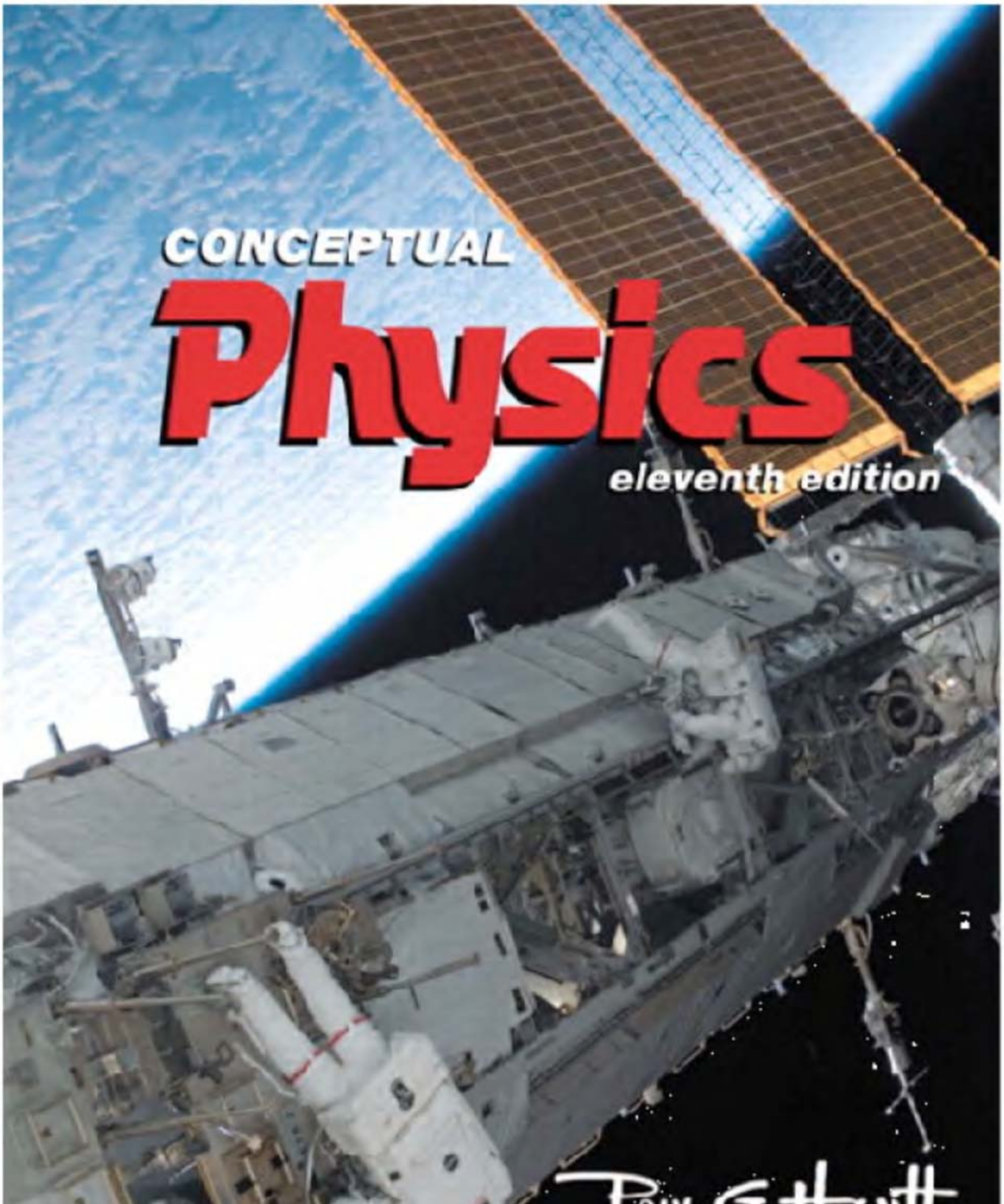
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Paul G. Hewitt

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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).

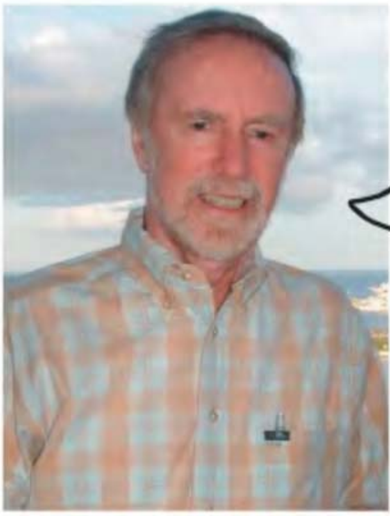
The inclusion of these people who are so dear to me makes *Conceptual Physics* all the more my labor of love.

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:

$$\begin{aligned} \varsigma &= \varsigma_0 + \delta\backepsilon \\ \varsigma &= \varsigma_0\backepsilon + \tfrac{1}{2}\delta\backepsilon^2 \\ \varsigma^2 &= \varsigma_0^2 + 2\delta\varsigma \\ \varsigma_a &= \tfrac{1}{2}(\varsigma_0 + \varsigma) \end{aligned}$$

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*.

More math-physics challenges are found in the sets of **Problems.** As with Rankings and Exercises, odd-numbered solutions are at the back of the book, and all solutions appear in the *Instructor Manual*. The problems are much less numerous than Exercises. Many more problems are available in the student supplement, **Problem Solving in Conceptual Physics,** co-authored with Phil Wolf. While problem solving is not the main thrust of a conceptual course, Phil and I, like most physics instructors, nevertheless love solving problems. In a novel and student-friendly way, our supplement features problems that are more physics than math, nicely extending *Conceptual Physics*—even to courses that feature problem solving. We think that many professors will enjoy the options offered by this student supplement to the textbook. Problem solutions are included in the Instructor Resources area of The Physics Place.

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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Next-Time Questions, familiar to readers of The Physics Teacher as Figuring Physics, are now available electronically. When sharing these with your classes, please do not show a question and follow it with the answer. Let there be a sufficient "wait-time" between the question and the answer. Allow your students to argue over the answer before showing it "next time" (which at minimum should be the next class meeting, or even next week). More learning occurs when students ponder answers before being given them. Next-Time Questions are now in a horizontal format to make them more compatible with computer monitors and PowerPoint® displays. Next-Time Questions are included on the Instructor Resource DVD, as well as in the Instructor Resources area of The Physics Place. They are also available at the click of a mouse on the Arborsci.com website.

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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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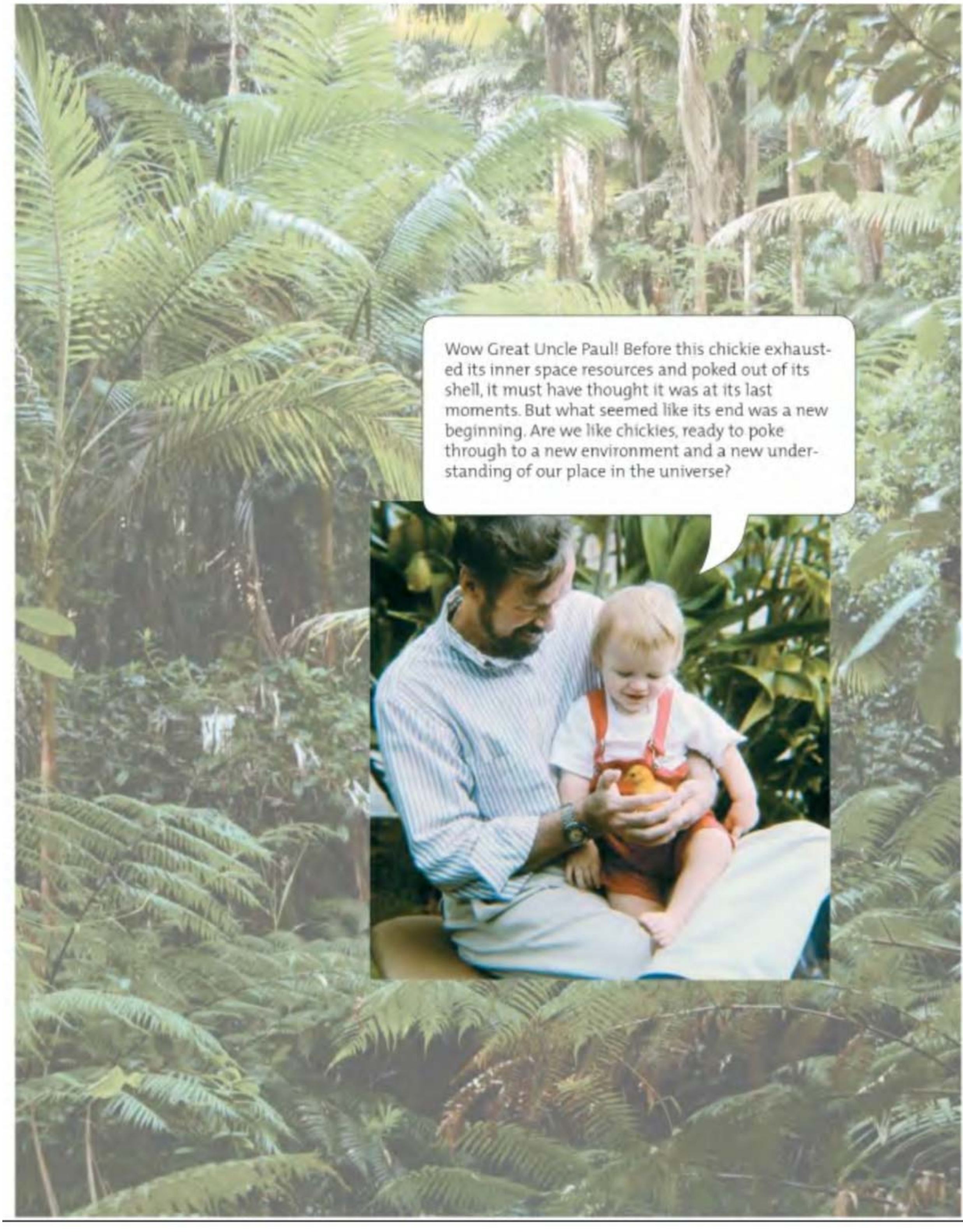
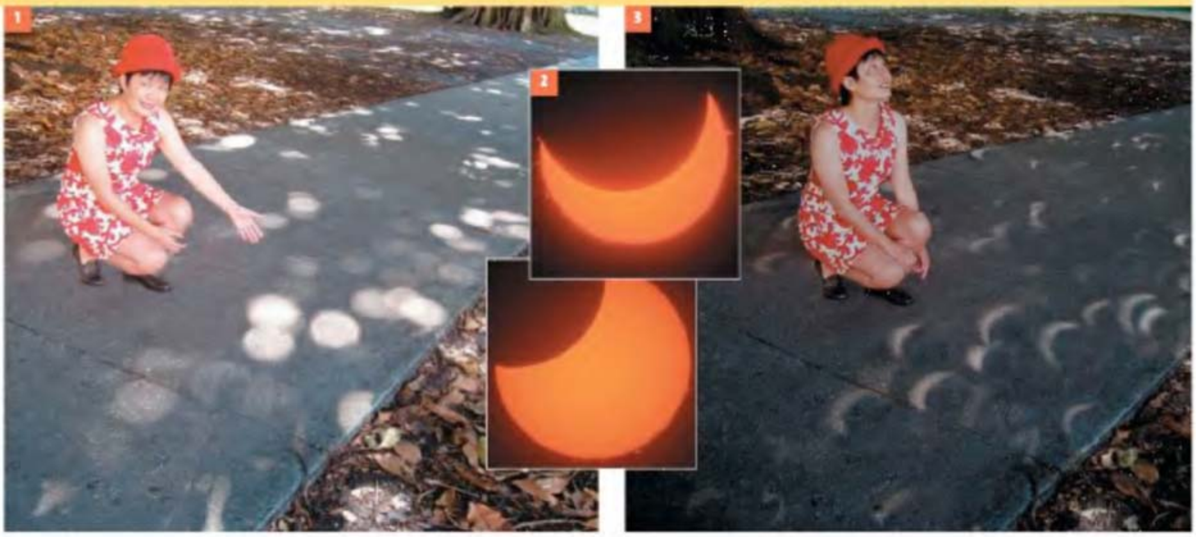
Paul G. Hewitt
St. Petersburg, Florida


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

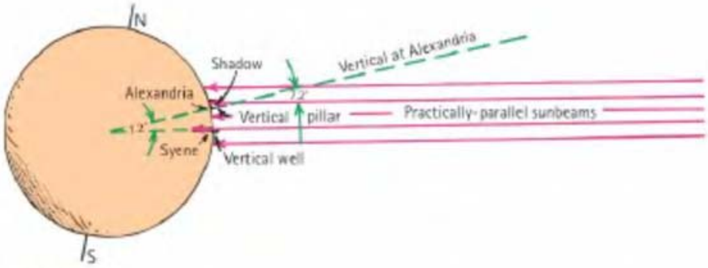

FIGURE 1.1

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."

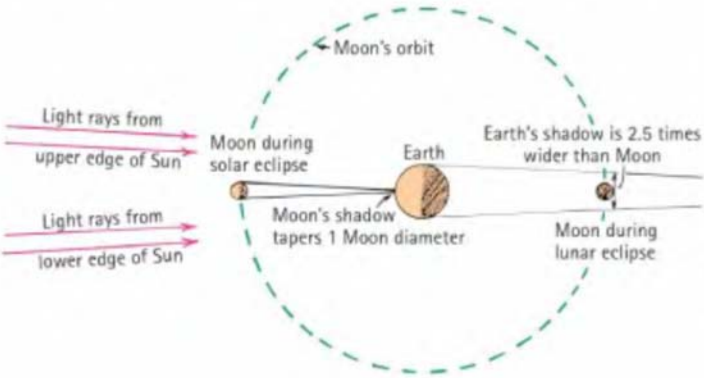

FIGURE 1.2

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.

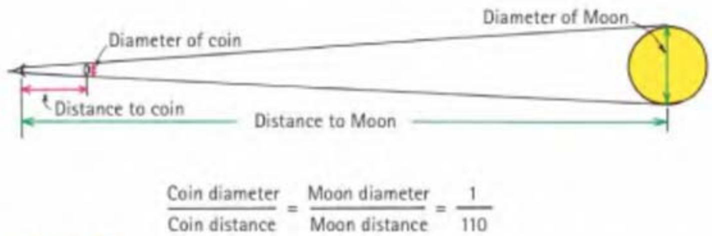

FIGURE 1.4

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 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.

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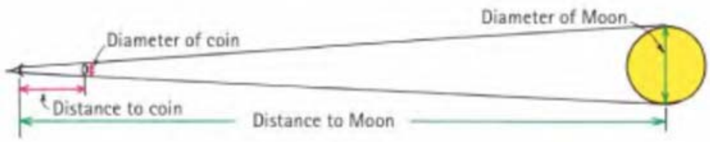

$$\frac{\text{Coin diameter}}{\text{Coin distance}} = \frac{\text{Moon diameter}}{\text{Moon distance}} = \frac{1}{110}$$

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DISTANCE TO THE SUN

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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.

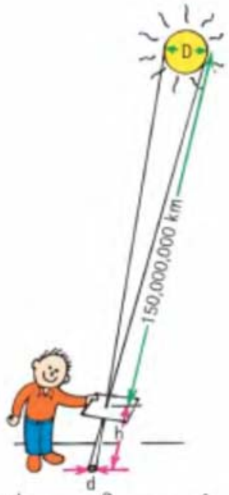
A rule of trigonometry states that, if you know all the angles in a right triangle plus the length of any one of its sides, you can calculate the length of any other side. Aristarchus knew the distance from Earth to the Moon. At the time of the half Moon he also knew one of the angles, 90°. All he had 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).



$$\frac{d}{h} = \frac{D}{150{,}000{,}000 \text{ km}} = \frac{1}{110}$$

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.

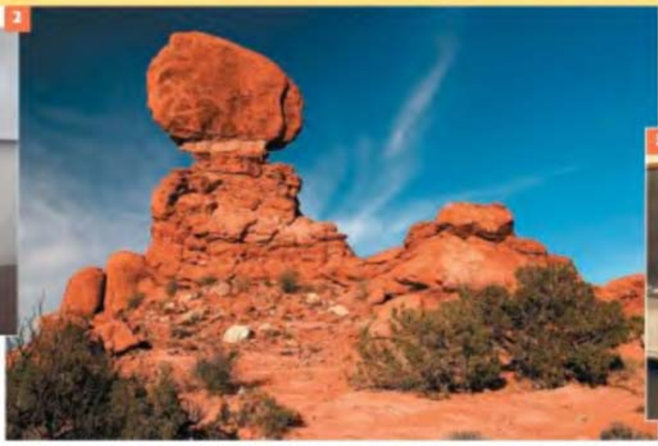
EXERCISES

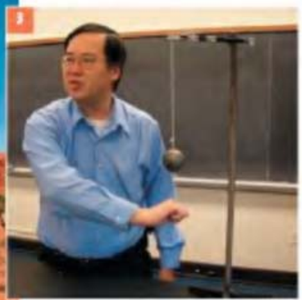
1. What is the penalty for scientific fraud in the science community?
2. Which of the following are scientific hypotheses? (a) Chlorophyll makes grass green. (b) Earth rotates about its axis because living things need an alternation of light and darkness. (c) Tides are caused by the Moon.
3. In answer 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.

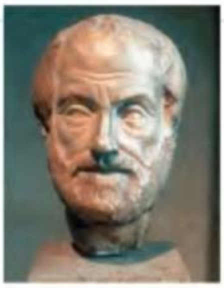
Copernicus and the Moving Earth

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.

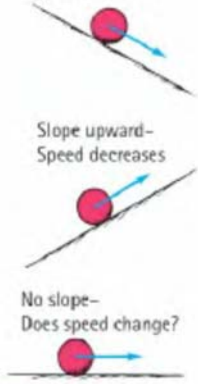


FIGURE 2.2
Motion of balls on various planes.

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

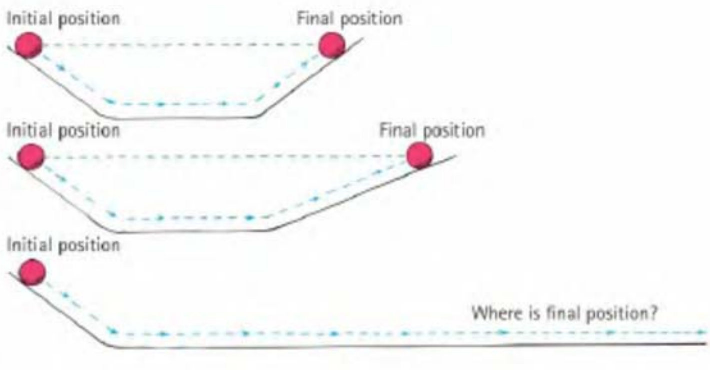


FIGURE 2.3
A ball rolling down an incline on the left tends to roll up to its initial height on the right. The ball must roll a greater distance as the angle of incline on the right is reduced.

[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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Videos

Newton's Law of Inertia
The Old Tablecloth Trick
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.

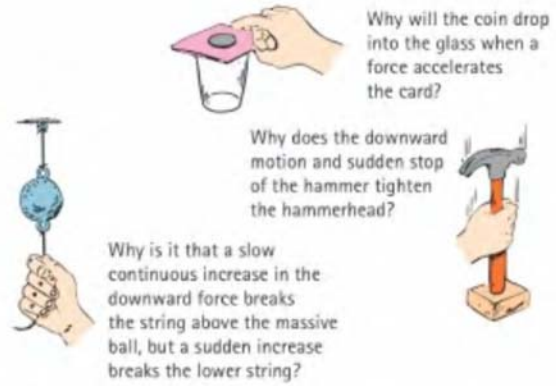

FIGURE 2.5
Examples of inertia.

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.

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

Net Force

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.

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Definition of a Newton

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.)

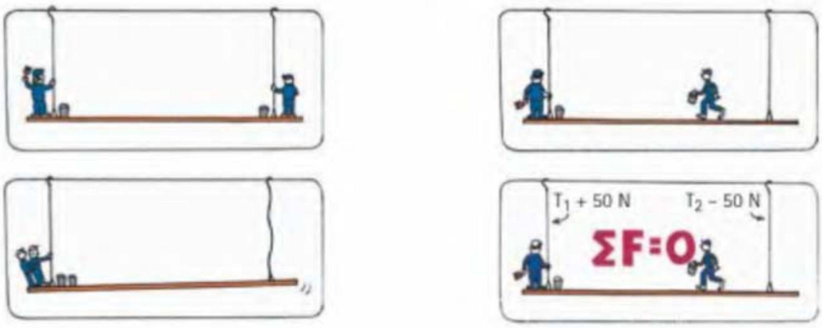
Personal Essay

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.[3]

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.

[3] 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.

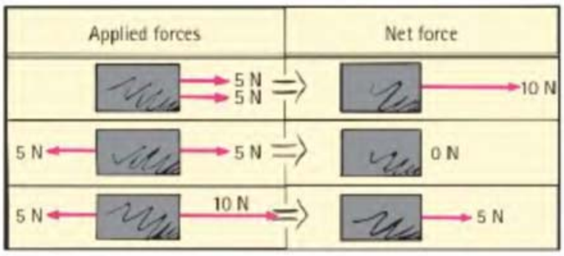


FIGURE 2.6
Net force (a force of 5 N is about 1.1 lb).

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 **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.

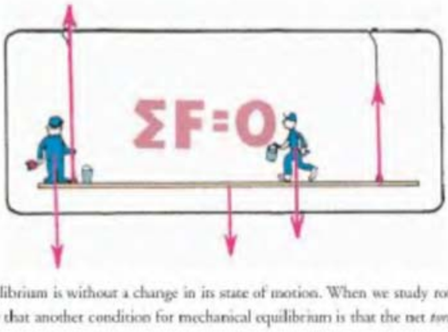


FIGURE 2.8
The sum of the upward vectors equals the sum of the downward vectors. $\Sigma \mathbf{F} = 0$ and the scaffold is in equilibrium.

[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?

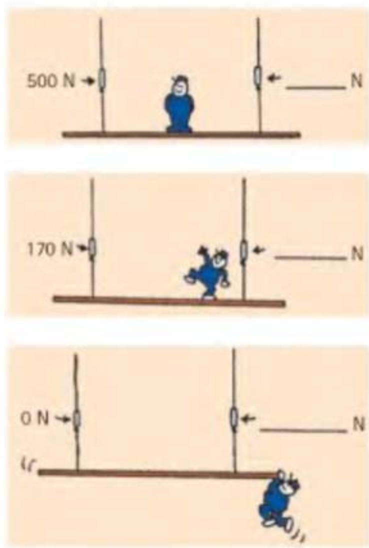
Check Your Answers

(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 ? $\Sigma F = 0$.

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

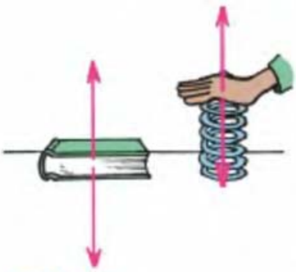


FIGURE 2.9
(Left) The table pushes up on the book with as much force as the downward force of gravity on the book. (Right) The spring pushes up on your hand with as much force as you exert to push down on the spring.

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.

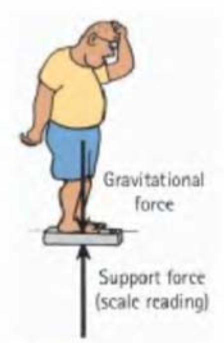


FIGURE 2.10
The upward support is as much as the downward gravitational force.

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.

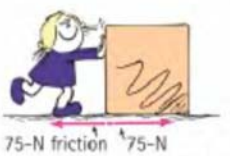


FIGURE 2.11
When the push on the crate is as great as the force of friction between the crate and the floor, the net force on the crate is zero and it slides at an unchanging speed.

The equilibrium rule, $\Sigma F = 0$, 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

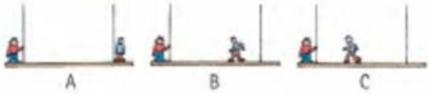
19. A bowling ball at rest is in equilibrium. Is the ball in equilibrium when it moves at constant speed in a straight-line path?
20. What is the test for whether or not a moving object is in equilibrium?
21. If you push on a crate with a force of 100 N and it slides at constant velocity, how much is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

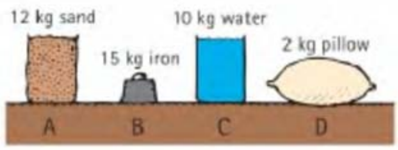
RANKING

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.

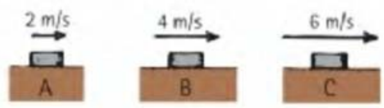


2. Rank the net force on the block from least to most in the four situations, A, B, C, and D.

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?

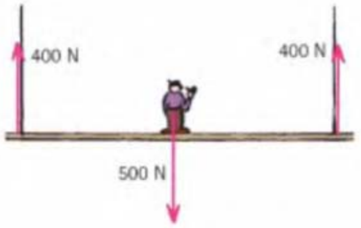
48. Consider an airplane that flies due east on a trip, then returns flying due west. Flying in one direction, the plane flies with Earth's rotation, and in the opposite direction, against Earth's rotation. But, in the absence of winds, the times of flight are equal either way. Why is this so?

PROBLEMS

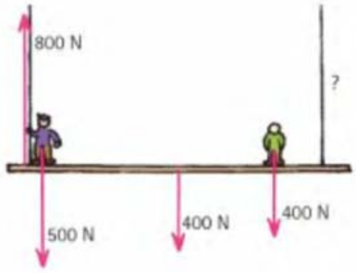
1. Lucy Lightfoot stands with one foot on one bathroom scale and her other foot on a second bathroom scale. Each scale reads 350 N. What is Lucy's weight?

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

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- 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 

2 

3 

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.

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.

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.

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

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 $= \frac{\text{total distance covered}}{\text{time interval}} = \frac{40 \text{ km}}{0.5 \text{ h}} = 80$ 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.

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.*

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

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.

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

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?

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.

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

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

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

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Definition of Acceleration
Numerical Example of Acceleration

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 $v = at$.

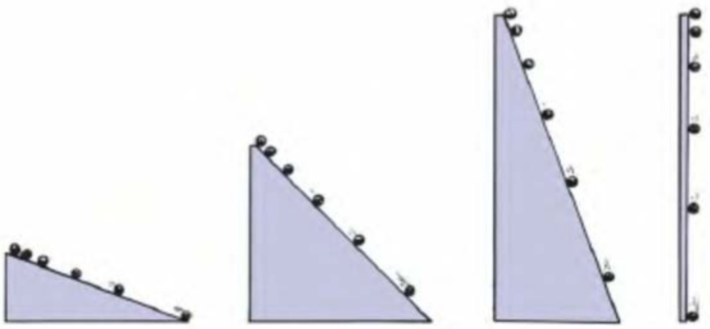

FIGURE 3.6

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	$10t$

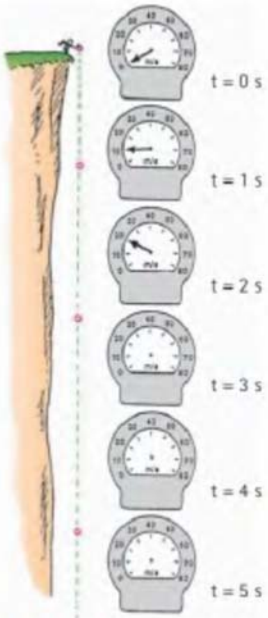

FIGURE 3.7
Pretend that a falling rock is equipped with a speedometer. In each succeeding second of fall, you'd find the rock's speed increasing by the same amount: 10 m/s. Sketch in the missing speedometer needle at t = 3 s, 4 s, and 5 s. (Table 3.2 shows the speeds we would read at various seconds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

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Air Resistance and Falling Objects
Falling Distance

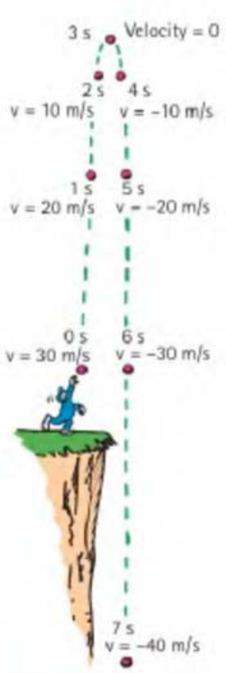


FIGURE 3.8
INTERACTIVE FIGURE

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

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: $v = gt = 10\ m/s^2 \times 1/2\ s = 5\ m/s$

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

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

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

Or equivalently,

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

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

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	$\frac{1}{2}10t^2$

[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.)

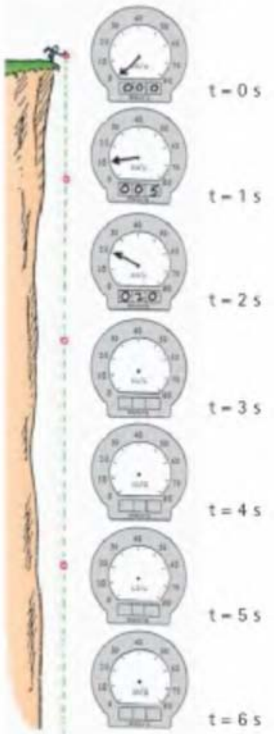


FIGURE 3.9
Pretend that a falling rock is equipped with a speedometer and an odometer. Speed readings increase by 10 m/s and distance readings by $1/2\,gt^2$. Can you complete the speedometer positions and odometer readings?

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.

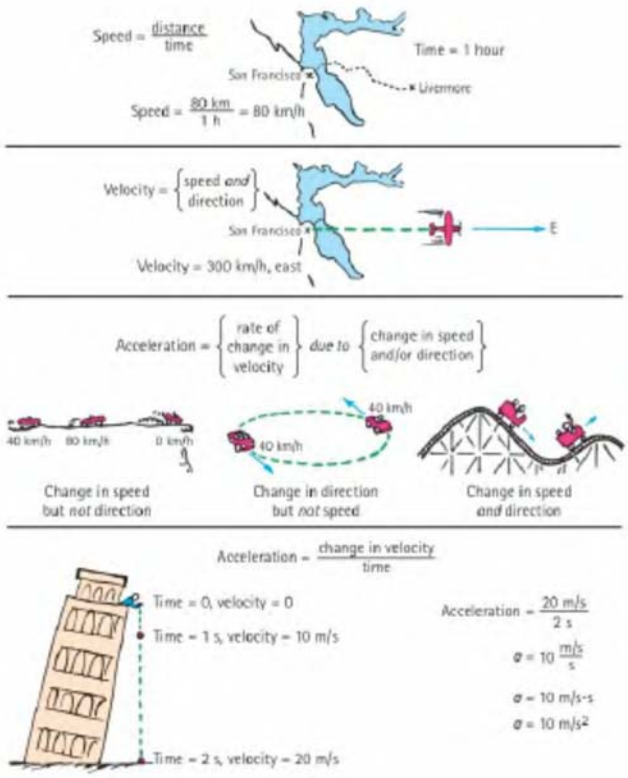


FIGURE 3.11
Motion analysis.

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/s^2. 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/s^2 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.

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

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.

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

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.

Distance = average speed × 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.

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

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.

Instantaneous speed = acceleration × 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:

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

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.

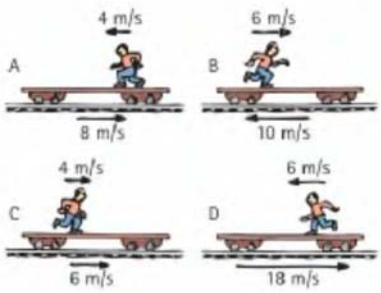
17. An object is dropped from rest and falls freely. After 7 s, calculate its instantaneous speed.
18. A skydiver steps from a high-flying helicopter. In the absence of air resistance, how fast would she be falling at the end of a 12-s jump?
19. On a distant planet, a freely falling object has an acceleration 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: $d = \frac{1}{2}gt^2$

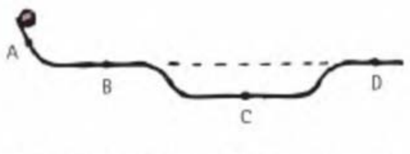
20. An apple drops from a tree and hits the ground in 1.5 s. Calculate how far it falls.
21. Calculate the vertical distance an object dropped from rest covers in 12 s of free fall.
22. On a distant planet a freely falling object has an acceleration of 20 m/s^2. Calculate the vertical distance an object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

RANKING

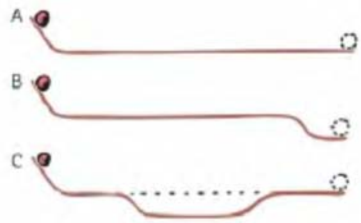
1. Jogging Jake runs along a train flatcar that moves at the velocities shown in positions A–D. From greatest to least, rank the velocity of Jake relative to a stationary observer on the ground. (Call the direction to the right positive.)



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.)

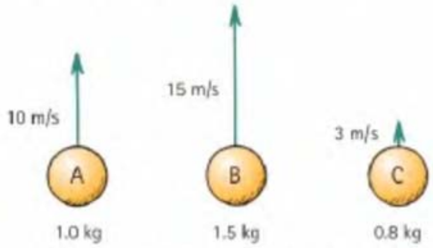


3. A ball is released at the left end of these different tracks. The tracks are bent from equal-length pieces of channel iron.



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.

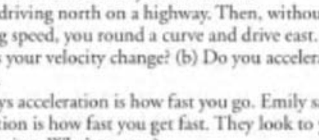


a. From fastest to slowest, rank the speeds of the balls 1 s after being thrown.
b. From greatest to least, rank the accelerations of the balls 1 s after being thrown. (Or are the accelerations the same?)

EXERCISES

1. What is the impact speed when a car 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

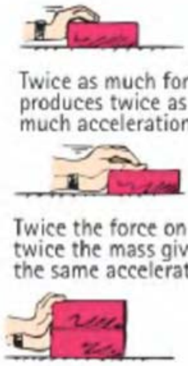

FIGURE 4.2
Acceleration is directly proportional to force.

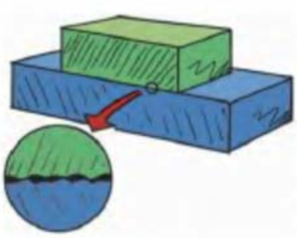

FIGURE 4.3
Friction results from the mutual contact of irregularities in the surfaces of sliding objects. Even surfaces that appear to be smooth have irregular surfaces when viewed at the microscopic level.

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.

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.

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

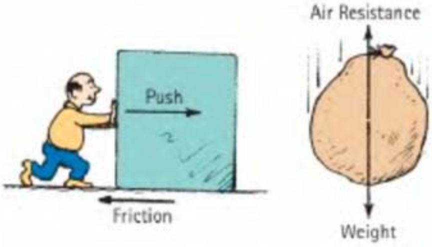

FIGURE 4.4

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]

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Video
Friction

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.

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.

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.

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.

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 4.9

INTERACTIVE FIGURE

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

FIGURE 4.10

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

Newton's Second Law of Motion

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

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

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

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.

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 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.*

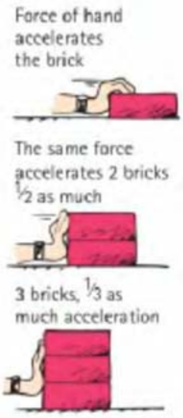

FIGURE 4.11

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,

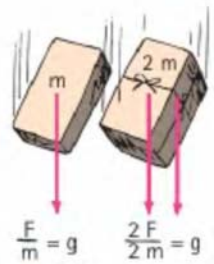


FIGURE 4.12
INTERACTIVE FIGURE

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.

fyi

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

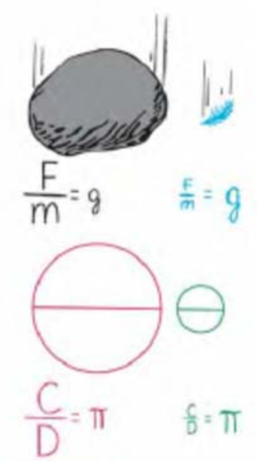


FIGURE 4.13

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.

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

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]

[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.

PhysicsPlace.com
Video
Falling and Air Resistance

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.

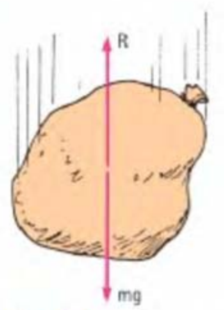


FIGURE 4.14
When weight mg is greater than air resistance R, the falling sack of mail accelerates. At higher speeds, R increases. When $R = mg$, acceleration reaches zero, and the sack reaches its terminal velocity.

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.

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. ($v_{man}^2/v_{woman}^2 = 1.41^2 = 2$.)

fyi

- 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/s².

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

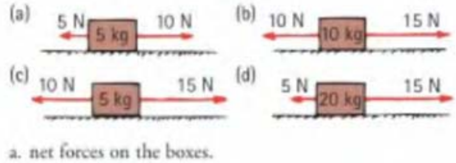
6. Calculate the acceleration of a 2000-kg, single-engine airplane just before takeoff when the thrust of its engine is 500 N.
7. Calculate the acceleration of a 300,000-kg jumbo jet just before takeoff when the thrust on the aircraft is 120,000 N.
8. (a) Calculate the acceleration of a 2-kg block on 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.

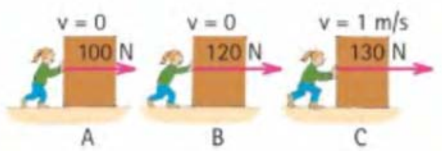
RANKING

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

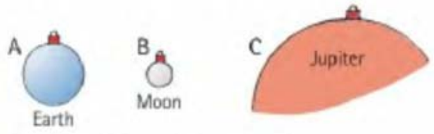


a. net forces on the boxes.
b. accelerations of the boxes.

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.

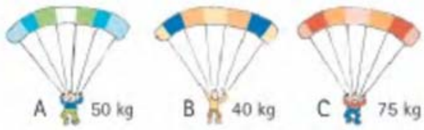


3. Consider a 100-kg box of tools in the locations A, B, and C. From greatest to least, rank the



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.

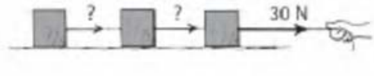


a. From fastest to slowest, rank the amount of their terminal velocities.
b. From longest to shortest times, rank their order in reaching the ground.

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?



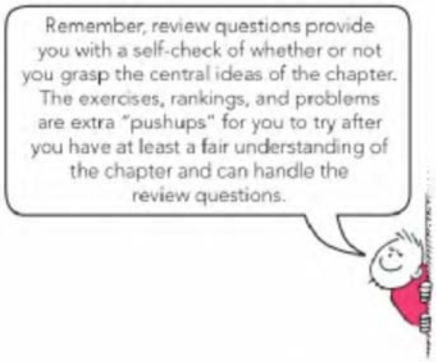
27. To pull a wagon across a lawn with constant velocity, you have to exert a steady force. Reconcile this fact with Newton's first law, which says that motion with constant velocity requires no force.
28. Free fall is motion in which gravity is the only force acting. (a) Is a skydiver who has reached 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

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

Quizzes

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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]

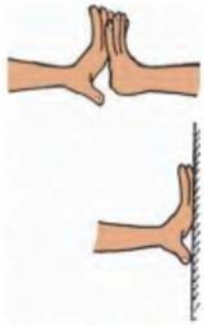

FIGURE 5.1
INTERACTIVE FIGURE

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.

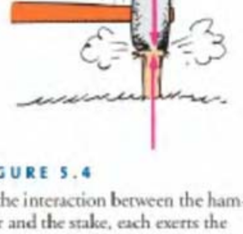

FIGURE 5.4

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.

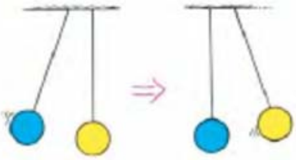

FIGURE 5.5
The impact forces between the blue ball and the yellow ball move the yellow ball and stop the blue ball.

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

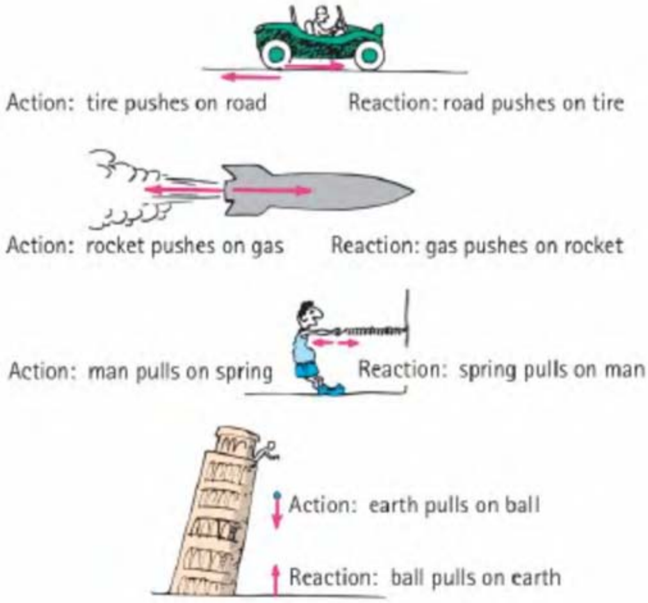

FIGURE 5.7
Action and reaction forces. Note that when action is "*A* exerts force on *B*," the reaction is then simply "*B* exerts force on *A*."

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.

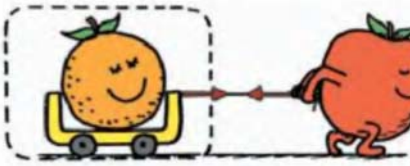

FIGURE 5.9
INTERACTIVE FIGURE
The force on the orange, provided by the apple, is not cancelled by the reaction force on the apple. The orange still accelerates.

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

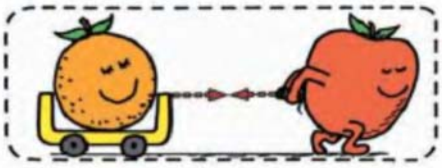

FIGURE 5.10
INTERACTIVE FIGURE
In the larger system of orange + apple, action and reaction forces are internal and cancel. If these are the only horizontal forces, with no external force, no acceleration of the system occurs.

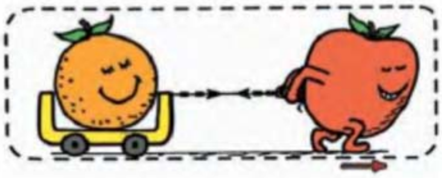

FIGURE 5.11
INTERACTIVE FIGURE
An external horizontal force occurs when the floor pushes on the apple (reaction to the apple's push on the floor). The orange–apple system accelerates.

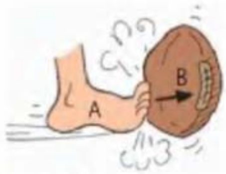

FIGURE 5.12
A acts on B, and B accelerates.

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).

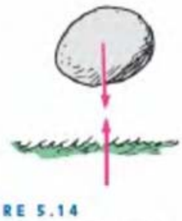

FIGURE 5.14
Earth is pulled up by the boulder with just as much force as the boulder is pulled downward by Earth.

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:

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

$$\text{Cannon: } \frac{F}{\Large m} = a$$

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

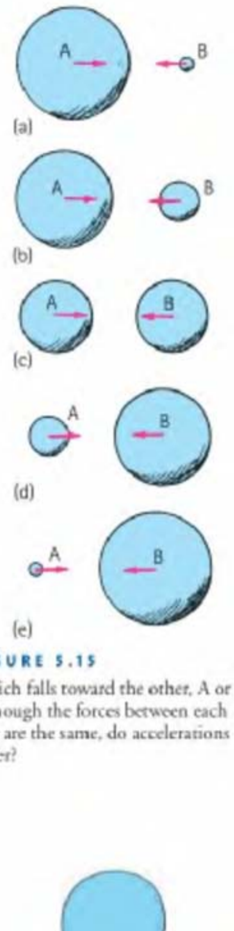


FIGURE 5.15

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

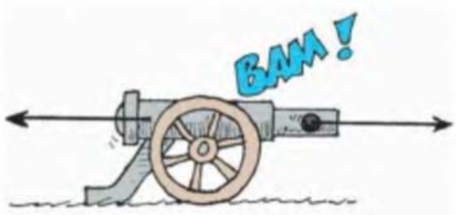


FIGURE 5.16

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.

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.

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.

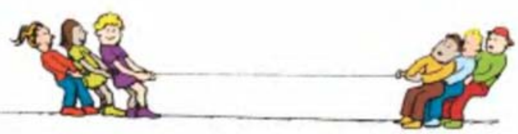
FIGURE 5.20

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?

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!)

Jellyfish have been using rocket or jet propulsion for eons.

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.

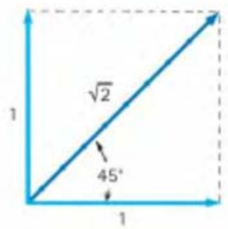

FIGURE 5.23
When a pair of equal-length vectors at right angles to each other are added, they form a square. The diagonal of the square is the resultant, $\sqrt{2}$ times the length of either side.

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

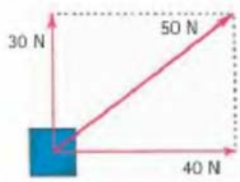

FIGURE 5.24
The resultant of the 30-N and 40-N forces is 50 N.

[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.

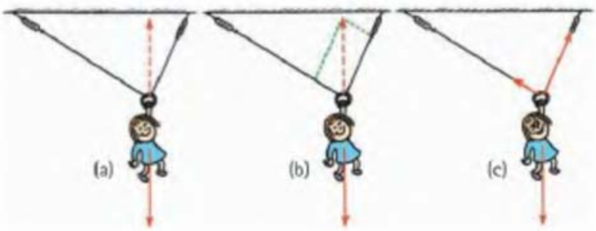

FIGURE 5.25
INTERACTIVE FIGURE

(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."

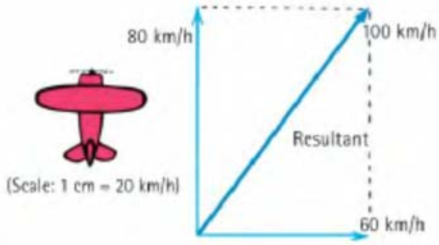


FIGURE 5.27
The 60-km/h crosswind blows the 80-km/h aircraft off course at 100 km/h.

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.

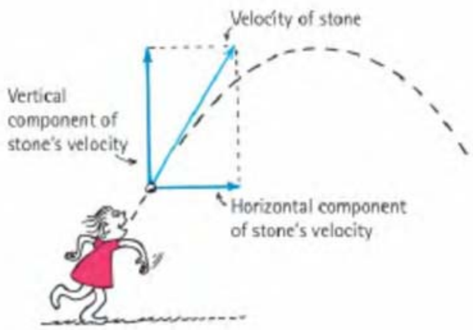


FIGURE 5.28
The horizontal and vertical components of a stone's velocity.

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

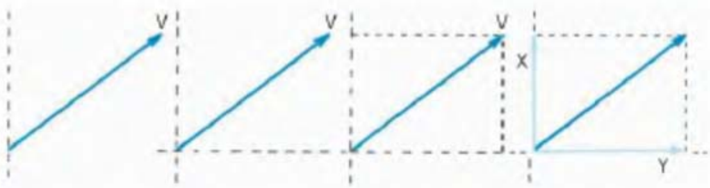


FIGURE 5.29
Construction of the vertical and horizontal components of a vector.

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

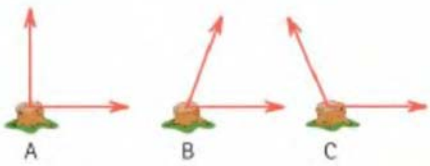
1. Calculate the resultant of the pair of velocities 100 km/h north and 75 km/h south. Calculate the resultant if both of the velocities are directed north.

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

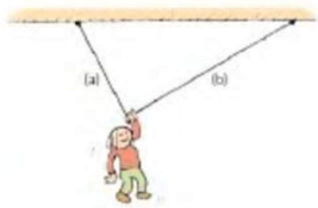
2. Calculate the magnitude of the resultant of a pair of 100-km/h velocity vectors that are at right angles to each other.
3. Calculate the resultant of a horizontal vector with a magnitude of 4 units and a vertical vector with a magnitude of 3 units.
4. Calculate the resultant velocity of an airplane 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.

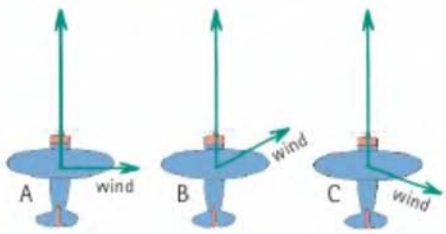


2. Nellie Newton hangs motionless by one hand from a clothesline. Which side of the line, a or b, has the greater

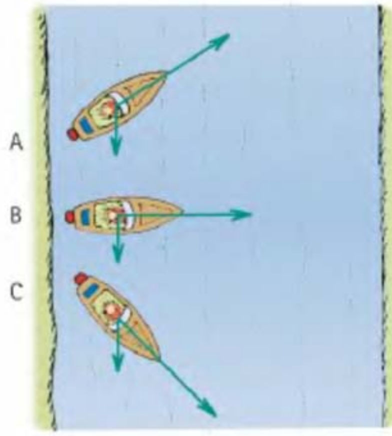


a. horizontal component of tension?
b. vertical component of tension?
c. tension?

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.



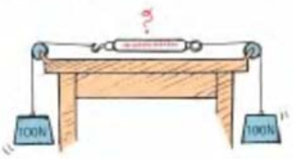
4. Here we see top views of three motorboats crossing a river. All have the same speed relative to the water, and all experience the same river flow. Construct resultant vectors showing the speed and direction of the boats. Rank them from most to least for
a. the time for the boats to reach the opposite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

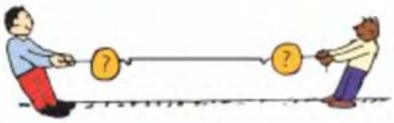
push? If the force of friction isn't the reaction force to your push, what is?

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.

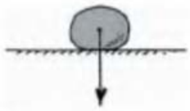
39. The rope is repositioned as shown and still supports the 50-N lantern. Is the tension in the rope less than, equal to, or more than 50 N? Use the parallelogram rule to defend your answer.

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?



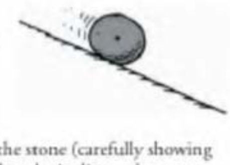
44. Here a stone is suspended at rest by a string. (a) Draw force vectors for all the forces that act on the stone. (b) Should your vectors have a zero resultant? (c) Why or why not?

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?

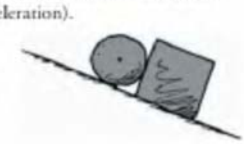
46. Suppose the string in the preceding exercise breaks and the stone slows in its upward motion. Draw a force vector diagram of the stone when it reaches the top of its path.

47. What is the acceleration of the stone of Exercise 46 at the top of its path?

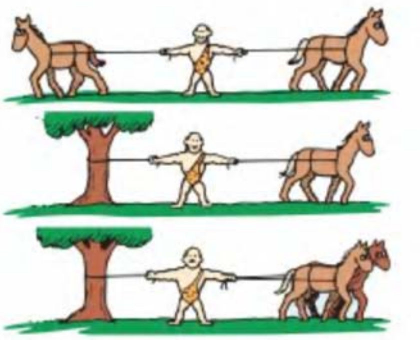
48. Here the stone is sliding down a friction-free incline. (a) Identify the forces that act on it, and draw appropriate force vectors. (b) By the parallelogram rule, construct the resultant force on the stone (carefully showing that it has a direction parallel to the incline—the same direction as the 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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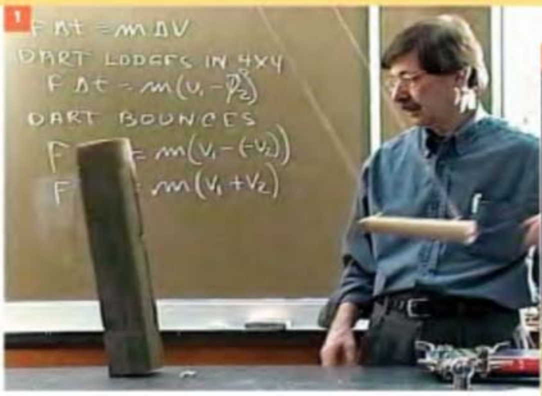
6 Momentum



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.

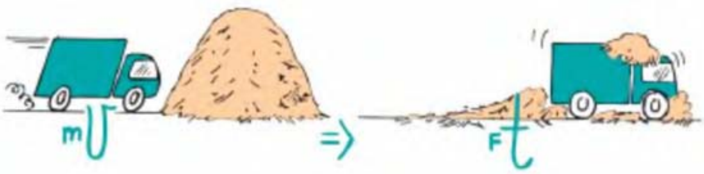


FIGURE 6.5
If the change in momentum occurs over a long time, the hitting force is small.

FIGURE 6.6
If the change in momentum occurs over a short time, the hitting force is large.

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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.

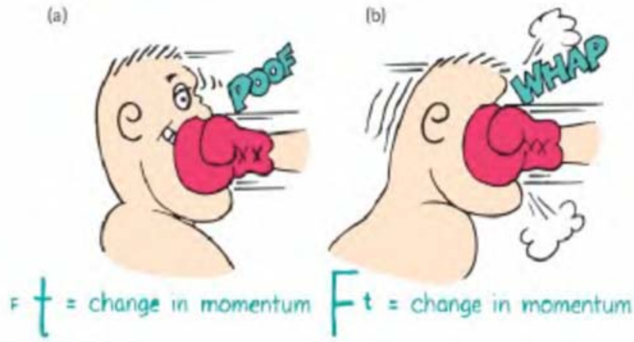


FIGURE 6.8

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 *Ft*

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.

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

Momentum is conserved for all collisions, elastic and inelastic (whenever external forces don't interfere).

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 $mV = Mv$.

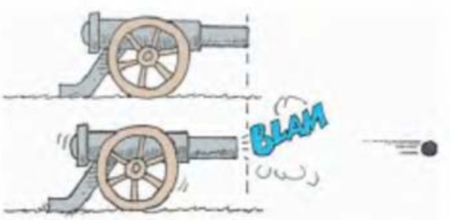


FIGURE 6.11

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.*

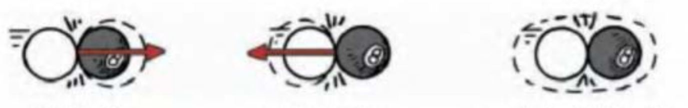


FIGURE 6.12

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.

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.

Can you see how Newton's laws relate to momentum conservation?

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?

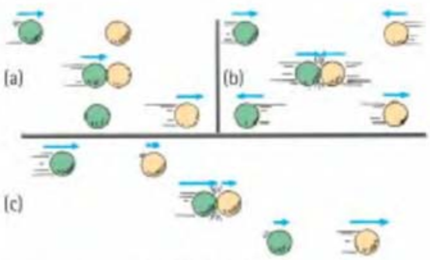


FIGURE 6.13
INTERACTIVE FIGURE

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.

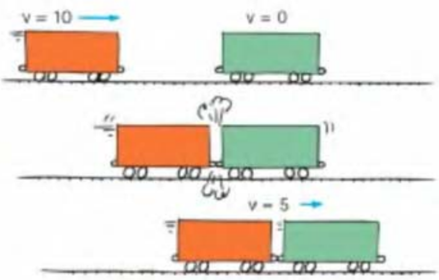


FIGURE 6.14
INTERACTIVE FIGURE

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.

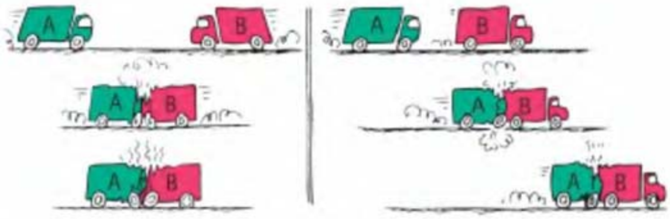


FIGURE 6.15

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.

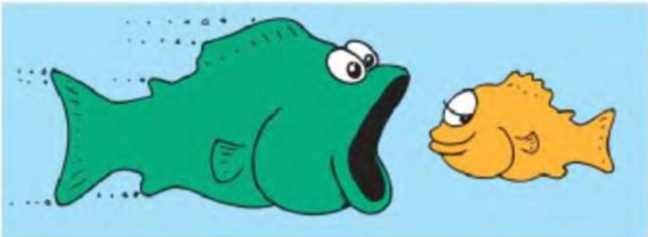


FIGURE 6.17
Two fish make up a system, which has the same momentum just before lunch and just after lunch.

$$\text{Net momentum before lunch} = \text{net momentum after lunch}$$
$$(5\text{ kg})(1\text{ m/s}) + (1\text{ kg})(0\text{ m/s}) = (5\text{ kg} + 1\text{ kg})\,v$$
$$5\text{ kg}\cdot\text{m/s} = (6\text{ kg})\,v$$
$$v = 5/6\text{ m/s}$$

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

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.

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.

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.

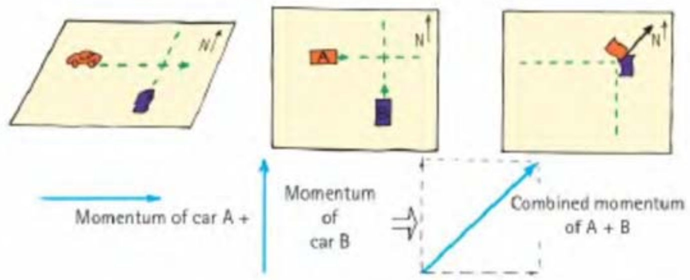


FIGURE 6.18
INTERACTIVE FIGURE
Momentum is a vector quantity.

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.

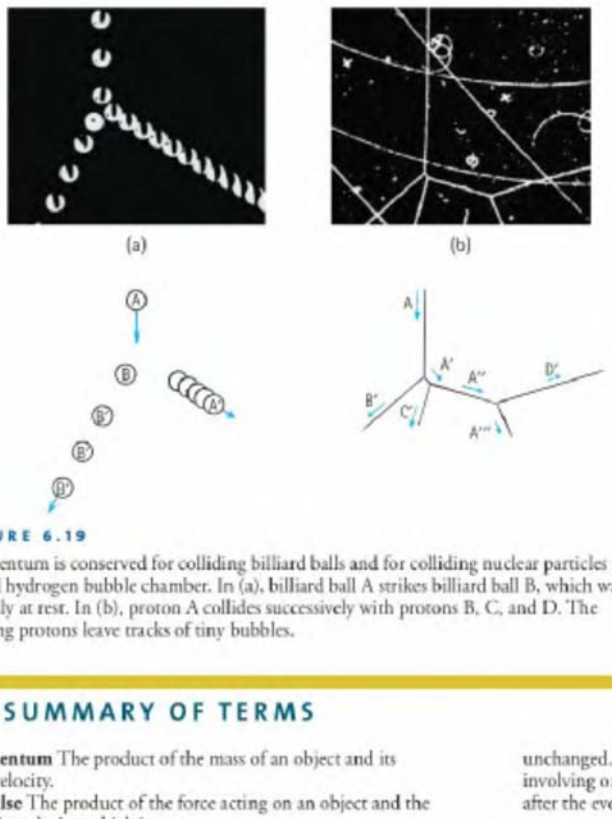


FIGURE 6.19

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.

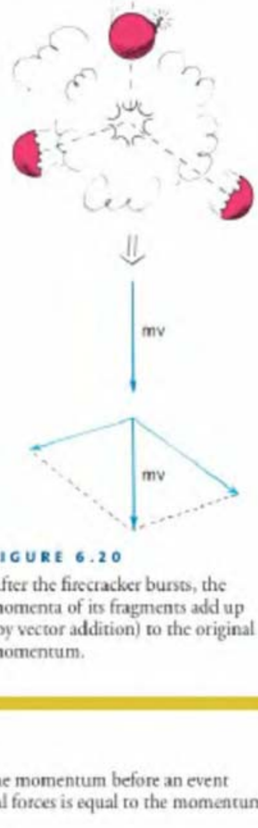


FIGURE 6.20

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: $Ft = \Delta mv$

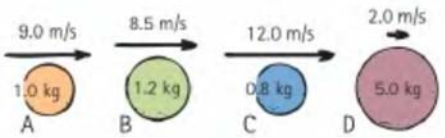
5. What is the impulse on an 8-kg ball rolling at 2 m/s when it bumps into a pillow and stops?
6. How much impulse stops a 50-kg carton sliding at 4 m/s when it meets a rough surface?

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.

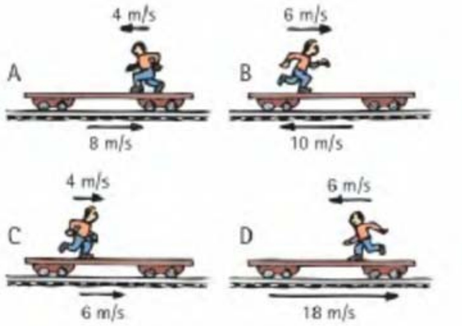
RANKING

1. The balls have different masses and speeds. Rank the following from greatest to least.



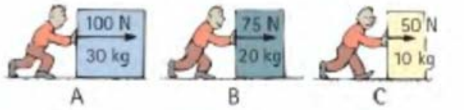
   a. Momentum
   b. The impulses needed to stop the balls

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.



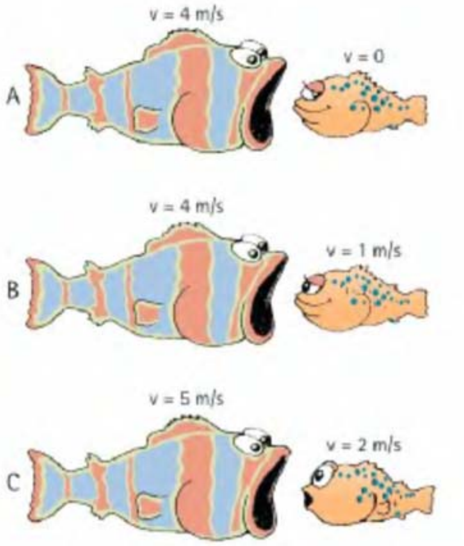
   a. The magnitude of Jake's momentum relative to the flatcar
   b. Jake's momentum relative to an observer at rest on the ground

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

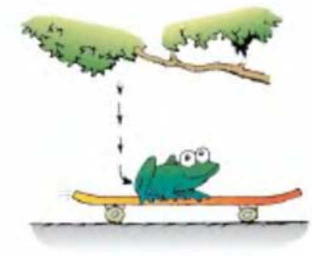
1. When a supertanker is brought to a stop, its engines are typically cut off about 25 km from port. Why is it so difficult to stop or turn a supertanker?
2. In terms of impulse and momentum, why do padded dashboards make automobiles safer?
3. In terms of impulse and momentum, why do air bags in cars 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.

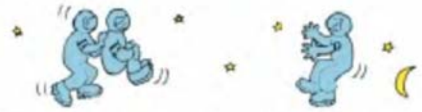
24. If only an external force can change the velocity of a body, how can the internal force of the brakes bring a moving car to rest?
25. You are at the front of a floating canoe near a dock. You jump, expecting to land on the dock easily. Instead you land in the water. Explain.
26. Explain how a swarm 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

PhysicsPlace.com

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.

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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.

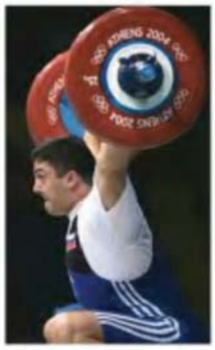

FIGURE 7.3
Work is done in lifting the barbell.

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.

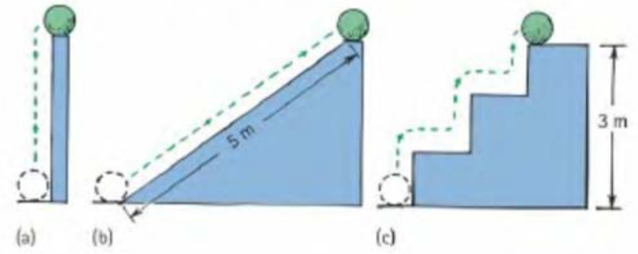

FIGURE 7.6

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.

$$\text{Gravitational potential energy} = \text{weight} \times \text{height}$$

$$PE = mgh$$

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.*

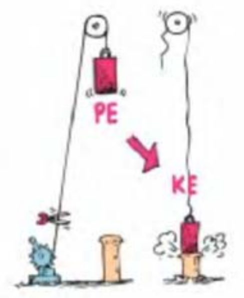

FIGURE 7.7

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.

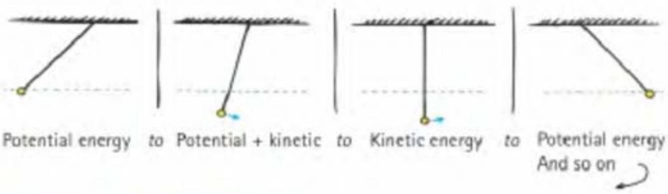

FIGURE 7.10

Energy transitions in a pendulum. PE is relative to the lowest point of the pendulum, when it is vertical.

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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 $Fd = ma(\frac{1}{2}at^2) = (\frac{1}{2})maat^2 = \frac{1}{2}m(at)^2$; and substituting $v = at$, we get $Fd = \frac{1}{2}mv^2$. That is, Work = KE gained.

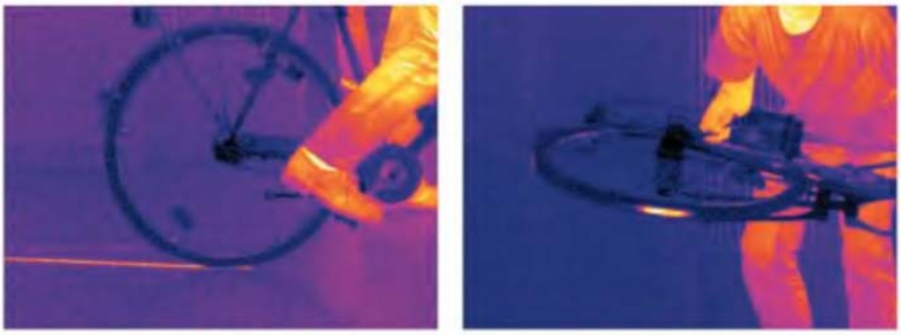

FIGURE 7.13

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: $\frac{1}{2}m(3v)^2 = \frac{1}{2}m9v^2 = 9(\frac{1}{2}mv^2)$. 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.

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!

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.

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.

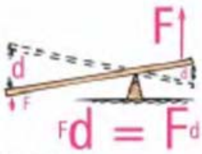

FIGURE 7.15
The lever.

FIGURE 7.16
Applied force × applied distance = output force × output distance.

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Machines: Pulleys

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

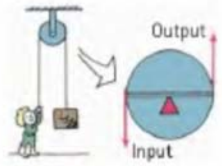


FIGURE 7.17
INTERACTIVE FIGURE
This pulley acts like a lever with equal lever arms. It changes only the direction of the input force.

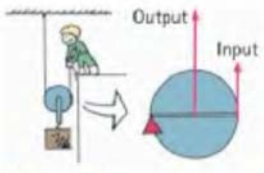


FIGURE 7.18
INTERACTIVE FIGURE
In this arrangement, a load can be lifted with half the input force. Note the "fulcrum" is at the left end rather than at the center.

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.

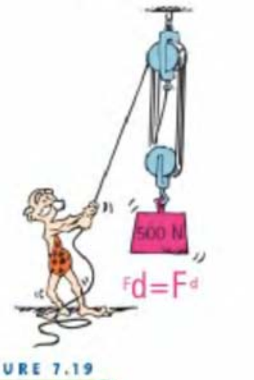


FIGURE 7.19
INTERACTIVE FIGURE

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!

fyi

- 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.

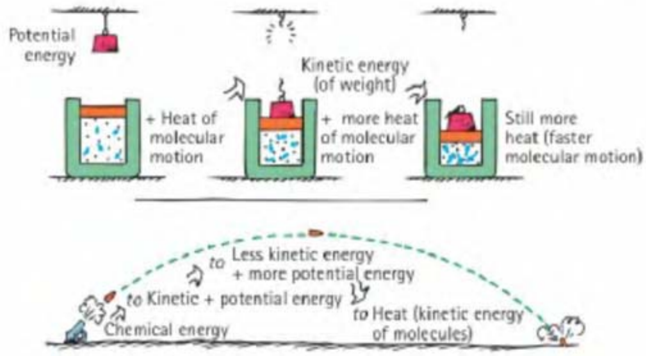


FIGURE 7.20
Energy transitions. The graveyard of mechanical energy is thermal energy.

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.

PhysicsPlace.com
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

fyi

- 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.

fyi

- 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.

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.

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.

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.)

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."

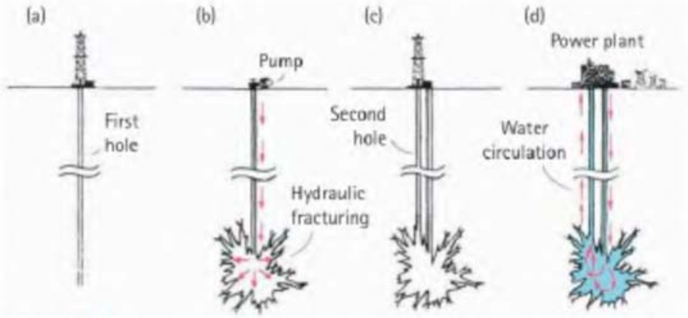


FIGURE 7.25

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, $\text{work}_{input} = \text{work}_{output}$; $(Fd)_{input} = (Fd)_{output}$.

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

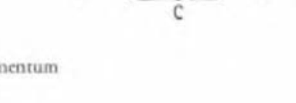
13. How much work is required to increase the kinetic energy of a car by 5000 J?
14. What change in kinetic energy does an airplane experience on takeoff if it is moved a distance of 500 m by a sustained net force of 5000 N?

RANKING

1. The mass and speed of the three vehicles, A, B, and C, are shown. Rank them from greatest to least for

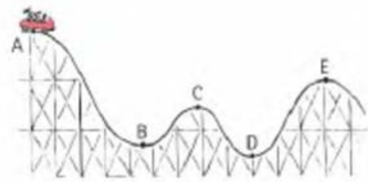
   a. momentum.
   b. kinetic energy.
   c. work done to bring them up to their respective speeds from rest.

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:



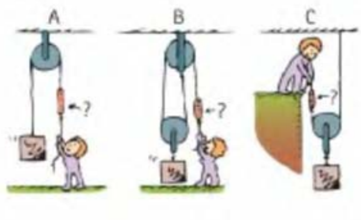
   a. Momentum
   b. KE
   c. PE

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.)

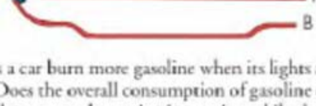


EXERCISES

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.

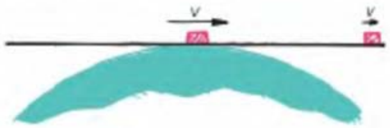
17. Does the International Space Station have gravitational PE? KE? Explain.
18. What does the work-energy theorem say about the speed of a satellite in circular orbit?
19. A moving hammer hits a nail and drives it into a wall. If the hammer hits the nail with twice the speed, how much deeper will the 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?)

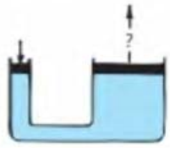
57. An inefficient machine is said to "waste energy." Does this mean that energy is actually lost? Explain.

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

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- 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.

PhysicsPlace.com
Video
Rotational Speed

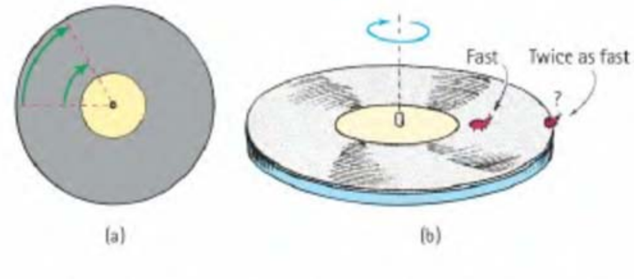

FIGURE 8.1
INTERACTIVE FIGURE

(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 point 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?

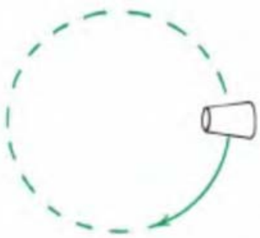

FIGURE 8.4

Because the wide part of the cup rolls faster than the narrow part, the cup rolls in a curve.

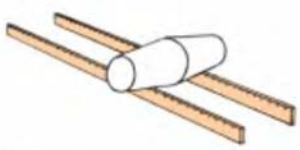

FIGURE 8.5

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.

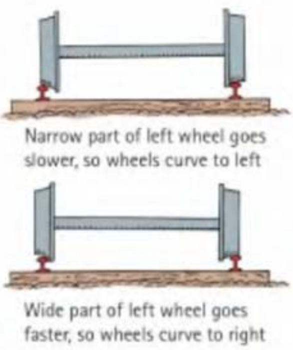

FIGURE 8.7

(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).

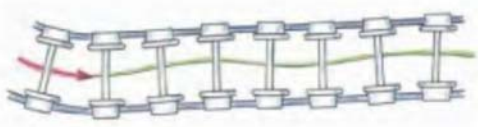

FIGURE 8.8

After rounding a curve, a train often oscillates on the straightaway as the wheels self-correct.

fyi

- 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!

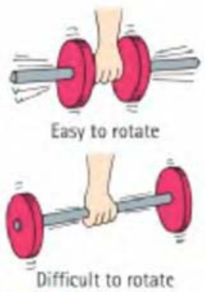

FIGURE 8.9

Rotational inertia depends on the distribution of mass relative to the axis of rotation.

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

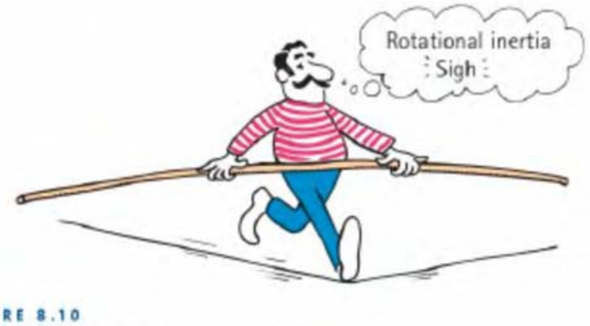

FIGURE 8.10

The tendency of the pole to resist rotation aids the acrobat.

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Videos

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.

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 8.11

The pencil has different rotational inertias about different rotational axes.

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 8.15 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?

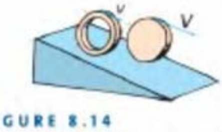

FIGURE 8.14

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.

[4] 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, $I = mr^2$.

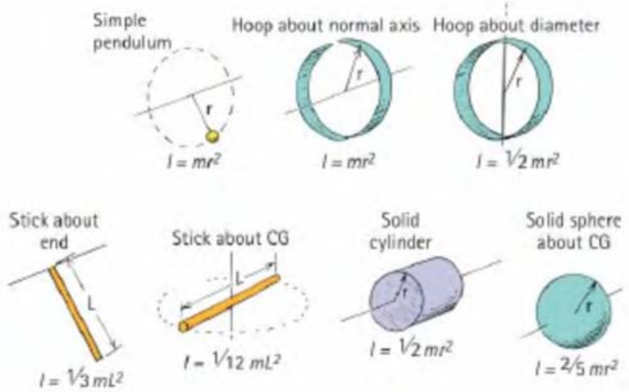

FIGURE 8.15

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.

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*.

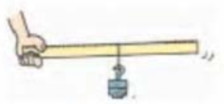

FIGURE 8.16

Move the weight farther from your hand and feel the difference between force and 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.

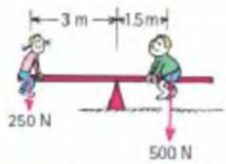

FIGURE 8.18

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.

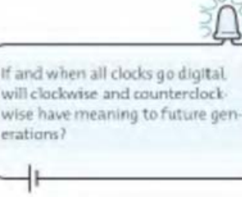

FIGURE 8.19

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.

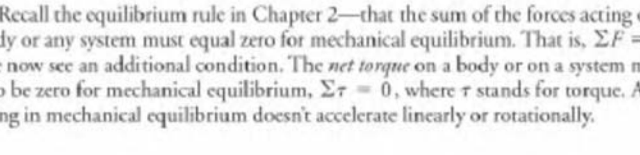

FIGURE 8.20

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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Videos

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: $300\ N \times 2.5\ m = 500\ N \times 1.5\ m$.

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.

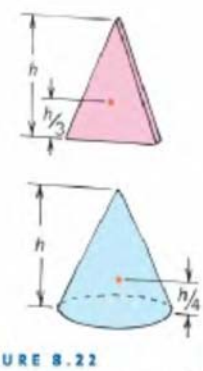

FIGURE 8.22
The center of mass for each object is shown by the red dot.

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.

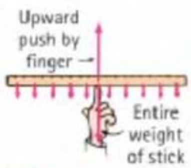

FIGURE 8.25
The weight of the entire stick behaves as if it were concentrated at the stick's center.

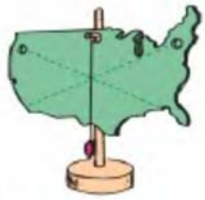

FIGURE 8.26

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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Video
Learning the Center of Gravity

FIGURE 8.28

The athlete executes a "Fosbury flop" to clear the bar while her center of gravity passes beneath the bar.

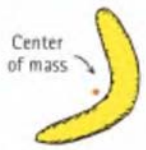
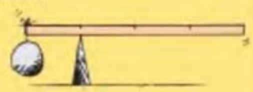


FIGURE 8.27

The center of mass can be outside the mass of a body.

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.

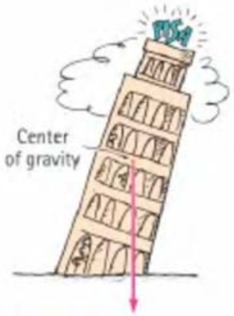


FIGURE 8.29

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.

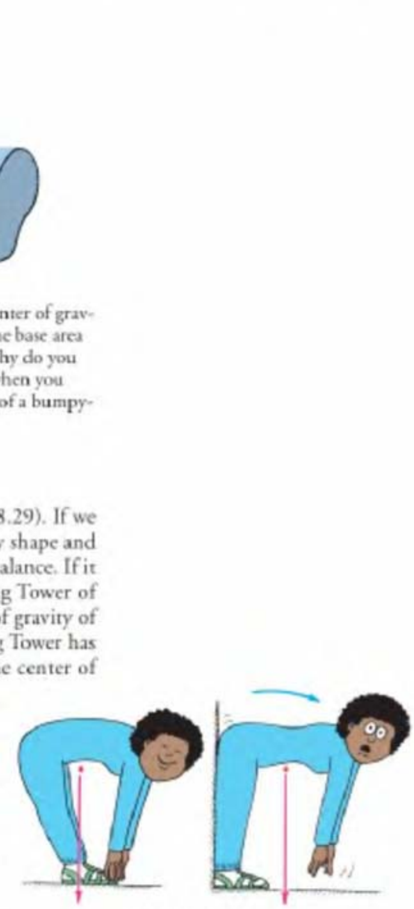


FIGURE 8.31

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.

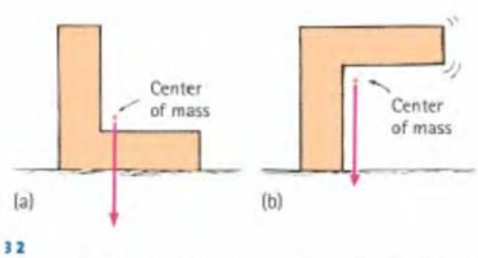


FIGURE 8.32

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.

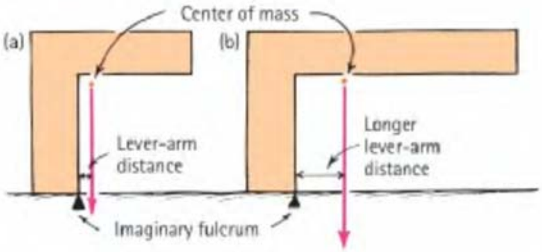

FIGURE 8.34
The greater torque acts on (b) for two reasons. What are they?

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.

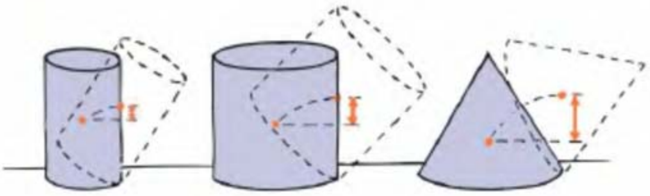

FIGURE 8.36
Stability is determined by the vertical distance that the center of gravity is raised in tipping. An object with a wide base and a low center of gravity is more stable.

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.

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.

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.

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).

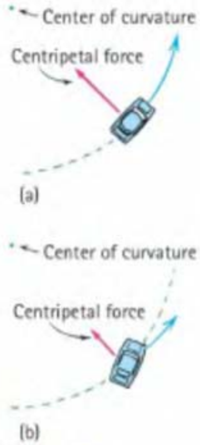

FIGURE 8.39

(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.

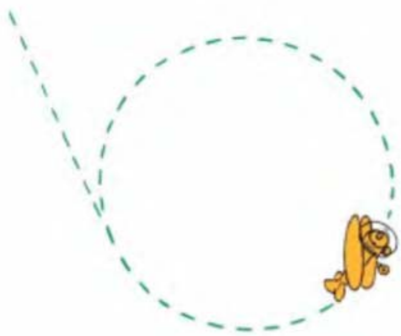

FIGURE 8.40

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.

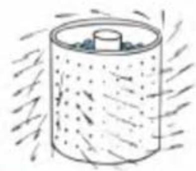

FIGURE 8.41

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.

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 8.42
When the string breaks, the whirling can moves in a straight line, tangent to—not outward from—the center of its circular path.

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.

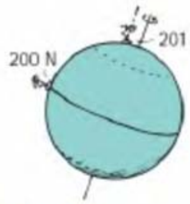

FIGURE 8.45

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!

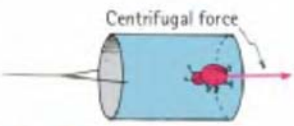

FIGURE 8.46

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.

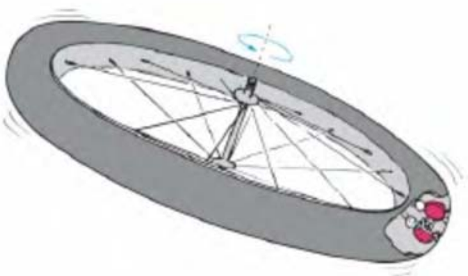

FIGURE 8.47

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.

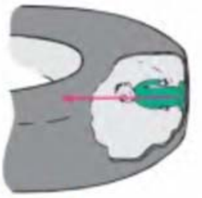

FIGURE 8.48

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.

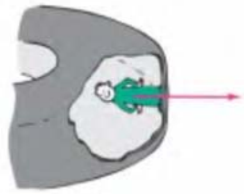

FIGURE 8.49

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,

$$\text{Angular momentum} = mvr$$

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.

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.

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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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.

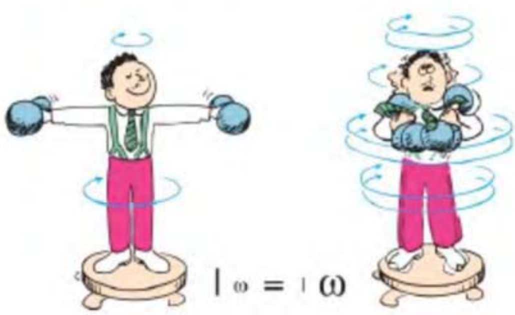


FIGURE 8.52
INTERACTIVE FIGURE
Conservation of angular momentum. When the man pulls his arms and the whirling weights inward, he decreases his rotational inertia I, and his rotational speed ω correspondingly increases.

Why do short acrobats have an advantage in tumbling or in other end-over-end rotational motions?

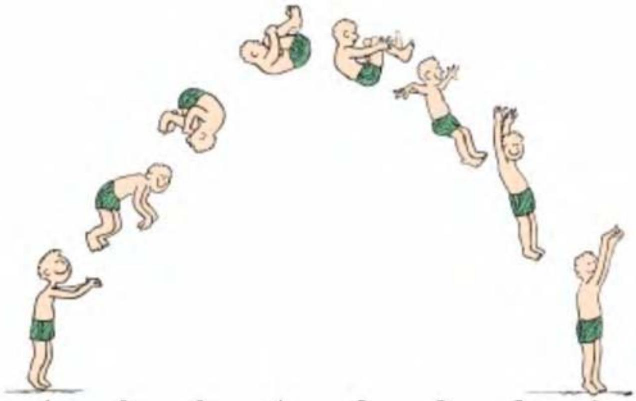


FIGURE 8.53
Rotational speed is controlled by variations in the body's rotational inertia as angular momentum is conserved during a forward somersault.

FIGURE 8.54
Time-lapse photo of a falling cat.

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!

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.

Torque = lever arm × 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

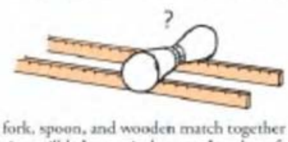
29. Distinguish between linear momentum and angular momentum.
30. What is the law of inertia for rotating systems in terms of angular momentum?

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.

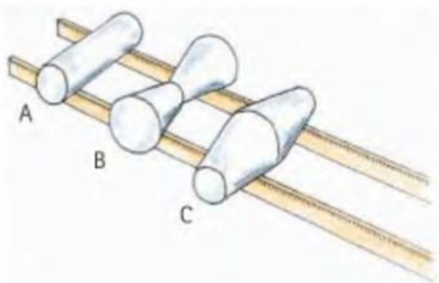
Angular Momentum $= mvr$

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

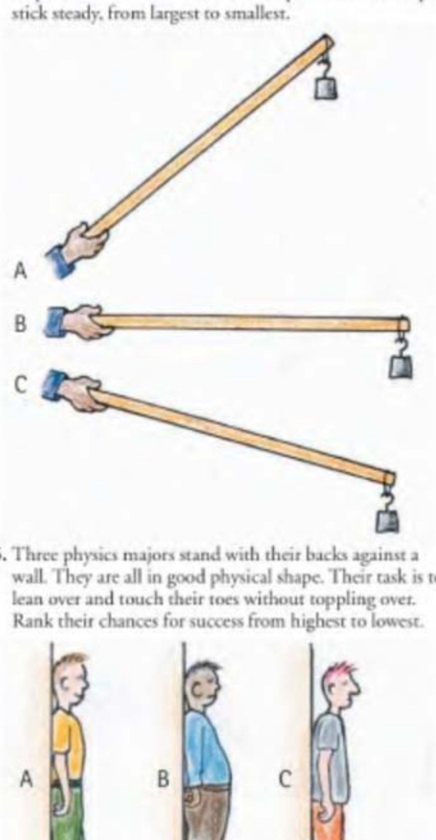
1. The three cups are rolled on a level surface. Rank the cups by the amount they depart from a straight-line path (most curved to least curved).

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.

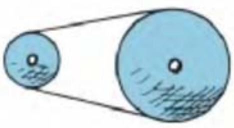
4. You hold a meterstick horizontally with the same mass suspended at the end. Rank the torque needed to keep the stick steady, from largest to smallest.



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

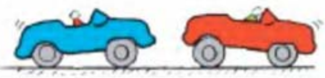
1. While riding on a carnival Ferris wheel, Sam Nasty horses around and climbs out of his chair and along the spoke so he is halfway to the axis. How does his rotational speed compare with that of his friends who remain in the chair? How does his tangential speed compare? Why are your answers different?
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)?



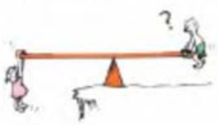
4. Dan and Sue cycle at the same speed. The tires on Dan's bike are larger in diameter than those on Sue's bike. Which wheels, if either, have the greater rotational speed?
5. Use the equation $v = r\omega$ to explain why the end of a fly-swatter moves much faster than your wrist when swatting a fly.
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?

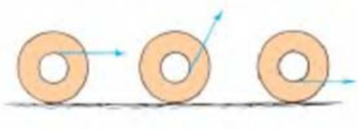


12. Which will have the greater acceleration rolling down an incline—a bowling ball or a volleyball? Defend your answer.
13. A softball and a basketball start from rest and roll down an incline. Which ball reaches the bottom first? Defend your answer.
14. How would a ramp help you to distinguish between 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?

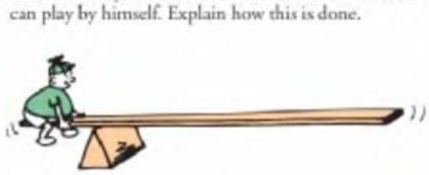
26. Explain why a long pole is more beneficial to a tightrope walker if the pole droops.

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.



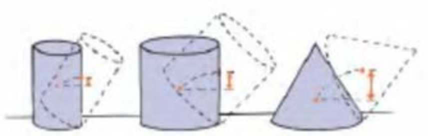
31. Where is the center of mass of Earth's atmosphere?

32. Using the ideas of torque and center of gravity, explain why a ball rolls down a hill.

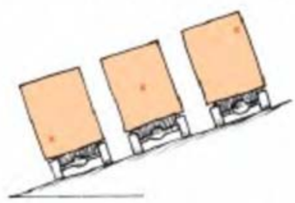
33. Why is it important to secure file cabinets to the floor, especially cabinets with heavy loads in top drawers?

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.

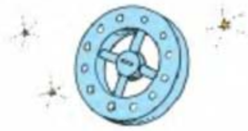
42. When you are in the front passenger seat of a car turning to the left, you may find yourself pressed against the right-side door. Why do you press against the door? Why does the door press on you? Does your explanation involve a centrifugal force, or Newton's laws?

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.)

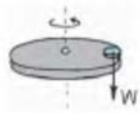
44. Under what conditions could a fast-moving car remain on a banked track covered with slippery ice?

45. Explain why a centripetal force does *not* do work on a circularly moving object.

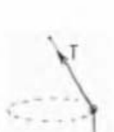
46. The occupant inside a rotating space habitat of the future feels that she is being pulled by artificial gravity against the outer wall of the habitat (which becomes the "floor"). Explain what is going on in terms of Newton's laws and centripetal force.



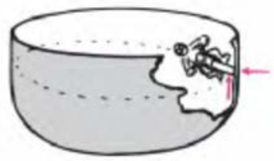
47. The sketch shows a coin at the edge of a turntable. The weight of the coin is shown by the vector **W**. Two other forces act on the coin—the normal force and a force of friction that prevents it from sliding off the edge. Draw in force vectors for both of these.



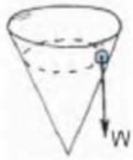
48. The sketch shows a conical pendulum. The bob swings in a circular path. The tension **T** and weight **W** are shown by vectors. Draw a parallelogram with these vectors and show that their resultant lies in the plane of the circle. (See the parallelogram rule in Chapter 5.) What is the name of this 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.

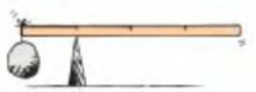
60. Earth is not spherical but bulges at the equator. Jupiter bulges more. What is the cause of these bulges?

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?

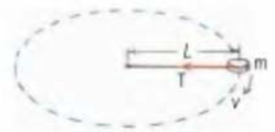
2. To tighten a bolt, you push with a force of 80 N at the end of a wrench handle that is 0.25 m from the axis of the bolt. (a) What torque are you exerting? (b) If you move your hand inward to be only 0.10 m from the bolt, to achieve the same torque show that you should exert 200 N of force. (c) Do 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.

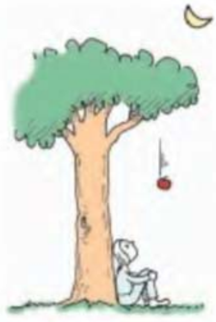


FIGURE 9.1
Could the gravitational pull on the apple reach to the Moon?

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.

PhysicsPlace.com
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.

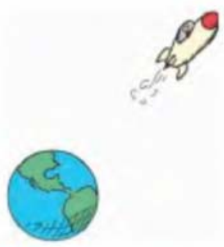


FIGURE 9.3
As the rocket gets farther from Earth, gravitational strength between the rocket and Earth decreases.

PhysicsPlace.com
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:

$$G = \frac{F}{\left(\frac{m_1 m_2}{d^2}\right)} = 6.67 \times 10^{-11}\ \text{N/kg}^2/\text{m}^2 = 6.67 \times 10^{-11}\ \text{N}\cdot\text{m}^2/\text{kg}^2$$

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,

$$9.8\ \text{N} = 6.67 \times 10^{-11}\text{N}\cdot\text{m}^2/\text{kg}^2\ \frac{1\ \text{kg} \times m_1}{(6.4 \times 10^6\text{m})^2}$$

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 sheet music guides a musician playing music, equations guide a physics student to understand how concepts are connected.

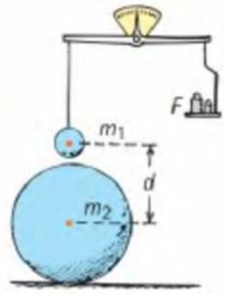


FIGURE 9.4
Jolly's method of measuring G. Balls of mass m_1 and m_2 attract each other with a force F provided by the weights needed to restore balance.

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.

PhysicsPlace.com
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.

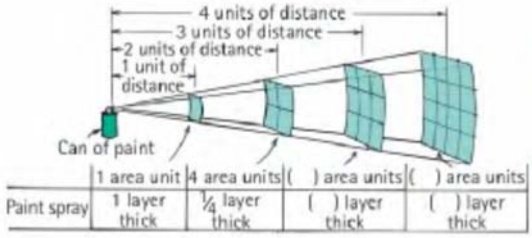


FIGURE 9.5
The inverse-square law. Paint spray travels radially away from the nozzle of the can in straight lines. Like gravity, the "strength" of the spray obeys the inverse-square law.

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

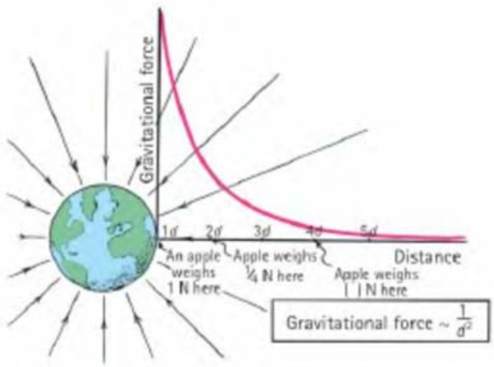


FIGURE 9.6
INTERACTIVE FIGURE
If an apple weighs 1 N at Earth's surface, it would weigh only 1/4 N twice as far from the center of Earth. At 3 times the distance, it would weigh only 1/9 N. Gravitational force versus distance is plotted in color. What would the apple weigh at 4 times the distance? Five 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.

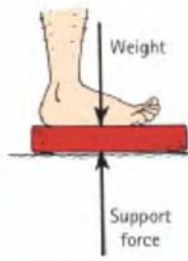


FIGURE 9.8
When you step on a weighing scale, two forces act on it: a downward force of gravity, mg, and an upward support force. These two forces are equal and opposite when no acceleration occurs, and they squeeze a spring-like device inside the scale that is calibrated to show your weight.

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

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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.

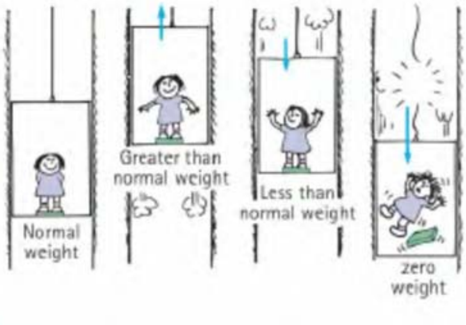

FIGURE 9.9
INTERACTIVE FIGURE

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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Tides

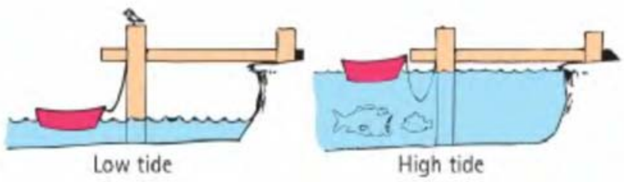

FIGURE 9.13
Ocean tides.

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

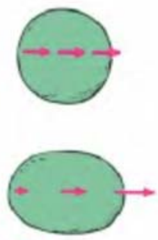

FIGURE 9.14
A ball of Jell-O stays spherical when all parts are pulled equally in the same direction. When one side is pulled more than the other, it is elongated.

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.

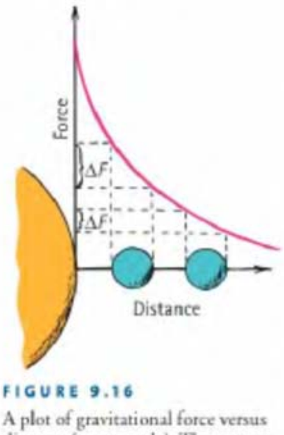

FIGURE 9.16

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!

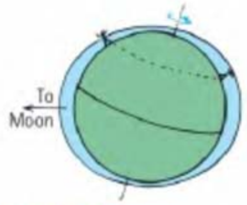

FIGURE 9.19

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

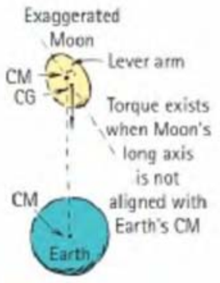

FIGURE 9.21

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.

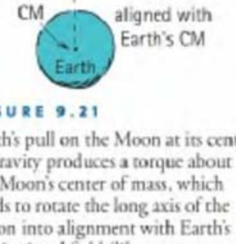

FIGURE 9.22

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.

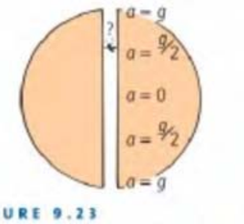

FIGURE 9.23

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.

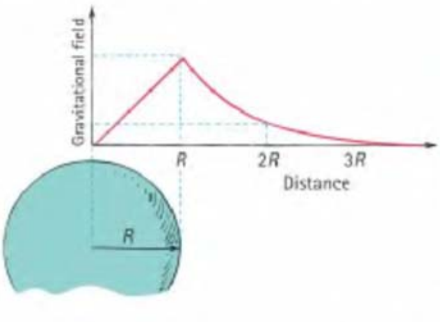

FIGURE 9.24

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,

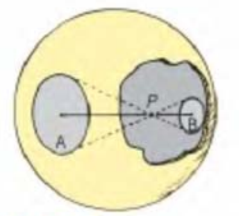

FIGURE 9.25

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.**

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- 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.

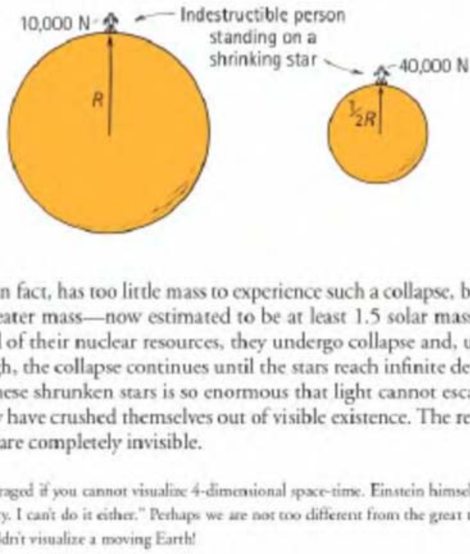

FIGURE 9.27

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!

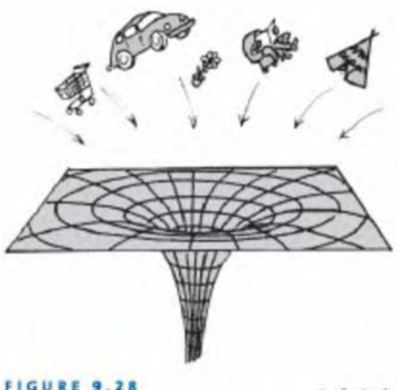

FIGURE 9.28

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]

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.

FIGURE 9.29

A speculative wormhole may be the portal to another part of our universe or even to another universe.

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.

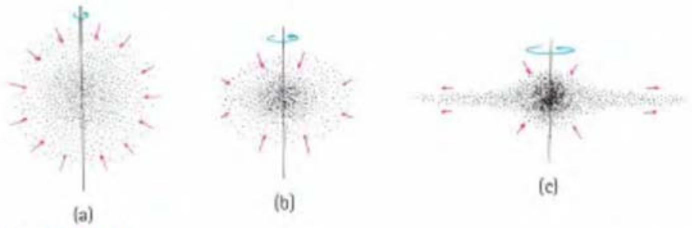

FIGURE 9.30

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?

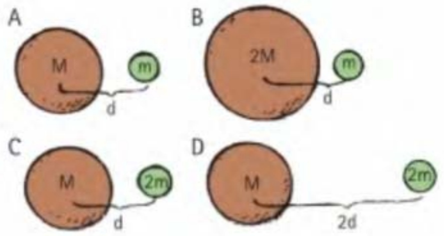
PLUG AND CHUG

$$F = G\frac{m_1 m_2}{d^2}$$

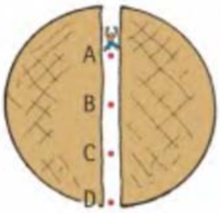
1. Calculate the force of gravity on a 1-kg mass at Earth's surface. The mass of Earth is 6.0×10^{24} kg, and its radius is 6.4×10^6 m.
2. Calculate the force of gravity on the same 1-kg mass if it were 6.4×10^6 m above Earth's surface (that is, if it were two Earth radii from Earth's center).
3. Calculate 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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Interactive Figures

- 9.6, 9.9

Tutorials

- Motion and Gravity
- Tides
- Black Holes

Videos

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- Inverse-Square Law
- Apparent Weightlessness
- 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

Quizzes

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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.

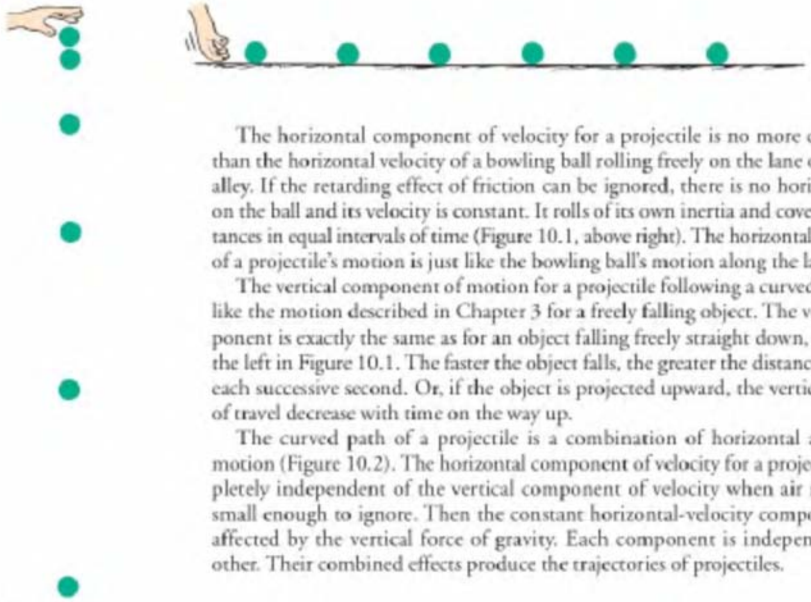


FIGURE 10.1
(Above right) Roll a ball along a level surface, and its velocity is constant because no component of gravitational force acts horizontally. (Above) Drop it, and it accelerates downward and covers a greater vertical distance each second.

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.

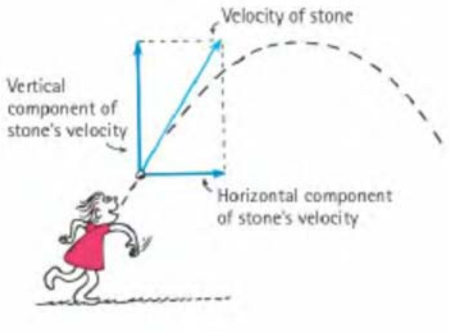


FIGURE 10.2
Vertical and horizontal components of a stone's velocity.

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.

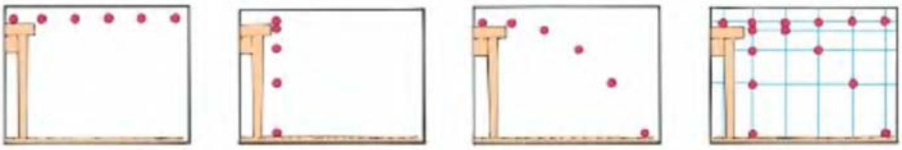


FIGURE 10.3
INTERACTIVE FIGURE
Simulated photographs of a moving ball illuminated with a strobe light.

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.

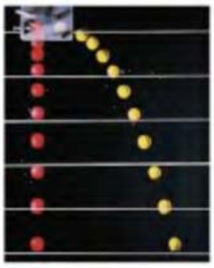


FIGURE 10.4
INTERACTIVE FIGURE
A strobe-light photograph of two golf balls released simultaneously from a mechanism that allows one ball to drop freely while the other is projected horizontally.

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.

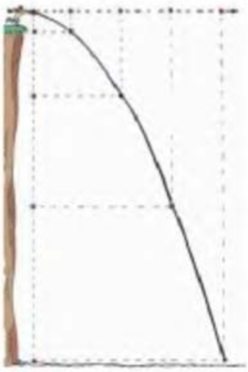


FIGURE 10.6

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.

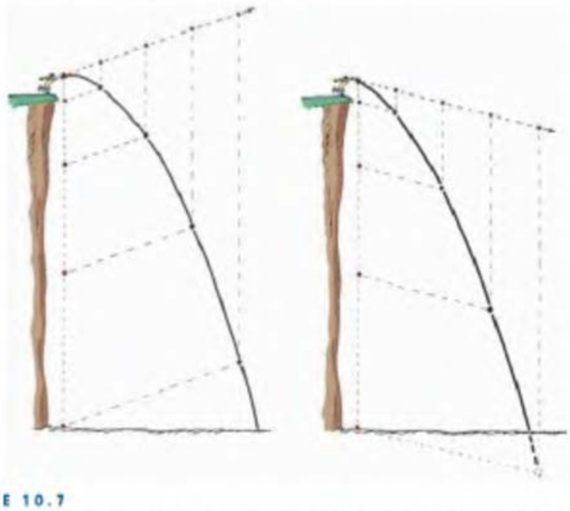


FIGURE 10.7

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.

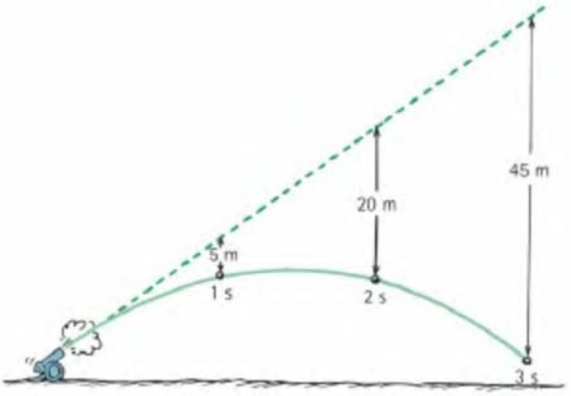


FIGURE 10.8

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 $g = 9.8\ m/s^2$, 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

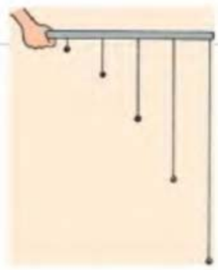
1. Suppose the cannonball in Figure 10.8 were fired faster. How many meters below the dashed line would it be at the end of the 5 s?
2. If the horizontal component of the cannonball's velocity is 20 m/s, how far downrange will the cannonball be in 5 s?

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 [$d = \bar{v}t = (20\ m/s)(5\ s) = 100$ 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.



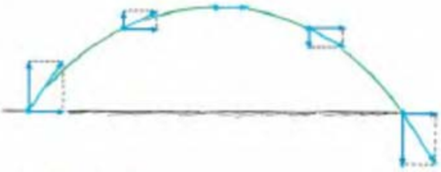


FIGURE 10.9

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.

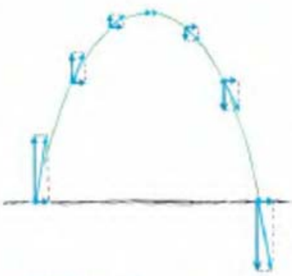


FIGURE 10.10

Trajectory for a steeper projection angle.

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.

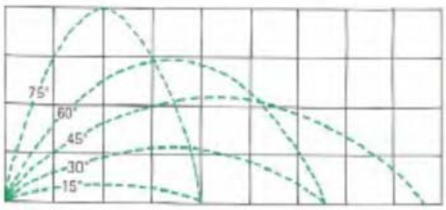


FIGURE 10.11

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.

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.

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.

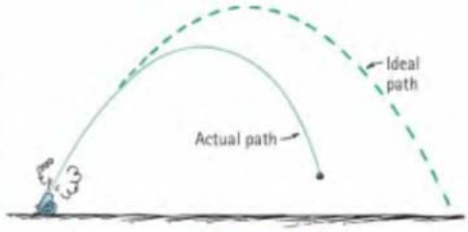


FIGURE 10.13
INTERACTIVE FIGURE

In the presence of air resistance, the trajectory of a high-speed projectile falls short of the idealized parabolic path.

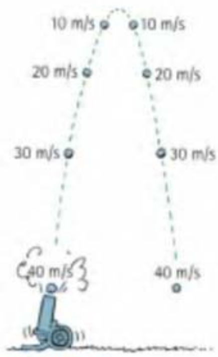


FIGURE 10.14

Without air drag, speed lost while going up equals speed gained while coming down: Time going up equals time coming down.

CHECK POINT

The boy on the tower throws a ball 20 m downrange, as shown in Figure 10.15. What is his pitching speed?

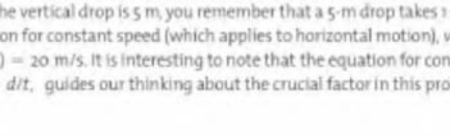


FIGURE 10.15

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.

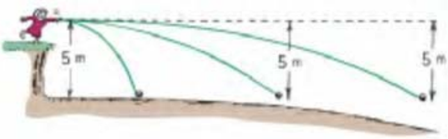


FIGURE 10.16
If you throw a ball at any speed, 1 s later it will have fallen 5 m below where it would have been without gravity.

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)!

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.

FIGURE 10.17
Earth's curvature—not to scale!

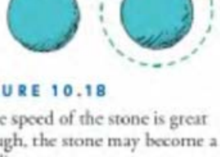


FIGURE 10.18
If the speed of the stone is great enough, the stone may become a satellite.

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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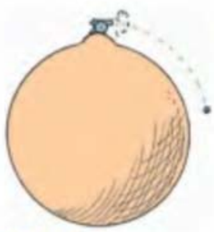


FIGURE 10.21

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.

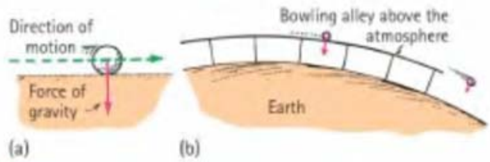


FIGURE 10.22

(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.

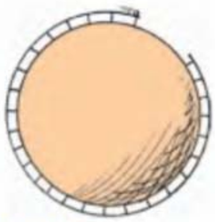


FIGURE 10.23

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.

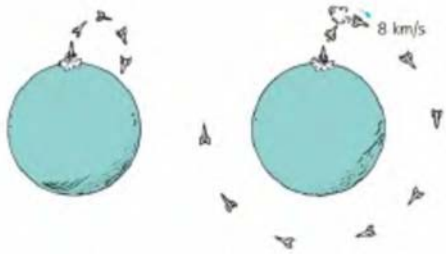


FIGURE 10.24
The initial thrust of the rocket pushes it up above the atmosphere. Another thrust to a tangential speed of at least 8 km/s is required if the rocket is to fall around rather than into Earth.

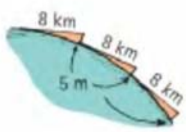
satellite is the entire single-stage rocket. With the proper tangential velocity, it falls around Earth, rather than into it, and becomes an Earth satellite.

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.

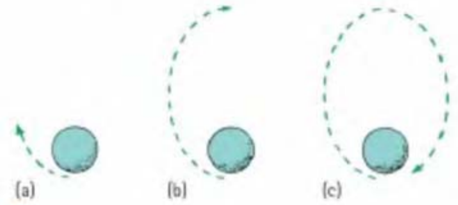


FIGURE 10.27

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.

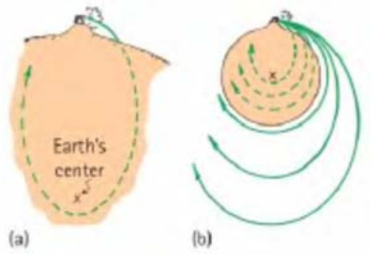
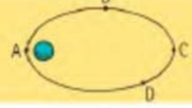


FIGURE 10.28

(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.

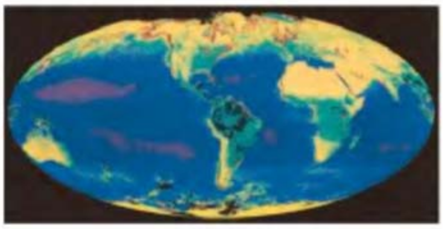


FIGURE C

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)

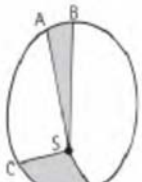


FIGURE 10.29

Equal areas are swept out in equal intervals of time.

With Kepler's third law, you can calculate the radius of a planet's orbit from its orbital period.

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- 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.

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.

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).

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.

[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).

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).

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.

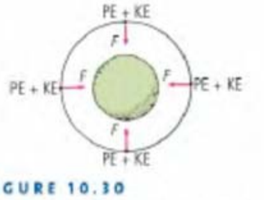


FIGURE 10.30
The force of gravity on the satellite is always toward the center of the body it orbits. For a satellite in circular orbit, no component of force acts along the direction of motion. The speed and thus the KE do not change.

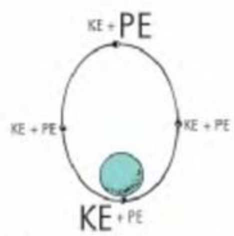
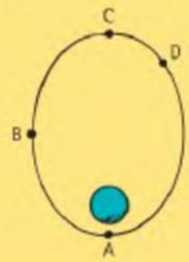


FIGURE 10.31
The sum of KE and PE for a satellite is a constant at all points along its orbit.

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.

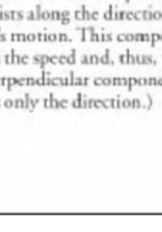


FIGURE 10.32
In elliptical orbit, a component of force exists along the direction of the satellite's motion. This component changes the speed and, thus, the KE. (The perpendicular component changes only the direction.)

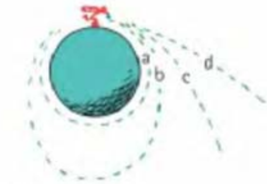


FIGURE 10.33

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.

Wouldn't Newton have relished seeing satellite motion in terms of *energy*—a concept that came much later?

Escape Speed

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.

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."

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 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.

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]

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.

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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.

[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

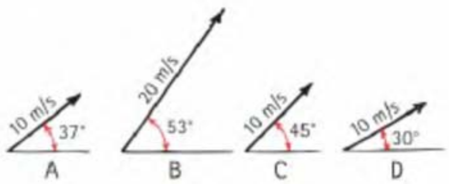
20. Why is kinetic energy a constant for a satellite in a circular orbit but not for a satellite in an elliptical orbit?
21. Is the sum of kinetic and potential energies a constant for satellites in circular orbits, in elliptical orbits, or in both?

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?

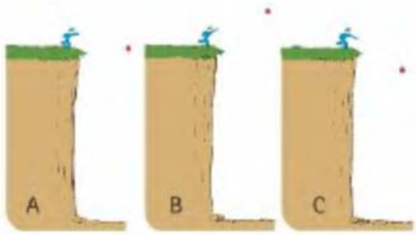
RANKING

1. A ball is thrown upward at velocities and angles shown. From greatest to least, rank them by their



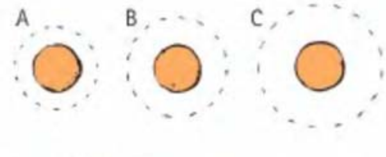
   a. vertical components of velocity.
   b. horizontal components of velocity.
   c. accelerations when they reach the top of their paths.

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



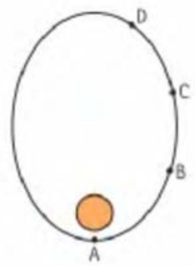
   a. initial PEs of the balls relative to the ground below.
   b. initial KEs of the balls when tossed.
   c. KEs of the balls when hitting the ground below.
   d. times of flight while airborne.

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?

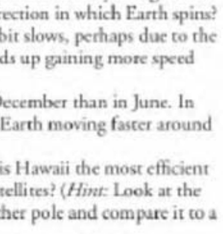
33. Of all the United States, why is Hawaii the most efficient launching site for nonpolar satellites? (*Hint:* Look at the spinning Earth from above either pole and compare it to a spinning turntable.)

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?

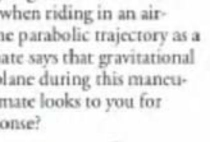
54. What is the advantage of launching space vehicles from high-flying aircraft instead of from the ground?

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?

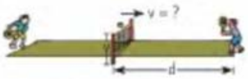


59. At what point in its elliptical orbit about the Sun is the acceleration of Earth toward the Sun at a maximum? At what point is it at a minimum? Defend your answers.

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

$$v = \frac{d}{\sqrt{\dfrac{2y}{g}}}$$

   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 $g = 10\ m/s^2$ 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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