the hammering stop. Explain how you calculate that Sally is 340 m away from you.
6. Imagine a Rip van Winkle type who lives in the mountains. Just before going to sleep, he yells, "WAKE UP," and the sound echoes off the nearest mountain and returns 8 hours later. Show that the distance between Rip and the imaginary mountain is nearly 5000 km (about the distance from New York to San Francisco).
7. What beat frequencies are possible with tuning forks of frequencies 256, 259, and 261 Hz?

• 8. A grunting porpoise emits sound at 57 Hz. What is the wavelength of this sound in water, where the speed of sound is 1500 m/s?

CHAPTER 20 ONLINE RESOURCES

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Interactive Figures

- 20.16, 20.17, 20.18

Videos

- Refraction of Sound
- Resonance
- Resonance and Bridges
- Interference and Beats

Quizzes

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