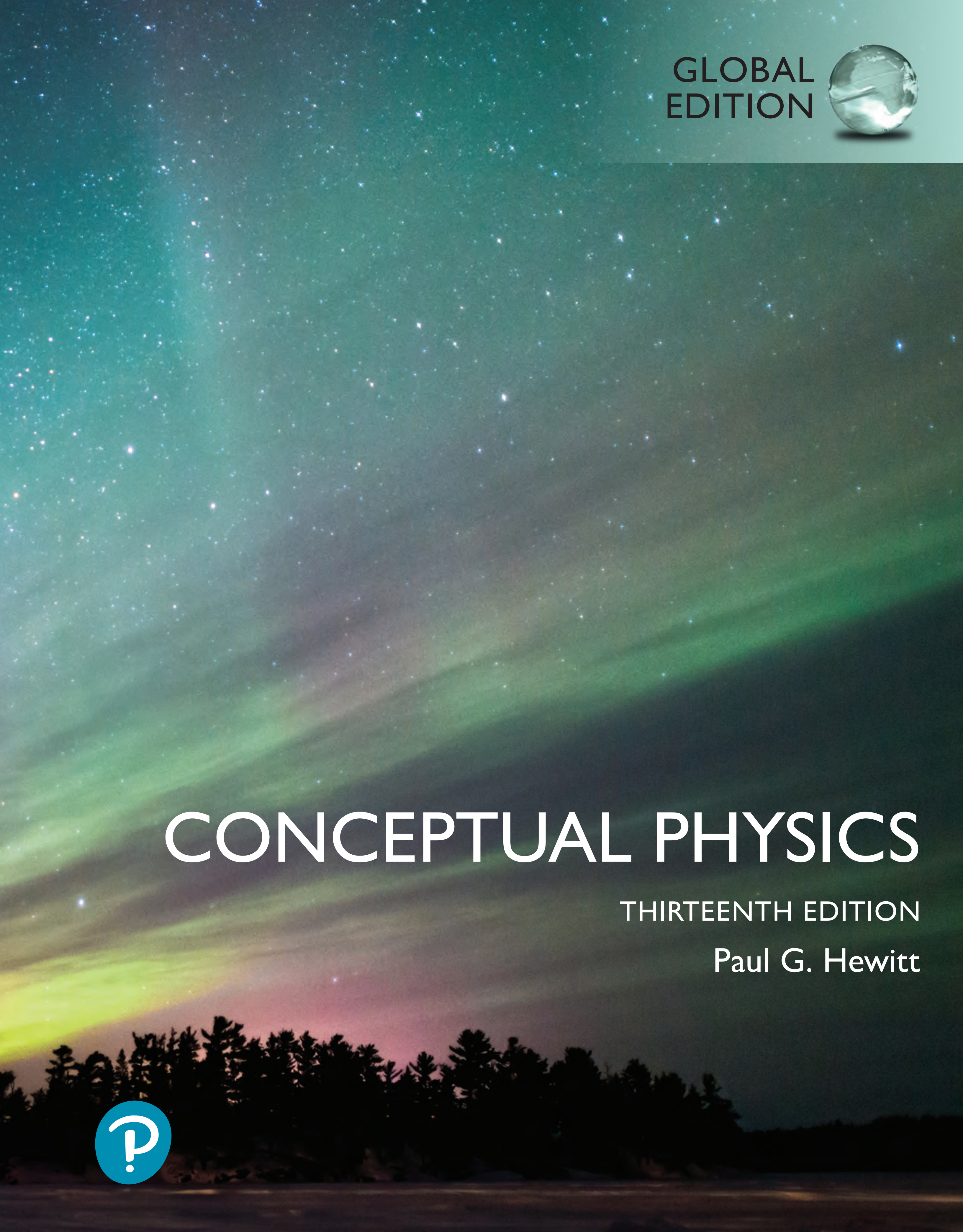

GLOBAL EDITION

CONCEPTUAL PHYSICS

THIRTEENTH EDITION

Paul G. Hewitt

CONCEPTUAL Physics

THIRTEENTH EDITION
GLOBAL EDITION

written and illustrated by

Paul G. Hewitt

City College of San Francisco

Pearson

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To my everything—my wife Lillian

SOME SIGNIFICANT DATES IN THE HISTORY OF PHYSICS

ca. 320 BC	**Aristotle** describes motion in terms of natural tendencies.
ca. 250 BC	**Archimedes** discovers the principle of buoyancy.
ca. AD 150	**Ptolemy** refines the Earth-centered system of the world.
1543	**Copernicus** publishes his Sun-centered system of the world.
1575–1596	**Brahe** measures precise positions of the planets in the sky.
1609	**Galileo** first uses a telescope as an astronomical tool.
1609/1619	**Kepler** publishes three laws of planetary motion.
1634	**Galileo** advances understanding of accelerated motion.
1661	**Boyle** relates pressure and volume of gases at constant temperature.
1676	**Roemer** demonstrates that light has finite speed.
1678	**Huygens** develops a wave theory of light.
1687	**Newton** presents the theory of mechanics in his *Principia.*
1738	**Bernoulli** explains the behavior of gases in terms of molecular motions.
1747	**Franklin** suggests the conservation of electrical “fire” (charge).
1780	**Galvani** discovers “animal electricity.”
1785	**Coulomb** precisely determines the law of electric force.
1795	**Cavendish** measures the gravitational constant *G*.
1798	**Rumford** argues that heat is a form of motion.
1800	**Volta** invents the battery.
1802	**Young** uses wave theory to account for interference.
1811	**Avogadro** suggests that, at equal temperature and pressure, all gases have equal numbers of molecules per unit volume.
1815–1820	**Young** and others provide evidence for the wave nature of light.
1820	**Oersted** discovers the magnetic effect of an electric current.
1820	**Ampère** establishes the law of force between current-carrying wires.
1821	**Fraunhofer** invents the diffraction grating.
1824	**Carnot** states that heat cannot be transformed wholly to work.
1831	**Faraday** and **Henry** discover electromagnetic induction.
1842–1843	**Mayer** and **Joule** suggest a general law of energy conservation.
1846	**Adams** and **Leverrier** predict the existence of the planet Neptune.
1865	**Maxwell** gives the electromagnetic theory of light.
1869	**Mendeleev** organizes the elements into a periodic table.
1877	**Boltzmann** relates entropy to probability.
1885	**Balmer** finds numerical regularity in the spectrum of hydrogen.
1887	**Michelson** and **Morley** fail to detect the ether.
1888	**Hertz** generates and detects radio waves.
1895	**Roentgen** discovers X-rays.
1896	**Bequerel** discovers radioactivity.
1897	**Thomson** identifies cathode rays as negative corpuscles (electrons).

1900	**Planck** introduces the quantum idea.
1905	**Einstein** introduces the light corpuscle (photon) concept.
1905	**Einstein** advances the special theory of relativity.
1911	**Rutherford** reveals the nuclear atom.
1913	**Bohr** gives a quantum theory of the hydrogen atom.
1915	**Einstein** advances the general theory of relativity.
1923	**Compton's** experiments confirm the existence of the photon.
1924	**de Broglie** advances the wave theory of matter.
1925	**Goudsmit** and **Uhlenbeck** establish the spin of the electron.
1925	**Pauli** states the exclusion principle.
1926	**Schrödinger** develops the wave theory of quantum mechanics.
1927	**Heisenberg** proposes the uncertainty principle.
1928	**Dirac** blends relativity and quantum mechanics in a theory of the electron.
1929	**Hubble** discovers the expanding universe.
1932	**Anderson** discovers antimatter in the form of the positron.
1932	**Chadwick** discovers the neutron.
1934	**Fermi** proposes a theory of the annihilation and creation of matter.
1938	**Meitner** and **Frisch** interpret results of **Hahn** and **Strassmann** as nuclear fission.
1939	**Bohr** and **Wheeler** give a detailed theory of nuclear fission.
1942	**Fermi** builds and operates the first nuclear reactor.
1945	**Oppenheimer's** Los Alamos team creates a nuclear explosion.
1947	**Bardeen**, **Brattain**, and **Shockley** develop the transistor.
1956	**Reines** and **Cowan** identify the antineutrino.
1957	**Feynman** and **Gell-Mann** explain weak interactions with a "left-handed" neutrino.
1960	**Maiman** invents the laser.
1965	**Penzias** and **Wilson** discover background radiation in the universe left over from the Big Bang.
1967	**Bell** and **Hewish** discover pulsars, which are neutron stars.
1969	**Gell-Mann** suggests quarks as the building blocks of nucleons.
1977	**Lederman** and his team discover the bottom quark.
1981	**Binning** and **Rohrer** invent the scanning tunneling microscope.
1987	**Bednorz** and **Müller** discover high-temperature superconductivity.
1995	**Cornell** and **Wieman** create a "Bose–Einstein condensate" at 20 billionths of a degree.
1998	**Perlmutter, Schmidt,** and **Riess** discover the accelerated expansion of the universe.
2000	**Pogge** and **Martini** provide evidence for supermassive black holes in other galaxies.
2000	Fermilab group identifies the tau neutrino, the last member of the lepton particle group.
2003	Scientists studying radiation in space put the age of the universe at 13.7 billion years.
2004	**Geim** and **Novoselov** discover graphene, a one-atom-thick form of carbon.
2005	**Gerald Gabrielse** measures the magnetism of the electron to 1 part in a trillion.
2006	U.S.–Russian team identifies elements number 116 and 118.
2012	CERN laboratory announces the discovery of the long-sought Higgs boson.
2015	LIGO team detects gravitational waves from coalescing black holes.
2018	Jarillo-Herrero discovers superconductivity in graphene.
2019	Event Horizon Telescope obtains first image of a supermassive black hole.
2020	The catalog of exoplanets (planets orbiting other stars) grows to more than 4,330.

Contents in Brief

Contents in Detail

Conceptual Physics Photo Album

Conceptual Physics is a very personal book, reflected in its many photographs of family, along with friends and colleagues worldwide. Many of these people are identified in chapter-opening photos, and, with some exceptions, I'll not repeat their names here. Family and friends whose photos are Part Openers, however, are listed. The book opens on page 21 with great-nephew Evan Suchocki sitting on my lap pondering life's opportunities with his pet chick.

Part One opens on page 43 with little Ian Evans, son of teacher friends Bart and Jill Evans. Part Two opens on page 257 with little Georgia Hernandez, my delightful great-great-niece. Part Three opens on page 345 with four-year-old Francesco Ming Giovannuzzi, grandson of friend Tsing Bardin, page 300. Part Four opens on page 425 with Abby Dijamco, daughter of my last CCSF teaching assistant, dentist Stella Dijamco. In Part Five on page 481 is my great-great-nephew Richard Hernandez, older brother to Georgia. Part Six opens on page 569 with my granddaughter Gracie Hewitt at age four. Part Seven opens with another granddaughter, Kara Mae Hurrell, as a four-year-old tot in a pot on page 707. Part Eight opens on page 771 with young London Dixon, the daughter of my physician's medical assistant, April Dixon.

The two friends most influential in my transition from a life of sign painting to a life of physics are Burl Grey, page 53, and Jacque Fresco, pages 172, 173. For success as an author I credit my friend and physics mentor, Ken Ford, pages 446, 772, to whom previous editions have been dedicated. Longtime best friend Huey Johnson, known as Dan, page 404, has also been personally influential.

Family photos include my first wife, Millie, on page 370. My eldest daughter is Jean Hurrell, page 281, and with her children Marie and Kara Mae on page 519, and both granddaughters shown separately on pages 87 and 122. Jean's husband Phil tinkers with electricity on page 508. My son Paul is with his daughter Grace, page 104, and doing some thermodynamics on page 409. Gracie plays music on page 466 and further speculates about science on page 569. Son Paul's former wife Ludmila is shown with Polaroids on page 656, and their son Alex skateboards on pages 124, 190. My daughter Leslie at age 16 is on page 269, a colorized photo that has been a trademark of *Conceptual Physics* since the third edition. Since then Leslie has been my earth-science coauthor of the *Conceptual Physical Science* textbooks. A more recent photo with her husband Bob Abrams, page 570. Their children, Megan and Emily, are on pages 369 and 230. A grand slam grandchildren photo is on page 599. My late son James is on page 191 with his best friend Robert Baruffaldi, also his cousin. Other photos of James are on pages 470 and 633. James left me my first grandson, Manuel, pages 288, 351, 456.

Millie's relatives include nephew Mike Luna, page 252. Grand-niece Angela Hendricks, page 676, is a teacher and amateur photographer who graciously supplied photos of her cousins Georgia Hernandez and her older brother Richard Hernandez on pages 314, 341, 446, 466 and 481, and her own child Hudson, page 314. Hudson also appears with his dad Jake Hendricks on page 117. Grand-niece Alejuandra Luna leans on Newton's third law, page 122. Great nephew Isaac Jones uses a sparkler, page 349, as his dad Terrence used back in the sixth and seventh editions. Terrence Jones is now on page 346.

A year after Millie's passing in 2004, I married my friend of many years, Lillian Lee. Lillian has wonderfully assisted me in all steps of textbook production, including ancillaries. Of the many photos of Lil throughout this edition, I'll mention two favorites: One with her pet bird Sneezlee on page 600, and the photo with me illustrating the essence of Newton's third law—you cannot touch without being touched—on page 112. Lillian's dad, Wai Tsan Lee, shows magnetic induction on page 537, and mom, Siu Bik Lee, making excellent use of solar energy on page 380 and with solar images on page 631. Lillian's niece Serena Sinn excels in sports, page 146. Lil's nephew Erik Wong with his sister Allison nicely illustrate thermodynamics on page 415.

Photos of my siblings begin with my sister Marjorie, author and theologian emerita at Claremont School of Theology in Claremont, California, illustrating reflection on page 616. Marjorie's daughter, occupational therapist Cathy Candler, page 177, and her son Garth Orr, page 280. Marjorie's daughter Joan Lucas's two children, SpaceX engineer Mike Lucas, page 792, and lawyer Alexandra Lucas, page 570. Marjorie's multitalented son, John Suchocki, page 386, the creator of Conceptual Academy, a chemistry professor and author, and my coauthor of the *Conceptual Physical Science* and *Conceptual Integrated Science* textbooks; he's also a singer-songwriter known as John Andrew strumming his guitar, pages 426, 553. The group listening to music, page 474, is of John and Tracy's Hawaii long-ago wedding party. My brother Dave and his wife Barbara pump water on page 329. Their electrician son Davey is on page 525, and the yum photos of solar cells, page 380, and the GPS unit, page 802, is courtesy of their daughter Dotty Jean Allen. My youngest brother Steve and his daughter Gretchen are shown on page 120. Steve's son, Navy pilot Travis is on page 196, and Steve's teacher daughter Stephanie on pages 639 and 802.

Photos of City College of San Francisco physics-instructor friends open several chapters and are named there. Others include Diana Lininger Markham, pages 172, 202. Fred Cauthen, pages 166, 560. Norman Whitlatch, page 474. Dave Wall, page 570. Roger King, pages 374, 708. Jill Evans, pages, 84, 160, and 508, and Chelcie Liu, page 64.

Suppliers of physics equipment are friends David and Christine Vernier of Vernier Software, page 146, Paul Stokstad of PASCO, page 172, and Peter Rea of Arbor Scientific, page 235.

The following people are personal American friends in order of appearance: Judith Brand, whose skillful edits grace this entire edition, page 22. David Vasquez, pages 22, 163. Will Maynez, pages 44, 136, 361, and 524. Sue Johnson, Huey Johnson's wife, p 64. Lab Manual author Dean Baird, pages 64, 65, 386, 577, 582, and 603. Paul Doherty, pages 104, 105, 570. David Kagan, pages 104, 708. Howie Brand from college days, pages 124, 404. David Manning, pages 140, 197, 324, and his daughter Brady, page 79. Bob Miner, page 149, his wife Ana, page 44, and Ana's daughter Estefania, page 388. Tenny Lim, page 153, draws her bow, a photo that has appeared in every book since the sixth edition. Tenny again on pages 204, 205. Young Andrea Wu, page 170. Marshall Ellenstein, pages 178, 322, 642, 643. Alexei Cogan, page 189. Alan Davis with son William, page 204, and William again, page 532, and a photo taken by his mom Fe, page 609. Chuck Stone, page 233. John Hubisz, page 280. Ray Serway, page 300. Evan Jones, page 324. Fred Myers, pages 324, 325, 532, 612, 732. Helen Yan, pages 366, 367, 642. Dennis McNelis, page 373, and his grandson Myles Dooley, page 443. Exploratorium physicist Ron Hipschman on pages 204, 386, 387, 393, 664. Childhood best friend Paul Ryan is on page 398. Huey and Sue Johnson's grandson Bay Johnson, page 472. Ryan Patterson, page 456. Elan Lavie, page 482. Kirby Perchbacher, pages 306 and 482. Karen Jo Matsler, pages 562 and 612. Bruce Novak, page 574, and his mom Greta Novak on page 322. Charlie Spiegel, page 579. Suzanne Lyons and children Simone and Tristan, page 592. Carlos Vasquez, page 592. Jeff Wetherhold, page 592. Bree Barnett Dreyfuss, page 642. Phil Wolf, page 686. Brad Huff, page 712. Stanley Micklavzina, page 724, Walter Steiger, page 737. Brenda Skoczelas, page 772. Mike and Jane Jukes, pages 800 and 816.

The physics community is global. International friends in order of appearance: My protégé Einstein Dhayal (India), pages 22, 550. Cedric and Anne Linder (Sweden), pages 44, 45. Carl Angell (Norway), page 64. Derek Muller (Canada), pages 124, 125. Peter Hopkinson (Canada), pages 162, 612. Bilal Gunes (Turkey), page 172. Ed van den Berg (Netherlands), page 204, and his wife Daday, page 508. Tomas Brage (Sweden), page 204, and with Barbara Brage, page 404. Ole Anton and Aage Mellem (Norway), page 346. Anette Zetterberg (Sweden), page 346, and husband P. O. page 404, with son Johan on page 324. Johan's wife Sara Bloomberg on page 302. Z. Tugba Kahyaoglu (Turkey), pages 482, 550. Mona El Tawil-Nassar (Egypt), page 500. David Housden (New Zealand), page 522. Roger Rasool (Australia), pages 724 and 736.

These are photographs of people very dear to me, which makes *Conceptual Physics* all the more a 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. If you get hooked and take a follow-up course, then you can focus on mathematical problems. Go for comprehension of concepts now, and if computation follows, it will be with understanding.

Enjoy your physics!

Paul G. Hewitt

To the Instructor

The sequence of chapters in this Thirteenth Edition is identical to that in the previous edition. Personality profiles continue with every chapter, highlighting a scientist, teacher, or historical figure who complements the chapter material. Each chapter begins with a photo montage of educators, and sometimes their students, who bring life to the learning of physics.

As in the previous edition, Chapter 1, "About Science," begins your course on a high note with coverage of early measurements of the Earth and distances to the Moon and the Sun. New to this edition is how an extension of Eratosthenes' measurements to calculating distances between far-apart schools. And also, a way that students can measure the distance to the Moon with a pea.

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. Force vectors are introduced, primarily for forces that are parallel to one another. Vectors are extended to velocity in the following Chapter 3, and Chapter 5 treats both force and velocity vectors and their components. Vector treatment is gradual, and, understandable.

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

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

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

Ask any college graduate two questions: What is the acceleration of an object in free fall? What keeps Earth's interior hot? You'll see what their education focused on because 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. Many third-law examples via vectors and their components should bring clarity to this commonly misunderstood law of motion. 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 first treating momentum is that the vectors of previous chapters 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 a whopping amount of chapter-end material (117 exercises). 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 even faster, it can become a satellite of the Sun. Projectile motion and satellite motion belong together.

Part Two, "Properties of Matter," features chapters on atoms, solids, liquids, and gases, which are much the same as the previous edition. New applications, some quite enchanting, enhance the flavor of these chapters.

Parts Three through Eight continue, like earlier parts, with enriched examples of current technology. The chapters with the fewest changes are Chapters 35 and 36 on special and general relativity, respectively.

Unlike the **practice exams** for the eight parts of the book, this thirteenth edition has them for each chapter. Answers are shown upside-down on each exam page. But more than answers are explanations for them. This is good pedagogy, heeding the adage that we learn best from our mistakes. Learning, more than assessment, is the goal. Your students will appreciate knowing why an answer is correct. This may also be a worthwhile in-class activity. Somewhat more detailed explanations are in the Instructor Manual.

The **Instructor Manual** for this edition, like previous ones, features demonstrations and suggested lectures for every chapter. It includes answers to all end-of-chapter material, many more detailed than the odd-numbered ones at the back of the book. If you're new to teaching this course, you'll likely find it enormously useful. It sums up "what works" in my more than 30 years of teaching.

As in previous editions, some chapters include short boxed **essays** on such topics as energy and technology, and magnetically levitated trains. Also featured are boxes on ocean tidal calendars, fuel cells, fractal antennas, constants of nature, and pseudoscience, culminating with the public phobia about food irradiation and anything nuclear. We who teach physics know about the care, checking, and cross-checking that go into understanding something. Fake news and its misconceptions are laughable. But to those who don't work in the science arena, including even your best students, weird stories 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 **Reading Check Questions** that summarize the main points of the chapter. Students can find the answers to these questions, word for word, in the reading. The **Plug and Chug** exercises are for familiarity with equations. As introduced in previous editions, many good comments have come from the **Think and Rank** exercises. Critical thinking is required in comparing quantities in 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 offering in the chapter-end material.

Think and Explain 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 also have **Think and Discuss** sections (which are tailored for student discussion). More math-physics challenges are found in the sets of **Think and Solve** exercises. These problems are much less numerous than Think and Explains and Think and Ranks. Many more problems are available in the student supplement, **Problem Solving in Conceptual Physics,** coauthored 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 student-friendly algebraic courses that feature problem solving. Problem solutions are included in the Instructor Resources area of MasteringPhysics.

The most important ancillary to this book is the **Practice Book,** which contains my most creative writings 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. Individual pages can be printed for class distribution. They can be used inside or outside of class. In my teaching I passed out copies of selected pages as home tutors.

The **Laboratory Manual** coauthored with Dean Baird for this edition is the same that accompanied the 12th edition. A great variety of activities and lab exercises, all polished by Dean, are extraordinary.

Next-Time Questions, familiar to readers of *The Physics Teacher* as *Figuring Physics*, are available electronically and are more numerous than ever before. When sharing these with your classes, please do not show the question(s) and the answer(s). Allow sufficient "wait time" between the question and the answer for your students to discuss the answer before showing it "next time" (which at a minimum should be the next class meeting, or even next week). Thus the title named appropriately "Next-Time Questions." More learning occurs when students ponder answers before being given them. Next-Time Questions are available in the Instructor Resource Area of Mastering. Some are also available at the Arborsci.com website.

Hewitt-Drew-It screencasts are simple hand-drawn tutorials narrated by the author. Any of these 149 screencasts can be accessed at www.HewittDrewIt.com. Importantly, these tutorials help to learn *correct* Physics!

Pearson eText
ADDITIONAL RESOURCES
Videos
Screencasts

At the start of each chapter in the printed version of this edition, the icon to the right serves as a call out to videos and screencasts that can be found in the eText.

MasteringPhysics, an innovative, targeted, and effective online learning media that is easily integrated into your course using MasteringPhysics to assign tutorials, quizzes, and other activities as out-of-class homework or projects that are automatically graded and recorded. These instructor resources are also available for download. A chapter section guide in the study area summarizes the media available to you and your students, chapter by chapter.

Mastering Physics

My Lil and I regard this as the best physics book we've ever written. For more information on the support ancillaries, see http://www.pearsonglobaleditions.com, contact your Pearson representative, or contact me at pghewitt@aol.com.

Acknowledgments

I remain enormously grateful to Kenneth Ford for checking accuracy and for his many insightful suggestions. Many years ago, I admired one of Ken's books, *Basic Physics*, which first inspired me to write *Conceptual Physics*. I am now honored that he has devoted so much of his time and energy to making this edition a beautiful book. I am also grateful to long-time friend and science writer Judith Brand, who like Ken, added clarity to my writing. Errors invariably appear after manuscript is submitted, so I take full responsibility for any errors that have survived their scrutiny.

For valued assistance to this edition I am most thankful to my talented wife Lillian for contributing to every stage of this book and its ancillaries, and also to Ken Ford, and Judith Brand. Fred Myers tweaked most chapters and nicely improved explanations of physics topics and clarified end-of-chapter exercises. David Manning made valued suggestions to Think-And-Do Activities. Alan Davis brightened up the chapter on gravity with his ocean tides chart. Jennifer Yeh assisted with profiles of great scientists. Ron Hipschman helped direct improvements throughout the book. Nephew John Suchocki gave valued general advice. For physics advice and accuracy, I turn to David Kagan and Bruce Novak, as well as to Ken Ford. Others listed alphabetically to whom I'm grateful are Robert Austin, Marshall Ellenstein, Scotty Graham, Jerry Hosken, Brad Huff, Evan Jones, Elan Lavie, John McCain, Anne Tabor Morris, Bruce Novak, Dan Styer, Dave Wall, Jeff Wetherhold, Norman Whitlatch, Phil Wolf, and David Vasquez.

For valued suggestions from previous editions, I thank my friends Dean Baird, Tomas Brage, Howard Brand, George Curtis, Alan Davis, Marshall Ellenstein, Mona El TawilNassar, Herb Gottlieb, Jim Hicks, Jerry Hosken, Peter Hopkinson, John Hubisz, Sebastian Kuhn, David Kagan, Carlton Lane, Juliet Layugan, Paul McNamara, Derek Muller, Fred Myers, Diane Riendeau, Gretchen Hewitt Rojas, Chuck Stone, Chris Thron, Lawrence Weinstein, Phil Wolf, and P.O. Zetterberg. Others who provided suggestions in years past include Matthew Griffiths, Paul Hammer, Francisco Izaguirre, Les Sawyer, Dan Sulke, and Richard W. Tarara. I am forever grateful to the input of my Exploratorium friends and colleagues: Judith Brand, Paul Doherty, Ron Hipschman, Eric Muller, and Modesto Tamez.

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

For their dedication, I am grateful to Jeanne Zalesky and the Pearson management team under the wing of Harry Misthos. I thank product managers Jessica Moro and Heidi Allgair, and for development, Judith Brand, and copyeditor Scott Bennett. I am especially grateful to Mary Tindle and for the competence of the production staff at SPI. I have been fortunate to work with this first-rate team!

Paul G. Hewitt
St. Petersburg, Florida

Global Edition

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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. Maybe we're like chicks breaking out of our shell—but with the realization that we're not apart from nature but very much a part of it. So we should learn nature's rules in order to live together sustainably in this world.

CHAPTER ONE

1

About Science

1

2

3

4

1 Circular images of the Sun are cast from above through small openings between tree leaves. **2** Sunlight also indicates daily time for Einstein Dhayal (right) and his friends in India. **3** Science writer Judith Brand holds a pea at just the right distance to eclipse a full moon. A specific number of end-to-end peas can fit in this "right distance." Aha! Does this relate to the number of end-to-end Moons between her eye and the Moon? **4** Phyllis Vasquez holds the basketball to represent Earth. Her five sons, all teachers, ponder how far a tennis ball representing the Moon should be held to approximate the Earth-Moon distance.

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 I 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 (2000 years ago with no computers and no artificial satellites—using only good thinking, geometry, and simple measurements). In this chapter you will see how he accomplished this.

1.1 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 the Earth, Moon, and Sun, as well as the distances between them.

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How Eratosthenes Measured the Size of Earth

The size of Earth was first measured in Egypt by Eratosthenes in 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 the day of the summer solstice (which occurs around June 21 on today's calendars). At this time, a vertical stick casts its shortest shadow. If the Sun is directly overhead, a vertical stick casts no shadow at all. Eratosthenes learned from library information that the Sun was directly overhead at noon on the day of the summer solstice in Syene, a city south of Alexandria (where the Aswan Dam stands today). 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.

The Sun is directly overhead at noon only near the equator. Standing in the sunshine at the equator, you cast no shadow at noon. At locations farther from the equator, the Sun is never directly overhead at noon. The farther you stand from the equator, the longer is the shadow your body casts.

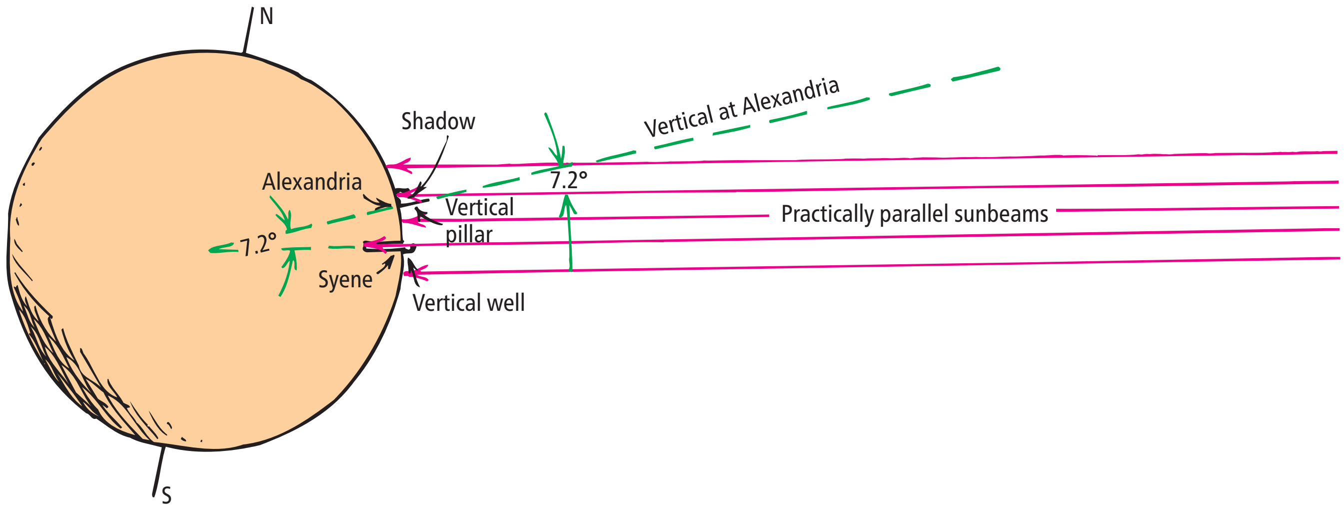


FIGURE 1.1
When the Sun is directly overhead at Syene, sunbeams in Alexandria make a 7.2° angle with the vertical. The verticals at both locations extend to the center of Earth, where they make the same 7.2° angle.

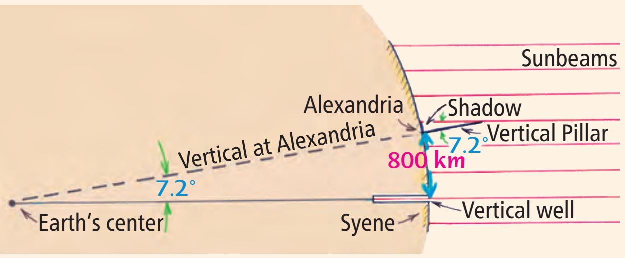
At noon of the summer solstice, Eratosthenes measured a 7.2° angle between sunbeams and a vertical pillar in Alexandria (Figure 1.1) . How many 7.2° segments make up Earth's circumference of 360°? The answer is $360°/7.2° = 50$. Since 7.2° is 1/50 of a complete circle, Eratosthenes reasoned that the distance between Alexandria and Syene is 1/50 Earth's circumference. 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 5000 stadia (800 kilometers). So Eratosthenes calculated Earth's circumference to be 50×5000 stadia $= 250{,}000$ stadia. In kilometers, Earth's circumference $= (50)(800\text{ km}) = 40{,}000\text{ km}$, very close to the currently accepted value of Earth's circumference.

fyi

- **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 and 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. Invading hordes destroyed almost everything in their paths as they overran Europe. Reason gave way to religion, which plunged Europe into the Dark Ages. During this time, the Chinese and Polynesians were charting the stars and the planets and Arab nations were developing mathematics. Greek science was reintroduced to Europe by Islamic influences that penetrated into Spain during the 10th, 11th, and 12th centuries. In the 15th century art and science were beautifully blended by Leonardo da Vinci. Scientific thought was furthered in the 16th century with the advent of the printing press.

CHECK POINT

If the same 7.2° subtended 500 km (instead of 800 km), would a measure of Earth's circumference be smaller, larger, or the same?



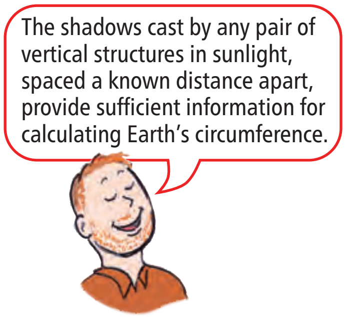
CHECK YOUR ANSWER

Smaller, as Earth's circumference would be $(50)(500\text{ km}) = 25{,}000\text{ km}$.

Seventeen hundred years after Eratosthenes's death, Christopher Columbus studied Eratosthenes's findings before setting sail for the East Indies. Rather than heed Eratosthenes's findings, however, Columbus chose to accept more up-to-date maps that indicated Earth's circumference was one-third smaller. If Columbus had accepted Eratosthenes's larger circumference, then he would have known that he had not landed in China or the East Indies, but rather the Caribbean.

PRACTICING PHYSICS

Earth's Size via Tree/Flagpole Shadows



In measuring the size of Earth, Eratosthenes considered two north–south locations that lie very close to a specific line of longitude. This need not be necessary. A line of longitude is one of many *great circles*. On Earth, *any* great circle, in any orientation, lends itself to a measurement of Earth's circumference.

A great circle is the largest possible circle that can be drawn around a sphere. Through any two points on a sphere such as Earth, whatever the direction of the line separating them, a great circle can be defined and drawn. Commonly charted great circles are Earth's lines of longitude, all passing through the north and south poles. Only one great circle lies along a line of latitude: that of the equator. But there are an infinite number of great circles about Earth, all with their centers at Earth's center (Figure 1.2).

Vertical structures in sunlight, such as pillars and trees, cast shadows. Because sunbeams reaching Earth's surface are parallel to one another, close-by vertical trees cast equal-angle shadows. But due to Earth's curvature, the shadows cast by trees many kilometers away at the same time of day are at different angles to the sunbeams. Due to the Sun's perceived continuous movement across the sky, minutes later a shadow will be at a slightly different angle. Amazingly, shadows cast by trees or other perpendicular structures on different parts of our planet, whether on or off a line of longitude, provide sufficient information for calculating the size of Earth.

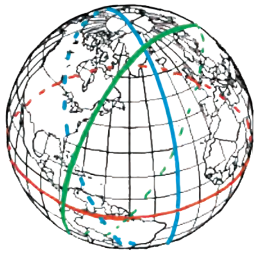


FIGURE 1.2
Three great circles, one at the equator (red), one along a line of longitude (blue), and another in a random direction (green).

Earth's size can be calculated with simply trigonometry when the shadow of one tree points directly toward or away from the second tree. At this special time, the plane of the sunbeams striking Earth coincides with the plane of the great circle defined by the pair of trees. Such is the case in Figure 1.3, where the 10° vertex at Earth's center is equal to the 10° difference in the angles of the sunbeams with vertical trees.

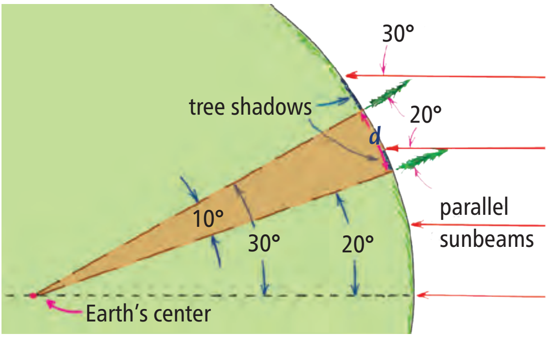
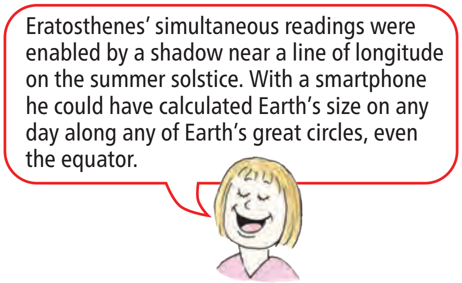


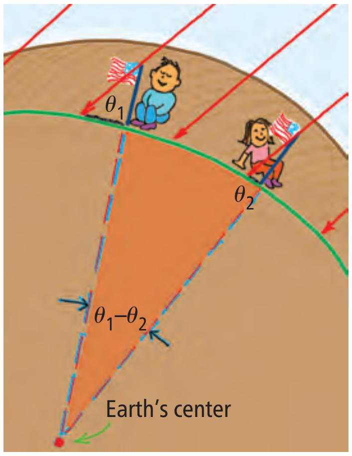
FIGURE 1.3
The two-tree arc *d* subtends an angle of 10° at Earth's center (shown by brown "wedge").

How many 10° segments of Earth make up a full 360° circumference of Earth? The answer is $360°/10° = 36$. This tells us that Earth's circumference is simply equal to 36 times the distance between the pair of trees. Mission accomplished!

Flagpoles are even better at casting well-defined shadows. For far-apart cities where the separation distances are known quantities, an interesting science project (or activity) is applying the pair-of-trees idea to shadow-casting flagpoles at your school and a school in another city where your instructor has a teacher friend.

Anywhere on the globe, with rare exceptions, the shadows of a pair of flagpoles in sunlight will align along a great circle at *some* time on *some* day. To calculate Earth's circumference, you must find a date and time when the shadow cast by your school flagpole points directly toward or directly away from the school flagpole in the other city. If the Sun is shining in that other city, shadows there will meet the same criterion at the same time. If the day is cloudy or rainy, or if it's a weekend, be patient: Very nearly the same conditions will apply for several days running. (Caution: Making measurements of incident sunbeams that don't fall on the plane of your great circle involves more complex spherical trigonometry.)





Enjoying flagpole physics.

You have what Eratosthenes could not dream of: the Internet and smartphones, and perhaps a compass to tell when the shadows cast are aligned (the first pointing toward the second and the second away from the first—or, in some cases, each pointing away from the other). Synchronized timing that was a problem for Eratosthenes is given by smartphones. The difference in the two measured angles (or, if the shadows point away from each other, the sum) equals the angle at the vertex at Earth's center where extended vertical lines of each flagpole intersect. Note in the sketch that the difference between sunbeam angles at the two flags equals the vertex angle at Earth's center when the plane of the parallel sunbeams coincides with the plane of the two-flagpole great circle. With good data, estimates of the circumference of Earth can be calculated.

Or consider doing the reverse: Use Earth's 40,000-km circumference as the known value, and find the unknown distance between far-apart flagpoles. Flagpoles would have to be really distant for good results. For example, a 100-kilometer separation distance corresponds to less than a 1° difference in sunbeam angles—difficult to distinguish. It's better that your locations are much farther apart.

Either way—whether you decide to calculate Earth's circumference, or your distance of separation—this is an engaging cooperative activity. Go for it!

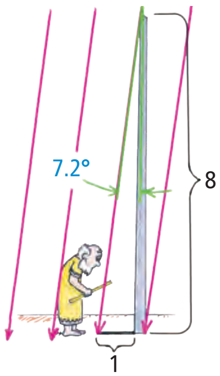


FIGURE 1.4
Two routes to the same solution.

Eratosthenes would have come to the same result by bypassing degrees altogether and comparing the length of the shadow cast by the pillar to the height of the pillar. When Eratosthenes measured the 7.2° angle of sunbeams with the vertical pillar, he also noted that the shadow cast by the pillar was 1/8 the height of the pillar (Figure 1.4). 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 taller 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.

So we learn there is more than one way in which Eratosthenes could measure the size of Earth. This feature of more than one path to a solution will be encountered time and again in chapters that follow. This hallmark of good science is one of many reasons that people devote their careers to physics or physics-related professions. Hats off to physics.

Size of the Moon

Another Greek scientist of the same era as Eratosthenes was Aristarchus, who was likely the first to suggest that Earth spins on its axis once a day, which accounted for the daily motion of the stars. Aristarchus also hypothesized that Earth moves around the Sun in a yearly orbit and that the other planets do likewise.[1] He correctly calculated the Moon's diameter and its distance from Earth. He accomplished all this in about 240 BC, 17 centuries before his findings were 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 in which the Moon passes into this

[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, 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.

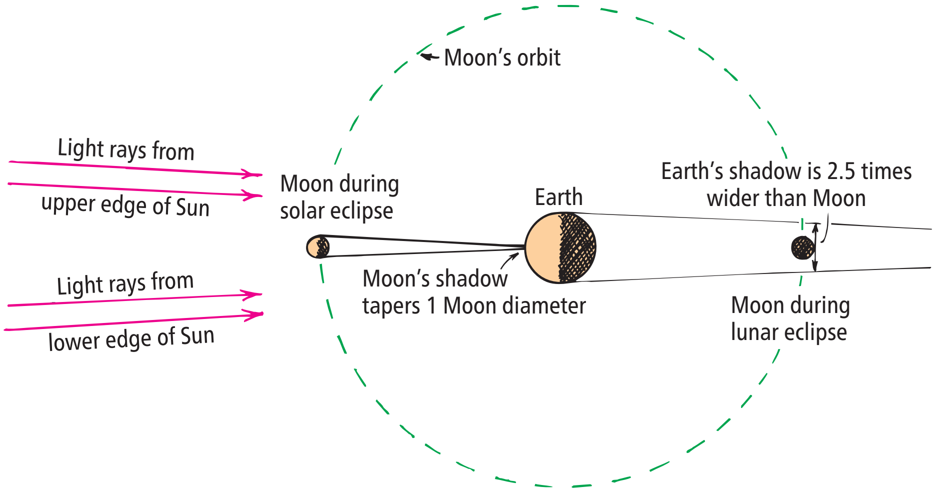


FIGURE 1.5
During a lunar eclipse, Earth's shadow is observed to be 2.5 times as wide as the Moon's diameter. Because of the Sun's large size, Earth's shadow must taper. The amount of taper is evident during a solar eclipse, where the Moon's shadow tapers a whole Moon diameter from Moon to Earth. So Earth's shadow tapers the same amount in the same distance during a lunar eclipse. Therefore, Earth's diameter must be 3.5 Moon diameters.

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. That's if light rays from the Sun's opposite edges were exactly parallel to one another. Although solar rays are practically parallel over a short range, their slight tapering due to the Sun's huge size are evident over longer distances, as during the time of a solar eclipse (Figure 1.5), when light rays from both upper and lower edges of the Sun taper to almost a point. Over the Moon–Earth distance the rays taper by about 1 Moon diameter. That same amount of taper over the same distance occurs with Earth's shadow during a lunar eclipse (right side of Figure 1.5). When the tapering of the Sun's rays is taken 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 1.6
Correct scale of solar and lunar eclipses, which shows why a perfect lineup of the Sun, Moon, and Earth doesn't occur monthly. (Eclipses 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

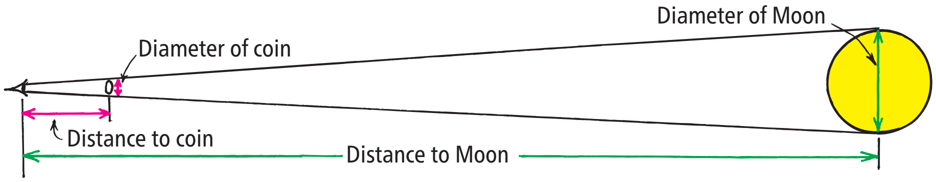
Tape a small coin, such as a dime, to a window and view it with one eye so that it just blocks out the full Moon. This occurs when your eye is about 110 coin diameters away from the coin. Then the ratio *coin diameter/coin distance* is about 1/110. Geometrical reasoning from similar triangles shows this is also the ratio *Moon diameter/Moon distance* (Figure 1.7). So the distance from you 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.

With this information, Aristarchus calculated the Earth–Sun distance.

fyi

- 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."



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

FIGURE 1.7
An exercise in ratios: When the coin barely "eclipses" the Moon, the ratio of the diameter of the coin to the distance between you and the coin is equal to the ratio of the diameter of the Moon to the distance between you and the Moon (not to scale here). Measurements give a value of 1/110 for both ratios.

Distance to the Sun

If you were to repeat the coin-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 sizes of the Sun and Moon are both the same to the eye. They both taper to the same angle (about 0.5°). However, 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 1.8).

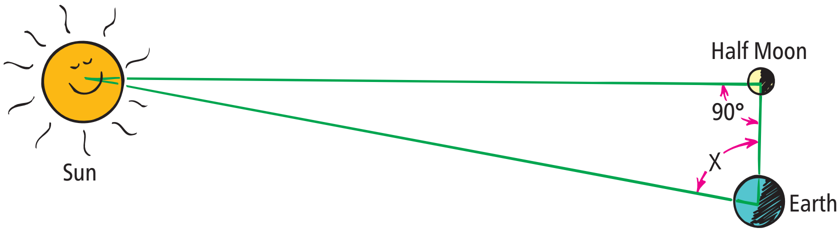


FIGURE 1.8
When the Moon appears exactly half full, the Sun, Moon, and Earth form a right triangle (not to scale). The hypotenuse is the Earth–Sun distance. By simple trigonometry, the hypotenuse of a right triangle can be found if you know the size of either nonright angle and the length of one side. The Earth–Moon distance is a side of known length. 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 is 89.8°. He figured the Sun to be about 20 times farther away than the Moon, when in fact it is about 400 times as distant. So, although his method was ingenious, his measurements were not. Perhaps Aristarchus found it difficult to believe the Sun was so far away, and he erred on the nearer side. We don't know.

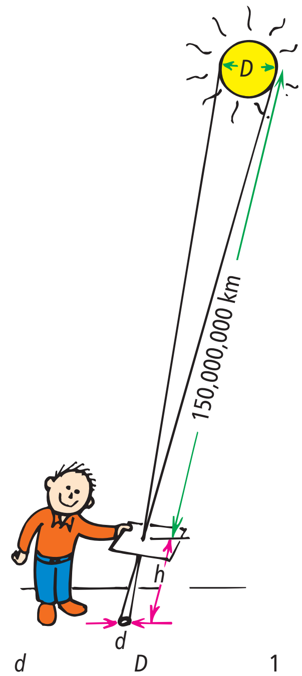
Today we know the Sun is an average of 150,000,000 kilometers from Earth. It is somewhat closer to Earth in early January (146,000,000 km) and somewhat farther away in early July (152,000,000 km).

CHECK POINT

1. **How did observations of a lunar eclipse enable Aristarchus to estimate the diameter of the Moon?**
2. **Aristarchus was the first to be credited for calculating Earth's distance to the Sun, using the half Moon as a reference. Why was it important that the Moon be in its half-Moon phase?**

CHECK YOUR ANSWERS

1. Aristarchus visually measured that Earth's shadow crossing over the Moon during a lunar eclipse is 2.5 times wider than the Moon. Adding to this the effect of solar-ray tapering, he estimated that Earth's diameter must be 3.5 Moon diameters. Put another way, the Moon's diameter is 1/3.5 that of Earth's. So the Moon's diameter is 1/3.5 the diameter of Earth as measured by his contemporary Eratosthenes.
2. As shown in Figure 1.8, a right triangle is formed by the distance from the Earth to the half Moon, the distance between the Sun and the half Moon, and the distance between the Earth and the Sun. A right triangle is important, for if you know the distance of any side of the triangle you can calculate the distances of the other two sides. From his measurements (imperfect at the time), Aristarchus calculated Earth's distance from the Sun.



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

FIGURE 1.9
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–Earth distance* ratio, 1/110. The Sun's diameter is 1/110 its distance from Earth.

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 1.7, 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. The size of the hole depends on its distance from the image it casts. The hole in Figure 1.9 can be the size that a sharp pencil makes when poked through cardboard, about 1 millimeter in diameter. The "pinhole" that makes up the opening between tree leaves above Lillian in Figure 1.10 can be a few centimeters wide. In any event, careful measurements show that the ratio of image size to "pinhole" distance is 1/110—the same as the ratio *Sun diameter/Sun–Earth distance* (Figure 1.9).

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 (Figure 1.10)? These are pinhole images of the Sun, where sunlight 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 produce large images; short trees produce small images.

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 (Figure 1.11). This provides an alternate way to view a partial eclipse without looking at the Sun.

FIGURE 1.10
Small openings between leaves above cast solar images around Lillian.

FIGURE 1.11
The crescent-shaped spots of sunlight are images of the Sun when it is partially eclipsed.

FIGURE 1.12
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.

CHECK POINT

1. **Using the method shown in Figure 1.9 we learn that our Sun is 110 Suns away. In Figure 1.7 we learn that our Moon is 110 Moons away. Is this a coincidence?**
2. **If the height of the card in Figure 1.9 were positioned so the solar image matched the size of a coin (an accurate means to measure the solar-image diameter), then 110 of these coins would fit end to end in the space between the card and the image below. How many Suns would similarly fit between the Earth and the Sun?**

CHECK YOUR ANSWERS

1. Yes. It is sheer coincidence that both the Sun and Moon subtend the same angle that produces the 1/110 ratio. In past times, the Moon was appreciably closer to Earth, subtending a larger angle. At present, the Moon is receding from Earth—very slowly at about 4 centimeters per year (due to the effect of tidal friction and the conservation of angular momentum). This means that in coming years the Moon will appear smaller in the sky, producing annular rather than total eclipses of the Sun.
2. The answer is 110 Suns would fit in the space between the Sun from Earth. If you perform the similar experiment of a coin taped to your window at the time of a low full Moon, you'll similarly find that 110 coins will fit between the window and your eye—illustrating that 110 Moons would fill the average space between Earth and the Moon.

Mathematics—The Language of Science

Science and human conditions advanced dramatically after the integration of science and mathematics 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]

1.2 Scientific Methods

There is no *one* scientific method. But there are common features in the way scientists do their work, dating 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 the 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.

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

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.

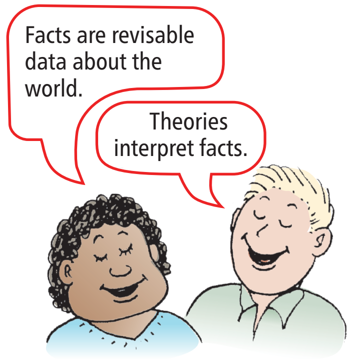
Although these steps are appealing, much progress in science has come from trial and error, experimentation without hypotheses, or just plain accidental discovery by a well-prepared mind. The success of science rests more on an attitude common to scientists than on a particular method. This **scientific 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, although 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*.

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

[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 are in the *Problem Solving in Conceptual Physics* ancillary book.



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]

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 adopt 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 a means of proving it right. This is a major factor that distinguishes science from nonscience. At first this may seem strange because 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."

[3]But appeal to *beauty* has value in science. More than one experimental result in modern times has contradicted a lovely theory that, 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.

[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.

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 steppingstone to additional knowledge.

Contemplate 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 scientific. It cannot be proved wrong, nor can it be proved right. It is *speculation*. Likewise, the hypothesis "Intelligent life exists on other planets somewhere in the universe" is not scientific. Although it can be proved 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 statement *a* is scientific, because there is a test for falseness. The statement not only *is 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.

Being scientific is being open to new knowledge.

None of us has the time, energy, or resources to test every idea, so most of the time we accept somebody else's word. How do we know whose word to accept? 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

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

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 discovered; 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.

Dealing with Misconceptions

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 that their own ideas about things are 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 opponents 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.

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.

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 a test 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.

Although the notion of being familiar with opposing points of view seems reasonable to most thinking people, just the opposite—shielding ourselves and others from different 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 discard only a part of that blockage.

1.3 Science, Art, and Religion

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 in 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.

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

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. Similarly, knowledge of science tells us what is possible in nature and helps us to 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 nature—the *natural;* the domain of religion is the *supernatural*. 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? 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.

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

FAKE SCIENCE

For a claim to qualify as "scientific," it must meet certain standards. For example, the claim must be reproducible by others who have no stake in whether the claim is true or false. The data and subsequent interpretations are open to scrutiny in a social environment where it's okay to have made an honest mistake but not okay to have been dishonest or deceiving. Claims that are presented as scientific but do not meet these standards are what we call **pseudoscience,** which literally means "fake science." In the realm of pseudoscience, skepticism and tests for possible wrongness are downplayed or flatly ignored.

Examples of fake science abound. For example, after being officially eliminated in the U.S. in 2000, measles is making a comeback. Officials blame low vaccination rates that are due in part to public distrust of government, science, big pharmaceutical corporations, and antivaccine propaganda. A search for information about vaccines on social media and other parts of the Internet often yields advice that is completely incorrect. The World Health Organization (WHO) has labeled "vaccine hesitancy" one of the top 10 global health threats for 2019. This junk science is now global.

For more examples of fake science, look no further than the Internet. You can find advertisements for a plethora of pseudoscientific products. Watch out for remedies for ailments from baldness to obesity to cancer, for air-purifying mechanisms, and for "germ-fighting" cleaning products in particular. While many such products do operate on solid science, others are pure pseudoscience. Buyer beware!

Humans are very good at denial, which may explain why pseudoscience is such a thriving enterprise. Many pseudoscientists themselves do not recognize their efforts as pseudoscience. A practitioner of "absent healing," for example, may truly believe in her ability to cure people she will never meet except through e-mail and credit card exchanges. She may even find anecdotal evidence to support her contentions. The placebo effect, as discussed in Chapter 20, can mask the ineffectiveness of various healing modalities. In terms of the human body, what people believe *will* happen often *can* happen because of the physical connection between the mind and the body.

That said, consider the enormous downside of pseudoscientific practices. Today, there are many thousands of practicing astrologers in the United States. Do people listen to these astrologers just for the fun of it? Or do they base important decisions on astrology?

Meanwhile, the results of science literacy tests given to the general public show that most Americans lack an understanding of the basic concepts of science. Most American adults are unaware that the mass extinction of the dinosaurs occurred long before the first human evolved; about three-quarters do not know that antibiotics kill bacteria but not viruses. What we find is a rift—a growing divide—between those who have a realistic sense of the capabilities of science and those who do not understand the nature of science and its core concepts or, worse, think that scientific knowledge is too complex for them to understand. Science is a powerful method for understanding the physical world—and a whole lot more reliable than pseudoscience as a means for bettering the human condition.

1.4 Science and Technology

> The good thing about science is that it's true whether or not you believe in it.—*Neil deGrasse Tyson*

Science and technology are also different from each other. Science is concerned with gathering knowledge and organizing it. **Technology** enables humans to use that knowledge for practical purposes, and it provides the instruments scientists need for conducting investigations.

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 stabbing is the fault of the knife. It is humans who use the technology, and humans who are responsible for how it is used.

> No wars are fought over science.

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.

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 3000 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 fossil fuels first powered industrial progress. Today 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 because all foods are toxic to some degree. You cannot avoid radioactivity because it's in the air you breathe and the foods you eat, and it has been that way since before humans first walked on 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, the assessment of the most probable gets closer to being on target. Acceptance of risk, on the other hand, is a societal issue. Making zero risk a societal goal would consume 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.

CHECK POINT

If a classmate is anti-science, does it follow that he or she is also anti-technology? Or conversely, is a classmate who is anti-technology also anti-science?

CHECK YOUR ANSWER

The classmate may be both, or one or the other. His or her perspective is the result of information acquired between childhood and the present. You may or may not share the same views, depending on how different or similar your backgrounds are. As a matter of self-interest, it is important to not automatically let differences of opinion ruin what could be a valued friendship. When everyone in your vicinity has the same views of science and technology, do yourself a favor and get to know those with opposing views. A wise person is acquainted with more than one point of view.

1.5 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, If I were ever to become a college professor, I would want to teach first-year physics or calculus. —*Astronaut Scott Kelly*

FIGURE 1.13
Planet Earth's "lifeboat"—a beautiful blend of science and technology.

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.

There is a pool of good. No matter where you put in your drop, the whole pool rises.—*Will Maynez*

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!

1.6 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 space vehicles 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 that 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!

Chapter 1 Review

For instructor-assigned homework, go to: www.masteringphysics.com

SUMMARY OF TERMS (KNOWLEDGE)

Science The collective findings of humans about nature, and the process of gathering and organizing knowledge about nature.

Scientific method An orderly method for gaining, organizing, and applying new knowledge.

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.

Technology The means of solving practical problems by applying the findings of science.

READING CHECK QUESTIONS (COMPREHENSION)

1.1 Scientific Measurements

1. Briefly, what is science?
2. Throughout the ages, what has been the general reaction to new ideas about established "truths"?
3. When the Sun was directly overhead in Syene, why wasn't it directly overhead in Alexandria?
4. What is the location of Earth's center relative to a great circle defined by a pair of widely spaced flagpoles on Earth's surface?
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 choose the time of a half Moon to make his measurements for calculating the Earth–Sun distance?
8. What are the circular spots of light seen on the ground beneath a tree on a sunny day?
9. What is the role of equations in this book?

1.2 Scientific Methods

10. The modern scientist works "upward." Explain.
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. When does a scientific hypothesis become a law?
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?

1.3 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. Must people 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?

1.4 Science and Technology

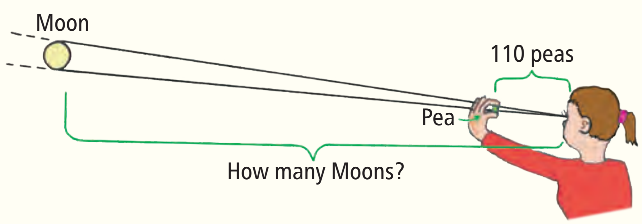
19. Clearly distinguish between science and technology.

1.5 Physics—The Basic Science

20. Why does an understanding of science begin with an understanding of physics?

THINK AND DO (HANDS-ON APPLICATIONS)

21. Poke a hole in a piece of cardboard and hold the cardboard horizontally in the sunlight (as in Figure 1.9). 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 using 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 also the ratio of the Sun's diameter to its distance to Earth. Using the information that the Sun is 150,000,000 kilometers from Earth, 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?)
22. When a full or nearly full moon appears in your view, do a version of Figure 1.7 with a pea instead of a coin. First, measure the diameter of a green pea (or any tiny sphere). With one eye closed, hold the pea at a distance from your open eye that just blocks out (eclipses) the Moon. With the help of a friend measure the distance from your eye to the pea. Compare this distance to the diameter of the pea. Then you know how many peas fit in the space between your eye and the pea. How does this compare with how many moons can fit in the space between you and the Moon?

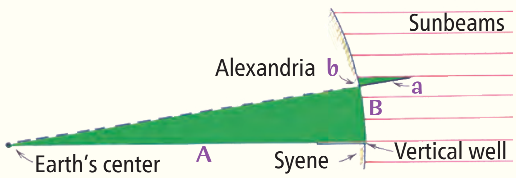


23. Do as Lillian does in Figure 1.10 and observe the round patches of light beneath sunlit trees. Ask friends if they see anything unusual about the shape of the spots of light. Chances are, they don't—until you point out that most of the spots are circular pinhole images of the Sun. When you do this, you'll experience the joy of teaching others to see what they otherwise would miss.

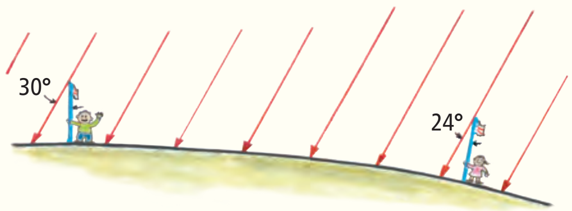
24. Choose a particular day in the very near future—and during that day access the notes on your smart phone and record every time you come in contact with modern technology. Then compose a page or two discussing your dependencies on your list of technologies. Make a note of how you'd be affected if each suddenly vanished, and how you'd cope with the loss.

THINK AND EXPLAIN (SYNTHESIS)

25. What is the penalty for scientific fraud in the science community?
26. Which of the following are scientific hypotheses? (a) The bacteria E. coli are happier in dark environments. (b) Wind is caused by the motion of trees. (c) There are an infinite number of parallel universes, but no communication is possible between them.
27. If a hypothesis cannot be proved wrong, does it mean that it is scientific?
28. If the Sun's rays were at 45° to a tall vertical flagpole, how would the shadow length compare to the flagpole height?
29. 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 800-km distance between Alexandria and Syene is 1/8 Earth's radius. From this information, calculate Earth's radius.



30. 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?



31. Phil and Nellie measure the angles of sunlight at their school flagpoles when the shadows fall along their common great circle. One angle is 30° and the other is 24°. Using Earth's circumference as 40,000 km, show that Phil and Nellie are 667 km apart.
32. You're a space-faring explorer and discover a spherical planet bathed in sunlight. To determine its size you drive a pair of widely spaced vertical stakes into its surface and wait until the shadow of one stake points to the other stake. Then the cast shadows lie along their own great circle. If sunbeams then make a 20° angle with one stake and 15° with the other, what will be the vertex angle at the planet's center? What other information would you need to calculate the planet's circumference?

THINK AND DISCUSS (EVALUATION)

33. The well-known astronomer and science communicator Carl Sagan (1934–1986) once explained, "science is more than a body of knowledge. It's a way of thinking." Discuss with your classmates how a scientific attitude uses facts, hypotheses, and theories to advance our understanding of the world around us. Compare this to a nonscientific approach.
34. "Imagination is more important than knowledge" is a statement attributed to Albert Einstein, and it highlights the creative aspect of the scientific approach. Discuss with your classmates how this relates to some of the scientific achievements outlined in the chapter (e.g., Eratosthenes' measurement of the size of the Earth).
35. A non-scientist friend tells you that science and religion are both based on references to authority, and that a science textbook (such as this one) is similar to a religious text (such as a bible). What argument(s) could you use to convince your friend that there are important differences between a science textbook and a religious text?

CHAPTER ONE Multiple-Choice Practice Exam

Choose the BEST answer to each of the following:

1. The main thrust of equations in this textbook is
   (a) guides to thinking.
   (b) recipes for solving algebraic problems.
   (c) a route to "plugging and chugging."
   (d) to challenge students weak in math.

2. The classic scientific method includes
   (a) guessing.
   (b) experimenting.
   (c) predicting.
   (d) All of the above

3. If the pillar in Alexandria were taller and the well in Syene were deeper, Eratosthenes's calculation of Earth's size would be
   (a) larger.
   (b) smaller.
   (c) no different.
   (d) impossible to determine.

4. If in the dime-Moon experiment you used a larger coin than a dime, your distance from the taped coin would be
   (a) closer.
   (b) farther.
   (c) the same distance.
   (d) None of these

5. Beneath a sunlit tree are pinhole images of the Sun. If the tree that cast the images is taller, then the images of the Sun are
   (a) larger.
   (b) smaller.
   (c) the same size.
   (d) Impossible to say

6. If the diameter of the solar image cast by a pinhole is the same as the diameter of a particular coin, and 110 coins would fit between the image and the pinhole, the Sun must be
   (a) 55 Sun diameters from Earth.
   (b) 110 Sun diameters from Earth.
   (c) Not enough information
   (d) Impossible to say

7. Which of these is a scientific hypothesis?
   (a) The full Moon is a poor time to make decisions.
   (b) Your truest friends and you have the same astrological sign.
   (c) The dumpster in your back alley is filled with garbage.
   (d) None of the above

8. Which of these is a scientific statement?
   (a) Candied walnuts contain no sugar.
   (b) Things exist that we will never know about.
   (c) Matter is filled with undetectable particles.
   (d) Parts of the universe exist that will never be discovered by humans.

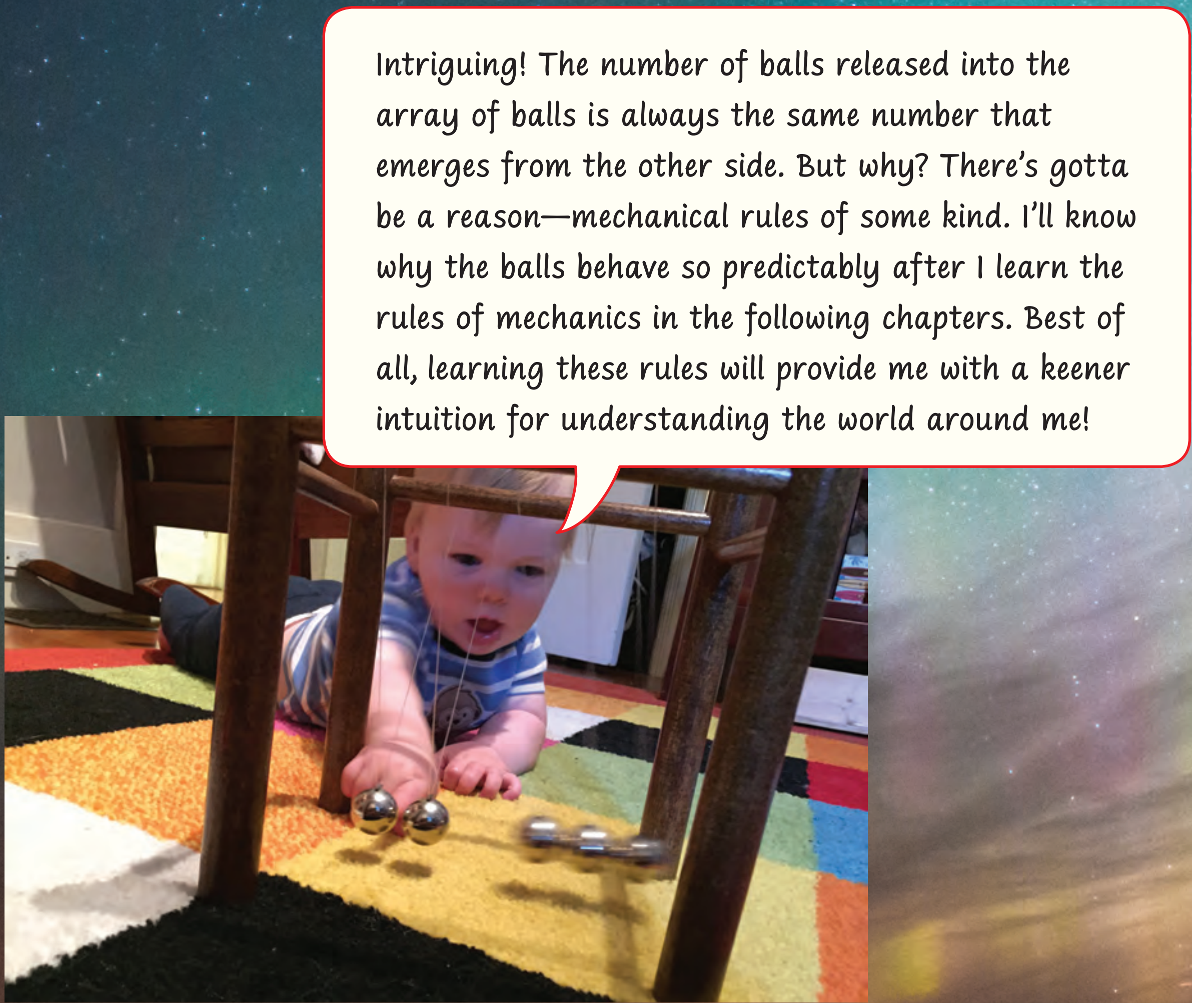
9. Reasonable statements that are not testable
   (a) are a small segment of the scientific method.
   (b) lie outside the domain of science.
   (c) have no value.
   (d) All of the above

10. Science, art, and religion need not contradict one another because
   (a) all three involve different domains.
   (b) choosing the right one means no need to heed the other two.
   (c) choosing religion and art means no need to heed science.
   (d) choosing science means no need to heed religion and art.

Answers and Explanations to Multiple-Choice Practice Exam

1. (a): Although the equations of physics are central to choices (b–d), the distinguishing feature of equations in Conceptual Physics is to guide thinking, which is of value in its own right and crucial to understanding whatever math problems are solved. **2. (d):** All of the above, with the reservation that other methods such as trial and error or just plain luck lead to scientific discoveries. **3. (c):** A crucial measurement is the angle of sunbeams with the pillar in Alexandria, which is 7.2 degrees for a short or tall pillar. Another crucial measurement is the distance between Alexandria and Syene, which has nothing to do with this question. So no difference occurs with a taller pillar and deeper well. **4. (b):** A larger coin would have to be positioned farther away to attain the same 1/110 ratio. Conversely, a coin smaller than a dime would be closer to your eye for the same ratio. **5. (a):** The ratio of (diameter of the solar image)/(tree height) is the same ratio (diameter of the Sun)/(distance to the Sun). So taller trees cast larger solar images. **6. (b):** The ratio for the coin (same size as solar image) to its distance to the pinhole is the same ratio as diameter of the Sun to its distance from Earth. Coincidentally, the same occurs for the Moon. Same 1/110 ratio! **7. (c):** Only choice (c) has a test for wrongness. Look and see! The other statements are speculation. **8. (a):** Only (a) has a test for wrongness. Choices (b–d) have no tests for wrongness, and are therefore nonscientific statements that may or may not be true. That each is devoid of any way to show it wrong makes it an unscientific statement. **9. (b):** Domains galore are everywhere, many highly valued and correct. But if not testable, they lie outside the domain of science. Claims that have no test for wrongness, however appealing, lie outside the domain of science. **10. (a):** Conflicts among science, art, and religion mainly occur when an idea or formulation from one domain is applied to a different domain. When ideas are kept within their own domain, conflicts are minimal.

PART ONE
Mechanics



CHAPTER TWO

2 Newton's First Law of Motion–Inertia

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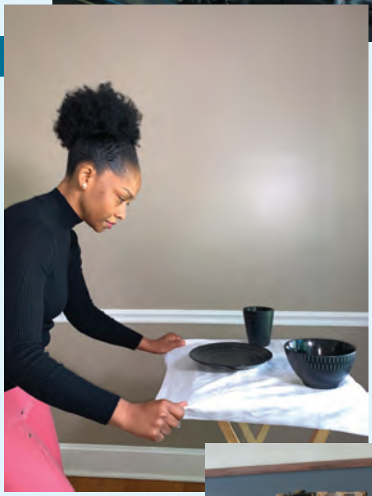

4

1 Cedric and Anne Linder compare the different tensions in the string that supports the red block. **2** Will Maynez shows that the inertia of the anvil on the author's chest is enough to shield the blow of the hammer. **3** Ana Miner in the process of demonstrating Newton's first law. **4** Karl Westerberg asks his students which string, the lower or the upper, will break when he suddenly yanks downward on the lower string.

Not all physics instructors are warm to *Conceptual Physics*. Some prefer a roll-up-the-sleeves approach that immediately gets into problem solving, with little or no time spent on conceptual understanding. In 1992 I was delighted to see an article in the journal *The Physics Teacher* by a professor in South Africa who reported great success with teaching physics conceptually. I contacted him, and we've been friends ever since.

I'm speaking of Cedric Linder, who grew up and taught physics for many years in South Africa before moving to the Department of Physics and Astronomy at Uppsala University in Sweden to establish the first Physics Education Research division in Sweden. In 2014 he received the International Commission on Physics Education ICPE Medal for outstanding contributions to physics education, partially in recognition of his efforts to bring conceptual physics into mainstream physics, and to provide pre- and in-service teacher education. Some physics teachers have a knack for enhancing students' learning experience and make physics a delightful experience. How nice that Cedric and his wife Anne are among this group. Today Cedric and Anne work together in the same research group and feel at home in both Uppsala and Cape Town.

2.1 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.

ADDITIONAL RESOURCES
Videos
Screencasts

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 will fall to the ground, but not as rapidly as a lump of clay. Aristotle 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 with all things on Earth, or it could be circular, as with 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.)

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- Rather than reading the chapters slowly, try reading them quickly and more than once. You'll learn physics better by going over the same material several times. With each time, it makes more sense. Don't worry if you don't understand things right away—just keep reading.

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

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

Aristotelian teaching was characterized by memorization. Experimentation and questioning did not become the norm until Galileo challenged the authority of Aristotle in the 16th century.

winning a tug-of-war. The wind imposed motion on ships. Floodwaters imposed motion 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, nor by their "nature," but because of pushes or pulls.

The concept of violent motion had its difficulties because 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.

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.

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

Yes. Common sense is relative to one's time and place. 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.

ARISTOTLE (384–322 BC)

Greek philosopher, scientist, and teacher, Aristotle was the son of a physician who personally served the king of Macedonia. At age 17, Aristotle 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 except 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

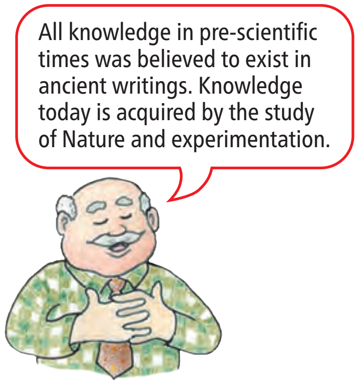
dominant political and cultural force in Western Europe, first prohibited the works of Aristotle but then accepted and incorporated them into Christian doctrine.

Copernicus and the Moving Earth

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) circles around the Sun. For years he worked without making his thoughts public—for two reasons. The first was the fear of 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.

Nicolaus Copernicus (1473–1543)

Most of us know about the reaction of the medieval Church to the idea that Earth travels around the Sun. Aristotle's views had become a formidable part of Church doctrine, so 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.



2.2 Galileo's Experiments

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 weights from the top of the tower. Legend has it that many observers 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.

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 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 earlier. But, quite important, Galileo's findings also threatened the authority of the Church, which 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 four years later. Every age has intellectual rebels, some of whom push the frontiers of knowledge further. Among them is certainly Galileo.

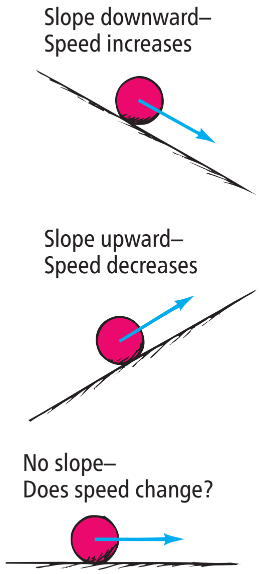


FIGURE 2.2
Motion of balls on various planes.

Galileo tested this hypothesis by experimenting with the motions 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

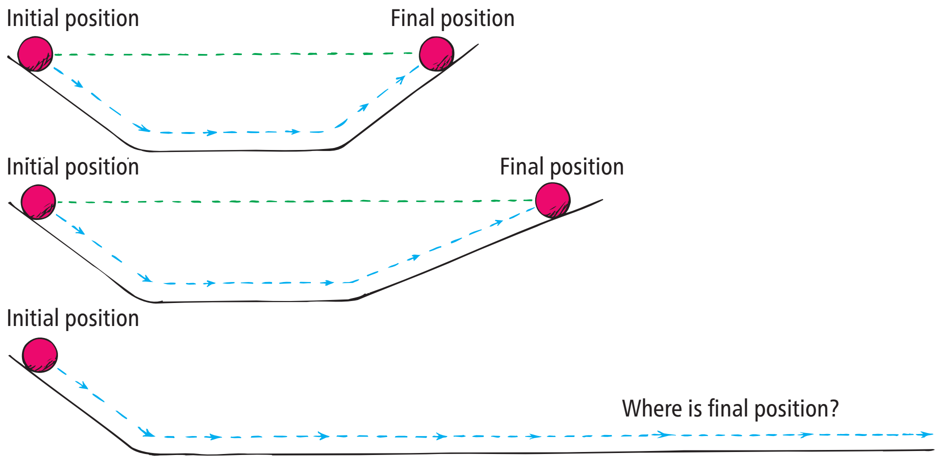


FIGURE 2.3
A ball rolling down an incline on the left tends to roll up to its initial height on the right. The ball must roll a greater distance as the angle of incline on the right is reduced.

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 the ball 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.**

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 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.

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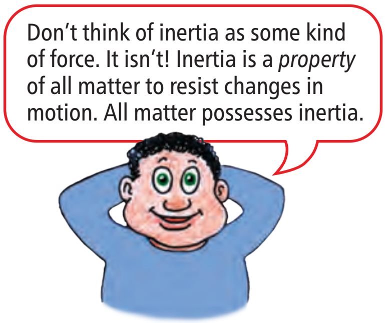
- Galileo published the first mathematical treatment of motion in 1632—12 years after the Pilgrims landed at Plymouth Rock.



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's death, 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 consider the first of Newton's laws, 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*.)

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

2.3 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 net external force.**

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. Or when riding your skateboard, you fly forward when it hits a curb that abruptly halts its motion. We stress that this property of objects to resist changes in motion is what we call inertia.

If an object is moving, it *continues* to move without turning or changing its speed. This is evident in space probes that continuously 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 external net forces, sometimes called unbalanced forces, a moving object tends to move along a straight-line path indefinitely.

FIGURE 2.4
Inertia in action.

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- Much of what you'll learn in this text is in the Check Points. They deserve your attention!

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

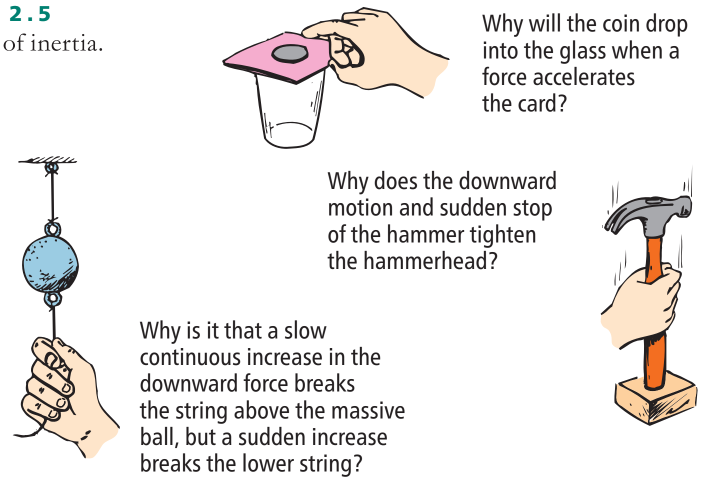
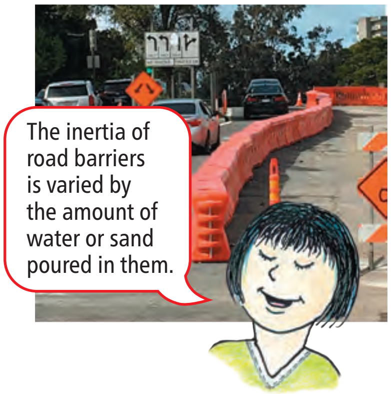


FIGURE 2.5
Examples of inertia.



CHECK POINT

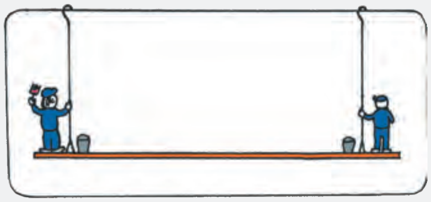
A hockey puck sliding across the ice finally comes to rest. How would Aristotle have interpreted this behavior? How would Galileo and Newton have interpreted it? How would you interpret it? *(Think before you read the answers below!)*

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 continues 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.

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.



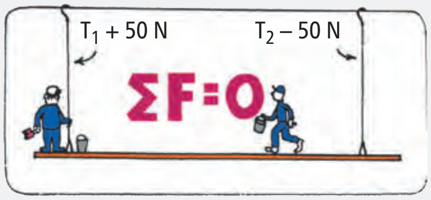
When I walked toward Burl to borrow one of his brushes, he asked if the tensions in the ropes had changed. Did the tension in his rope increase as I moved closer? We agreed that it should have, because even more of the load was supported by Burl's rope. How about my rope? Would its tension decrease? 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 that 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 *exactly* compensate the increase in tension 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.

We say that the forces on the scaffold balance to zero, which is saying that the net force on the scaffold is zero. In shorthand notation, $\sum \boldsymbol{F} = 0$.

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. Then 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 continued in spirited conversations until the time of his passing at age 93.

2.4 Net Force and Vectors

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 you both pull with equal forces in *opposite* directions, the net force is zero. The equal but oppositely directed forces cancel each other. One of the forces can be considered to be the negative of the other, and they add algebraically to zero, with a resulting net force of zero.

Figure 2.6 shows how forces combine to produce a net force on a box of cookies. 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 are 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. When the length and direction of such arrows are drawn to scale, we refer to the arrow as a **vector.**

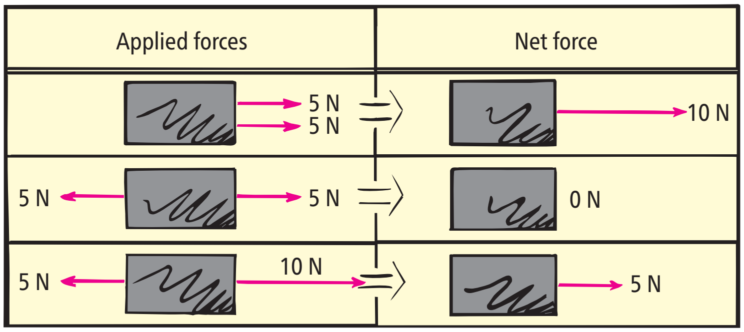


FIGURE 2.6
Net force (a force of 5 N is about 1.1 lb).

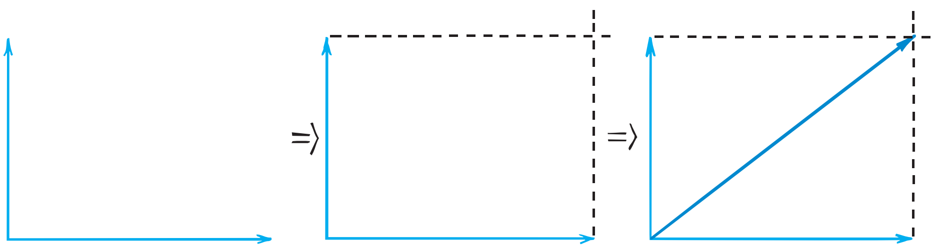
FIGURE 2.7
This vector, scaled so that 1 cm equals 20 N, represents a force of 60 N to the right.

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

Any quantity that requires both magnitude and direction for a complete description is a **vector quantity** (Figure 2.7). 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.

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 construct a parallelogram in which the two vectors are adjacent sides—the diagonal of the parallelogram shows the resultant. In Figure 2.8, the parallelograms are rectangles.

FIGURE 2.8
The pair of vectors at right angles to each other make two sides of a rectangle, the diagonal of which is their resultant.



In the special case of two vectors that are equal in magnitude and perpendicular to each other, the parallelogram is a square (Figure 2.9). 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.

More about vectors are in Chapter 5, in Appendix D at the end of this book, and in the *Practicing Physics* book. In the next chapter we'll discuss velocity vectors.

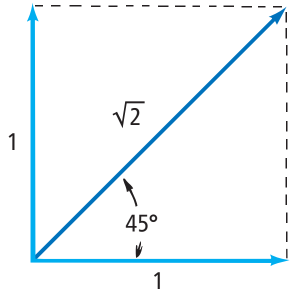


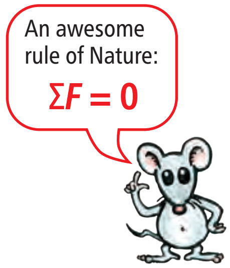
FIGURE 2.9
When a pair of equal-length vectors at right angles to each other are added, they form a square. The diagonal of the square is the resultant, $\sqrt{2}$ times the length of either side.

CHECK POINT

What is the net force of a pair of 1.0-N aligned vectors pointing in the same direction? When they point in opposite directions? When they are at right angles to each other?

CHECK YOUR ANSWERS

When aligned in the same direction, the net force is 1.0 N + 1.0 N = 2.0 N. When aligned in opposite directions, 1.0 N − 1.0 N = 0 N. When at right angles, net force is $\sqrt{[(1.0\text{ N})^2 + (1.0\text{ N})^2]} = \sqrt{2.0}\text{ N} = 1.4\text{ N}$, at a 45° angle.



2.5 The Equilibrium Rule

If you tie a string around a 2-pound bag of flour and hang it on a weighing scale (Figure 2.10), 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.

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

$$\Sigma F = 0$$

The symbol Σ stands for "the vector sum of" and $\boldsymbol{F}$ 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 to zero. (Vector quantities take direction into account, so if upward forces are +, downward ones are −, and, when added, they actually subtract.)

FIGURE 2.10
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.

[4]Something that is 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.

In Figure 2.11, we see the forces involved for Burl and Paul 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. The net force on the scaffold is zero, so we say it is in mechanical equilibrium.

Everything not undergoing changes in motion is in mechanical equilibrium. That's when $\sum F = 0$.

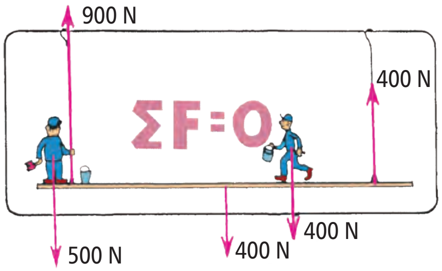


FIGURE 2.11
The sum of the upward forces equals the sum of the downward forces. $\sum F = 0$ and the scaffold is in mechanical equilibrium.

CHECK POINT

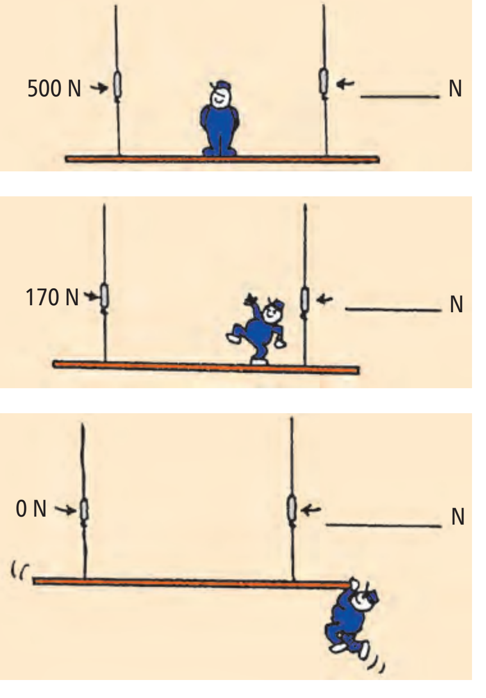
Red force vectors are shown in Figure 2.11. What is the sum of the two upward vectors that represent rope tensions? What is the sum of the three downward weight vectors? What is the vector sum of all vectors?

CHECK YOUR ANSWERS

The sum of the two upward vectors is 900 N + 400 N = 1300 N. The sum of the three downward vectors is 500 N + 400 N + 400 N = 1300 N. The sum of all vectors is 1300 N − 1300 N = 0, which means the system is in mechanical equilibrium.

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 end. 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 undergoes **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 $\sum F = 0$.

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 is, 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 $\sum F = 0$?

2.6 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 Earth's 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 zero. The net force on the book is zero. Another way to say the same thing is $\sum F = 0$.

To understand better that the table pushes up on the book, compare the case of compressing a spring (Figure 2.12). 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 2.13). The force with which you push down on the scale is due to gravity, your weight, which has the same magnitude as the floor's upward support force. When you are in equilibrium your weight equals the force of gravity acting on you.

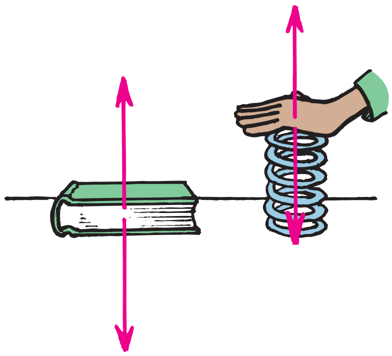


FIGURE 2.12
(Left) The table pushes up on the book with as much force as the downward force of gravity on the book. (Right) The spring pushes up on your hand with as much force as you exert to push down on the spring.

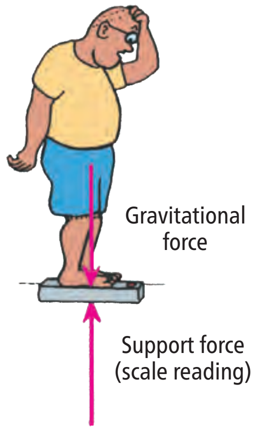


FIGURE 2.13
Your weight is the force you exert on a supporting surface, which when in equilibrium is the force due to gravity on you. The scale reading shows both your weight and the support force.

CHECK POINT

Suppose you stand on two bathroom scales with your weight evenly divided between the two scales. What will each scale read? How about if you stand with more of your weight on one foot than the other?

CHECK YOUR ANSWERS

The readings on both scales add up to your weight. This is because the sum of the scale readings, which equals the supporting normal force by the floor, must counteract your weight so the net force on you will be zero. That is, the vector sum $\sum F = 0$. If you stand equally on each scale, each will read half your weight. 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. For example, if one scale reads two-thirds your weight, the other scale will read one-third your weight. In whatever case, $\sum F = 0$. Get it?

[5]In geometry, "normal to" means "at right angles to." Since this force pushes up at right angles to the surface, it is called a "normal force."

A zero net force on an object doesn't mean that 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.

2.7 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 an object is at rest (static equilibrium) or steadily rolling in a straight-line path (dynamic equilibrium), $\Sigma \boldsymbol{F} = 0$.

It follows from Newton's first law that an object that is under the influence of only one force cannot be in equilibrium. The net force couldn't be zero. Only when two or more forces act on an object 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 (Figure 2.14). 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—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.

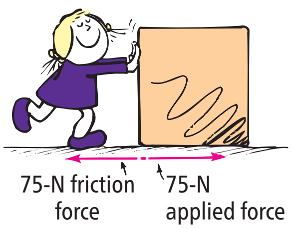


FIGURE 2.14
When the push on the crate is as great as the force of friction that the floor exerts on the crate, the net force on the crate is zero and it slides at an unchanging speed.

The equilibrium rule, $\Sigma \boldsymbol{F} = 0$, 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 an object is 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 propeller that pushes 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 propeller positive. Then the backward force of air resistance is negative. Since the plane is in dynamic equilibrium, can you see that the two forces combine to equal zero? Hence the plane neither gains nor loses speed.

2.8 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, drops vertically, 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 get 30 kilometers per second. Even if the bird could descend from its branch in 1 second, the worm would have been swept away by the moving Earth a distance of 30 kilometers. 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.

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 tree branch, the bird on the branch, the worm below, and even the air in between. All 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 horse-drawn 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.

FIGURE 2.15
Can the bird drop down and catch the worm if Earth moves at 30 km/s?

FIGURE 2.16
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!

CHECK POINT

China's bullet train travels at its top speed, 120 meters per second. If you jump upward in the aisle of the train for 0.5 second, why do you not land 50 meters from your starting point?

CHECK YOUR ANSWER

You land exactly at your starting point because during your half-second jump both the train *and you* cover the same straight-line distance. With no external force to change your horizontal motion, Newton's first law tells us that no horizontal change in speed occurs. Although your speed relative to the ground is 120 m/s, your speed relative to the train is zero. We'll say more about relative speeds in the next chapter.

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 the rules for motion in the heavens were very different from the rules for 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.

Chapter 2 Review

For instructor-assigned homework, go to:
www.masteringphysics.com

SUMMARY OF TERMS (KNOWLEDGE)

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.

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

Vector quantity A quantity that has both magnitude and direction, such as force.

Scalar quantity A quantity that has magnitude but not direction, such as mass and volume.

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

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 an object is at rest, the state of rest persists. If an object is moving, its 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, $\Sigma F = 0$.

READING CHECK QUESTIONS (COMPREHENSION)

Most chapters in this book conclude with a set of questions, activities, problems, and exercises. ***Reading Check Questions*** *are designed to help you comprehend ideas and catch the essentials of the chapter material. Answers can be found within the chapters.* ***Think and Do*** *activities focus on hands-on applications.* ***Plug and Chugs*** *are simple one-step problems for equation familiarization (although none in this chapter). Your math skills are applied to the* ***Think and Solve*** *problems, followed by* ***Think and Rank*** *tasks that prompt comparisons of the magnitudes of various concepts. The most important end-of-chapter items are* ***Think and Explains,*** *which stress synthesizing of material with focus on thinking rather than mere recall of information.* ***Think and Discuss*** *questions follow and, as the name implies, are meant to illicit discussions with your classmates. Put on your thinking cap and begin!*

2.1 Aristotle on Motion

1. Into which two main classes did Aristotle divide motion?
2. What state of motion did Aristotle attribute to Earth?
3. What was the main assumption on which Copernicus based his theory of the moving Earth?

2.2 Galileo's Experiments

4. What did Galileo discover in his legendary experiment on the Leaning Tower of Pisa?
5. What did Galileo discover about moving bodies and force in his experiments with inclined planes?
6. Is inertia the reason balls moving along a horizontal plane ultimately come to rest?

2.3 Newton's First Law of Motion

7. How does Newton's first law of motion relate to Galileo's concept of inertia?
8. Why do space probes continuously move in outer space?
9. How much force is required to keep a moving hockey puck in motion on a perfectly frictionless surface?

2.4 Net Force and Vectors

10. What is the net force on a block that is pulled to the right with 50 pounds of force and to the left with 60 pounds of force?
11. Can a certain force be negative?
12. What is the resultant of a pair of 20-pound forces at right angles to each other?
13. What is the resultant of a 40-N horizontal force and a 30-N vertical force?

2.5 The Equilibrium Rule

14. Can force be expressed in units of pounds and newtons?
15. What is the net force on an object that is pulled with 30 N to the right, 30 N to the left, 40 N upward, and 40 N downward?
16. A person is standing on a painter's scaffold. The right-hand scale reads a higher value than the left scale. Is he nearer the left scale or the right-hand scale?
17. What does it mean to say that something is in mechanical equilibrium?
18. State the equilibrium rule for forces in symbolic notation.

2.6 Support Force

19. A 500-g book lays at rest on top of your head. How much support force does your head provide to the book? What is the net force on the book?
20. When you stand at rest on a bathroom scale, how does your weight compare with the support force by the scale?

2.7 Equilibrium of Moving Things

21. A bowling ball at rest is in equilibrium. Is the ball in equilibrium when it moves at a constant speed along a curved path?

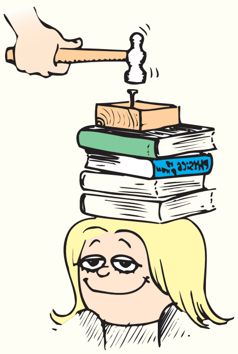
22. What is the net force acting on a body moving at a uniform velocity?
23. A block is being pushed with a force to make it slide at constant velocity. What is the role of friction in deciding the force needed?

2.8 The Moving Earth

24. A boy flips a coin in a moving car. Will he be able to catch the coin as it falls?
25. 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 move at 30 km/s, or does this speed become zero?
26. 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?

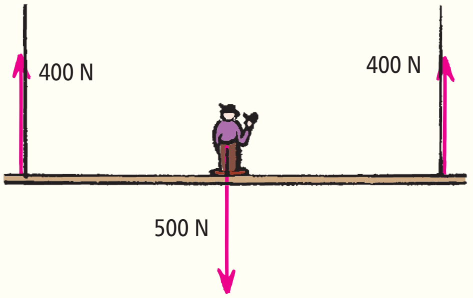
THINK AND DO (HANDS-ON APPLICATIONS)

27. Contact your grandparents and tell them about your experience with *Conceptual Physics* and the importance of knowing the rules of nature to better appreciate nature that surrounds us. Tell them that learning the equilibrium rule enhances the way you see structures, from tree branches to the frameworks in the construction of buildings.
28. Place a coin on top of a sheet of paper on a desk or table. Pull the paper horizontally with a quick snap. What concept of physics does this illustrate?
29. Ask a friend to drive a small nail into a piece of wood placed on a stack of books on the top of your head. Why doesn't this hurt you? (Be careful! Wear a helmet and safety glasses in case your friend misses.)

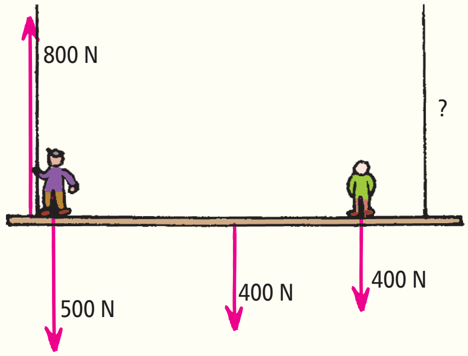


THINK AND SOLVE (MATHEMATICAL APPLICATION)

30. Consider two forces, 30 N and 40 N, applied to an object. Calculate the magnitude of the net force when: (a) the two forces have the same direction and (b) the two forces are perpendicular to each other.
31. A table rests on a floor without being pushed.
    (a) How much friction acts on it?
    (b) If the table is pushed horizontally with 100 N and doesn't slide, how much friction acts on it?
    (c) If a horizontal push of 120 N causes it to slide at constant speed, how much friction acts on it?
32. A person carrying a 10-kg box stands on a bathroom scale that reads 588 N. What are the person's weight and mass?
33. Judy weighs 640 N and stands with one foot on one bathroom scale and the other on a second bathroom scale. If one scale reads thrice as much as the other, find the readings on both scales.
34. The sketch shows a painter's scaffold in mechanical equilibrium. The painter weighs 500 N, and the tensions in each rope are 400 N. What is the weight of the scaffold?

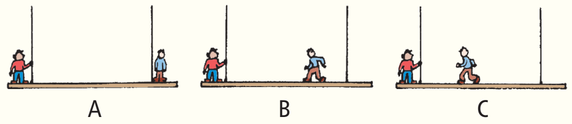


35. A 400 N scaffold supports two painters, one 500 N and the other 400 N. The reading in the left scale is 800 N. What is the reading in the right-hand scale?

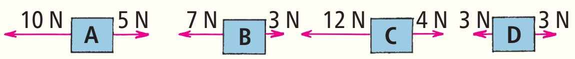


THINK AND RANK (ANALYSIS)

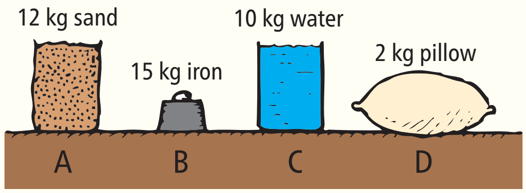
36. The weights of Burl, Paul, and the scaffold produce tensions in the supporting ropes. Rank the tension in the *left* rope, from most to least, in the three situations, A, B, and C.



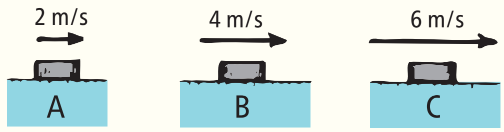
37. For the four situations, A, B, C, D, rank the net force on the block, from least to most.



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



39. Three pucks, A, B, and C, are shown sliding across ice at the noted speeds. Air and ice friction forces are negligible.
    (a) Rank the force needed to keep them moving, from greatest to least.
    (b) Rank the force needed to stop them in the same time interval, from greatest to least.

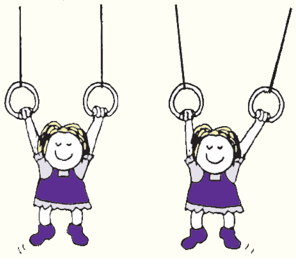


THINK AND EXPLAIN (SYNTHESIS)

40. Knowledge can be gained by philosophical logic and also by experimentation. Which of these did Aristotle favor, and which did Galileo favor?
41. A ball rolling along a floor doesn't continue rolling indefinitely. Is that because the ball is seeking a place of rest or because some force is acting upon it? If the latter, identify the force.
42. Copernicus postulated that Earth moves around the Sun (rather than the reverse), but he was troubled about the idea. What concept of mechanics was he missing (later introduced by Galileo and Newton) that would have eased his doubts?
43. What Aristotelian idea did Galileo discredit in his fabled Leaning Tower demonstration?
44. What Aristotelian idea did Galileo demolish with his inclined planes experiments?
45. Was it Galileo or Newton who first proposed the concept of inertia?
46. What keeps asteroids moving through space for billions of years?
47. A space probe may be carried by a rocket into outer space. What keeps the probe moving after the rocket no longer pushes it?
48. Why is it important to pull the tablecloth slightly downward when attempting to demonstrate the tablecloth pull in Figure 2.4 (What occurs if you pull slightly upward?)
49. Why is a sharp jerk more effective than a slow pull when tearing a paper towel or plastic bag from a roll?
50. Suppose you are in a car that is traveling on a straight path. Why do you feel an outward pull when the car navigates a sharp curve?
51. When a bus that is moving forward suddenly stops, the passengers are thrown forward. Explain why this happens.
52. Why do you seem to lurch forward in a bus that suddenly slows? Why do you seem to lurch backward when it picks up speed? What law applies here?
53. Consider a pair of forces having the same magnitude of 30 N. What are the maximum and minimum possible net forces for these two forces?
54. Is it safe to say that there is no force acting on an object if it experiences no net force?
55. Can an object be in mechanical equilibrium when only a single non-zero force acts on it? Explain.
56. A hockey puck at rest is in equilibrium. Is it in equilibrium if it slides across ice at constant velocity? Defend your answer.
57. A child is playfully tossed upward by his dad. When the child reaches the top of her trajectory where her speed reduces to zero, is she momentarily in equilibrium? Why or why not?
58. Can a basketball player halfway through a jump in midair be in equilibrium? Why or why not?
59. When you are standing still on the ground, you are in equilibrium. When you jump, your body momentarily stops at the highest point before going back down to the ground. Are you in equilibrium at that instance? Why or why not?

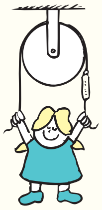
60. Is a vertically tossed ball at the top of its path undergoing a change in its velocity? Why or why not?

61. Nellie Newton hangs at rest from the rings attached by vertical ropes as shown. How does the tension in each rope compare with her weight?

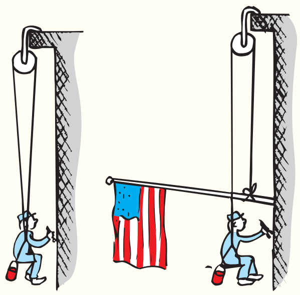


62. A book placed on top of a table is in equilibrium. (a) Is it safe to say that no force acts on it? (b) Or is it safe to say that no net force acts on it? Briefly explain your answer.

63. Nellie Newton hangs at rest from the ends of the rope as shown. How does the reading on the scale compare with her weight?



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



65. How many significant forces act on a book at rest on an inclined plane? Identify the forces.

66. You exert a force when you push your hands against a concrete wall. Why doesn't this force cause your hands to penetrate the wall?

67. 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?

68. If you jounce up and down while weighing yourself on a bathroom scale, the reading will fluctuate. Which fluctuates—the upward support force or the gravitational force on you? Why is your weight reading best shown when you stand at rest on the scale.

69. A bucket of water of weight W hangs steadily by a rope. Identify the forces acting on the bucket.

70. A tractor is pulling a sled horizontally, sliding at constant velocity with a 750-N force. What kind of friction exists between the surfaces of the sled and the ground? How much frictional force is acting on the sled?

71. If you push a crate across the floor in dynamic equilibrium with a force of 500 N, is the friction force between the surfaces of the crate and the floor greater than, less than, or equal to 500 N?

72. If you push a heavy cabinet across the floor at increasing speed with a force of 900 N, is the friction force between the surfaces of the cabinet and the floor greater than, less than, or equal to 900 N?

73. Emily Easygo 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?

THINK AND DISCUSS (EVALUATION)

74. A bowling ball rolling along a lane gradually slows as it rolls. How would Aristotle likely interpret this observation? How would Galileo interpret it?

75. In Figure 2.5 why does a slow continuous increase in pull break the string above the massive ball? And why does a sudden increase in pull break the lower string?

76. You are riding on a bullet train traveling at a constant velocity of 320 km/h, and you wonder why you can stand still without being thrown. What could explain this?

77. In answer to the question "What keeps Earth moving around the Sun?" a friend asserts that inertia keeps it moving. Discuss and correct your friend's erroneous assertion.

78. Your doormat at home becomes dirty and dusty. Using Newton's first law, explain briefly how can you quickly clean the doormat of dirt and dust.

79. A person is standing in the back of a truck that is initially at rest. When the truck suddenly starts to move forward, the person falls against the back of the truck. Using Newton's first law, discuss why this happens.

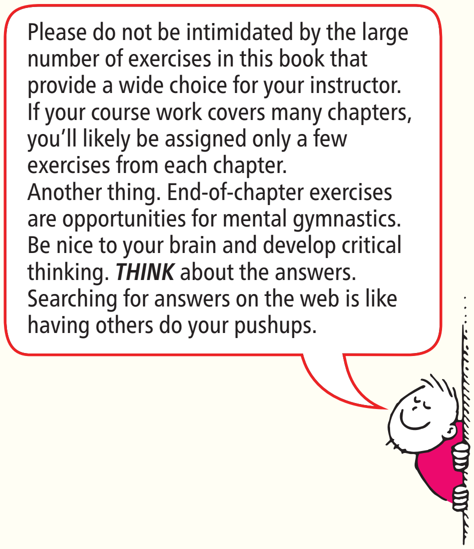
80. Suppose you hit a puck on a frictionless floor. Once released, will the puck continue to slide eternally, or it will come to rest?

81. When people push a stalled car, it moves. Does this violate Newton's first law of motion? Explain your reasoning.

82. Each bone in the skeletal 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.) Discuss why you think you are a little taller in the morning than at night.

83. Starting at rest, a box slides down an inclined plane and speeds up with time. Does this violate Newton's first law of motion? Explain your reasoning.

84. A book is at rest on a horizontal plane. If the inclination of the plane is increased while keeping the book at rest, does the magnitude of the normal force change? If yes, how? If not, why not?
85. When you press a book against a concrete wall, you feel a reaction force from the wall. Does this reaction force depend on friction? Briefly explain your reasoning.
86. A photographer aboard a helicopter cruising at constant velocity accidentally drops his camera. If air resistance is ignored, would the camera fall vertically and hit the ground at a distance equal to how far the helicopter had moved forward while the camera was falling, or would it hit the ground at a location right below the helicopter's position? Use Newton's first law to justify your answer.
87. 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?
88. 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?
89. Discuss and answer the preceding question for when the train is rounding a corner.
90. When a ball rolls down an inclined plane, it gains speed because of gravity. When a ball rolls up an inclined plane, it loses speed because of gravity. Why doesn't gravity play a role when it rolls on a horizontal surface?



CHAPTER TWO Multiple-Choice Practice Exam

Choose the BEST answer to each of the following:

1. According to Galileo, inertia is a
   (a) force like any other force.
   (b) special kind of force.
   (c) property of all matter.
   (d) concept attributed to Aristotle.

2. Galileo's use of inclined planes allowed him to effectively
   (a) slow down the ball's changes in speed.
   (b) reduce the time of the ball's changes in speed.
   (c) eliminate major changes in speed.
   (d) eliminate friction.

3. A space probe flying in remote space continues traveling
   (a) due to a force acting on it.
   (b) in a curved path.
   (c) even if no force acts on it.
   (d) due to gravity.

4. A hockey puck slides along an icy pond. Without any kind of friction, the force needed to sustain sliding is
   (a) none at all.
   (b) equal to the weight of the puck.
   (c) the weight of the puck divided by its mass.
   (d) the mass of the puck multiplied by 10 m/s^2.

5. What is the net force on a box of chocolates when pushed across a table with a horizontal force of 10 N while friction between it and the surface is 6 N?
   (a) 16 N
   (b) 10 N
   (c) 6 N
   (d) 4 N

6. The sum of the forces that act on any object moving at constant velocity is
   (a) zero.
   (b) 10 m/s^2.
   (c) equal to its weight.
   (d) about half its weight.

7. The equilibrium rule $\sum \boldsymbol{F} = 0$ applies to
   (a) objects or systems at rest.
   (b) objects or systems in uniform motion in a straight line.
   (c) both.
   (d) neither.

8. The tensions in each of the two supporting ropes that support Burl and Paul on opposite ends of a scaffold
   (a) are equal.
   (b) depend on the relative weights of Burl and Paul.
   (c) combine to equal zero.
   (d) none of the above

9. A man weighing 800 N stands at rest on two bathroom scales so that one scale shows a reading of 500 N. The reading on the other scale is
   (a) 200 N.
   (b) 300 N.
   (c) 400 N.
   (d) 800 N.

10. If you leap straight up inside a high-speed train while it gains speed, you land
    (a) slightly ahead of your original position.
    (b) at your original position.
    (c) slightly behind your original position.
    (d) none of the above

Answers and Explanations to Multiple-Choice Practice Exam

1. (c): By definition, inertia is a property of all matter. It is not a force in any regard. This is a definition, pure and simple. **2. (a):** Galileo lacked suitable time devises (clocks had not yet been invented) so he used small-angle inclines to look for a pattern of changes in a ball's downward motion—effectively slowing time. By successively increasing the angle of a plane to vertical, he found the acceleration of the ball to be that of free fall. **3. (c):** In accord with Newton's first law a body in motion tends to remain in motion in a straight-line path unless acted upon by a force. With no applied force, the space probe will move continuously. That's in accord with the law! **4. (a):** In accord with Newton's first law of motion, with no friction to overcome, the puck will slide indefinitely until it encounters a force. So no force is required for sustained motion. **5. (d):** The net force along the table is simply the vector sum of the horizontal forces 10 N − 6 N, which is 4 N. **6. (a):** In accord with Newton's first law, no force is needed for a moving object to continue moving. It will "move of itself."
7. (c): By definition, the equilibrium rule applies to objects at rest or in straight-line motion—both. **8. (b):** According to the equilibrium rule, the upward tensions must be equal and opposite to the combined weights of Burl and Paul, plus the weight of the scaffold. The tensions are not equal because the weights of Burl and Paul are not equal, nor do they combine to zero. What *does* combine to zero is the vector sum of upward forces (tensions in the two ropes) and downward forces of the weights the ropes support. **9. (b):** This is a numerical example of $\sum F = 0$. What number + 500 N = 800 N? Simple math tells you that number must be 800 N − 500 N = 300 N. **10. (c):** The train *gains speed* while you are airborne. Your horizontal component of speed during your jump remains the same as the speed *when* you jumped. While you are jumping the floor below gains speed, which means you'll land behind your original position.

CHAPTER THREE

3 Linear Motion

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2

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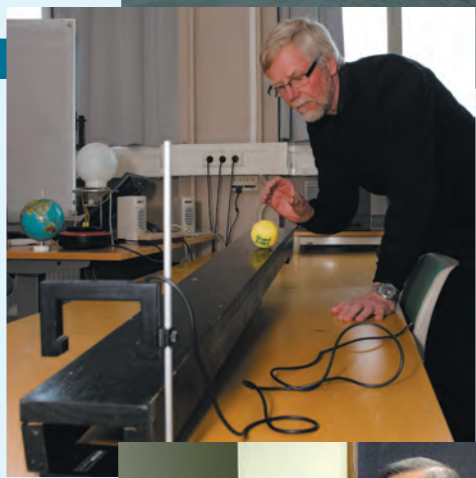

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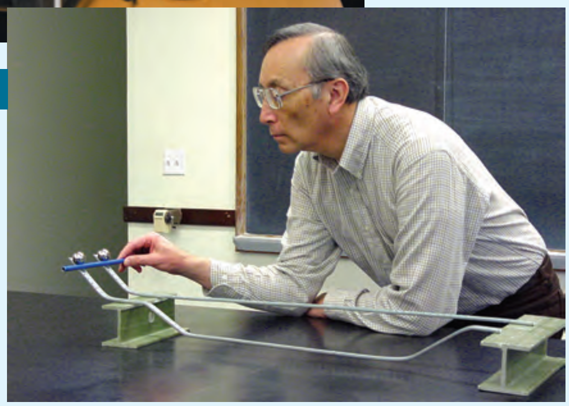


1 Dean Baird is a world traveler and nature photographer who enjoys sky diving, bungee jumping, and flightseeing. Here he's embarking on an air tour of Alaskan glaciers. **2** Sue Johnson (the first rower) and her crew win medals for high speed in their racing shell. **3** Carl Angell at the University of Oslo does what Galileo did some 400 years earlier, but with a photogate for measuring the ball's speed. **4** 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.

Dean Baird began his teaching career at Rio Americano High School in Sacramento, California, at the age of 21. He enjoyed teaching physics so much that he advertised his course to the student body so he could fill his schedule with physics classes every period of the day. His colleagues were surprised by the large enrollments in Dean's classes and the unprecedented success of Advanced Placement students on the national exams. As the photo shows, students enjoy Dean's teaching.

In addition to coaching science teams at his school, mentoring statewide workshops for new physics teachers, and serving as an appointed content expert on statewide science exams, he shares his lessons and observations via *The Blog of Phyz* and *phyz.org*. Since the early 2000s, he has authored my physics, physical science, and integrated science laboratory manuals. He is an accomplished photographer, contributing many photos to my books. He hauls his gear to the far corners of the world and hopes to see even more of it.

Dean has been recognized at the local, state, and national levels for outstanding service in physics education. He has been made a Fellow of the American Association of Physics Teachers and was honored with the Presidential Award for Excellence in Mathematics and Science Teaching during the Obama administration.

Dean's specialties as a teacher are curricular diversity and skepticism. He mixes labs, demos, presentations, simulations, and web video with critical thinking lessons to keep students engaged every day.

When it comes to linear motion, the topic of this chapter, Dean knows the trick is to cover the basics with engaging activities and demonstrations, but not to get bogged down in algebraic detail. Too many days spent on motion means less time later when the course gets to the wonder of the blue sky, the beauty of rainbows, and other high-interest topics. He paces his coverage of linear motion as a stepping stone to the delightful topics that await in the chapters beyond.

3.1 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.

ADDITIONAL RESOURCES
Videos
Screencasts

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

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

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) and 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 lists some approximate speeds in different units.[1]

TABLE 3.1
APPROXIMATE SPEEDS IN DIFFERENT UNITS

5 m/s =	11 mi/h =	18 km/h
10 m/s =	22 mi/h =	36 km/h
20 m/s =	45 mi/h =	72 km/h
30 m/s =	67 mi/h =	107 km/h
40 m/s =	89 mi/h =	142 km/h
50 m/s =	112 mi/h =	180 km/h

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

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

FIGURE 3.1
A speedometer gives readings in both miles per hour and kilometers per hour.

looking at its 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.

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.

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

Average speed can be calculated rather easily. For example, if we travel 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 distance traveled 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 at any particular moment.

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

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

If your average speed is 80 kilometers per hour on a 4-hour trip, for example, you travel a distance of 320 kilometers (80 km/h $\times$ 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 the answers in your mind? As mentioned in Chapter 2, when you encounter Check Point 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:

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

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

4. No, not if the trip starts from rest. There are times in which the instantaneous speeds are less than 80 km/h, so the driver must drive at speeds higher 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 highest instantaneous speeds.

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.

FIGURE 3.2
When you sit on a chair, your speed is zero relative to Earth but 30 km/s relative to the Sun.

CHECK POINT

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

CHECK YOUR ANSWER

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

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

3.2 Velocity

When we know both the speed and the direction of motion for an object, we know its **velocity.** Velocity combines the ideas of speed and direction of motion. For example, if a car travels at 60 km/h, we know its speed. But if we say the car travels 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.

Constant Velocity

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

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

Changing Velocity

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

CHECK POINT

1. **"She moves at a constant speed in a constant direction." Rephrase the same sentence in fewer words.**
2. **The speedometer of a car moving to the east reads 100 km/h. The car passes another car that is moving to the west at 100 km/h. Do both cars have the same speed? Do they have the same 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.

FIGURE 3.4
We say that a body is accelerating when its velocity is changing.

3.3 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 and in what direction velocity changes is **acceleration:**[2]

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

We are familiar with acceleration in an automobile. When the driver depresses the gas pedal (appropriately called the accelerator), the passengers experience acceleration (or "pickup," as it is sometimes called) as they are pressed against

[2]The phrases "change in" and "difference in" can be represented with the Greek symbol delta, Δ. Then we can express acceleration as $\frac{\Delta v}{\Delta t}$, where Δv is the change in velocity and Δt is the corresponding change in time. The expression gives *average acceleration*. Most accelerated motions treated in this book will be of constant acceleration.

their seats. The key idea that defines acceleration is *change*. Suppose we are driving and, in 1 second, we steadily increase our velocity from 30 kilometers per hour to 35 kilometers per hour, and then to 40 kilometers per hour in the next second, to 45 in the next second, and so on. We change our velocity by 5 kilometers per hour each second. This change in velocity is what we mean by acceleration.

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

In this case, the acceleration is 5 kilometers per hour second (abbreviated as 5 km/h · s), in the forward direction. Note that a unit for time enters twice: once for the unit of velocity and again for the time interval 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.

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?**

FIGURE 3.5
Rapid deceleration is sensed by the driver, who seems to lurch forward (in accord with Newton's first law).

CHECK YOUR ANSWERS

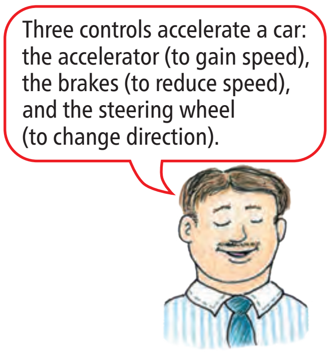
1. The acceleration is 9 km/h · s. Strictly speaking, this would be its average acceleration because there may have been some variation in its rate of picking up speed.
2. The accelerations of both the car and the bicycle are the same: 2 km/h · s.

$$\text{Acceleration}_{\text{car}} = \frac{\Delta v}{\Delta t} = \frac{65\text{ km/h} - 60\text{ km/h}}{2.5\text{ s}} = \frac{5\text{ km/h}}{2.5\text{ s}} = 2\text{ km/h}\cdot\text{s}$$

$$\text{Acceleration}_{\text{bike}} = \frac{\Delta v}{\Delta t} = \frac{5\text{ km/h} - 0\text{ km/h}}{2.5\text{ s}} = \frac{5\text{ km/h}}{2.5\text{ s}} = 2\text{ km/h}\cdot\text{s}$$

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

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

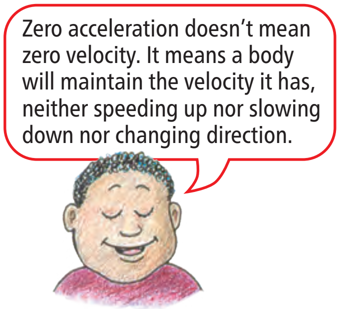


We accelerate whenever we move in a curved path, even if we are moving at constant speed, because our direction is changing every instant—hence, our velocity is changing. We distinguish speed and velocity for this reason and define *acceleration* as the rate at which velocity changes, thereby encompassing 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 one-way straight-line motion is being considered, it is common to use the terms *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 undergoes 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 the acceleration of the slower-moving skateboard is 5 km/h · s. Velocity and acceleration are very different concepts. Distinguishing between them is very important.

Why do we study idealized cases of balls on smooth planes and falling with no air resistance? Why this focus on idealized cases that don't occur in the everyday world? Few pure examples exist in nature, for most real situations involve a combination of effects. There is usually a "first order" effect that is basic to the situation, but then there are second, third, and even fourth or more order effects also. If we begin studying a concept by considering all effects together, before studying their contributions separately, understanding will be more difficult. Instead, we strip a situation of all but the first order effect, and then we examine that. After a good understanding, we then proceed to investigate the other effects for a fuller understanding. If Galileo hadn't freed his thinking from real-world friction, he might not have made his great discoveries about motion.

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—constant 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

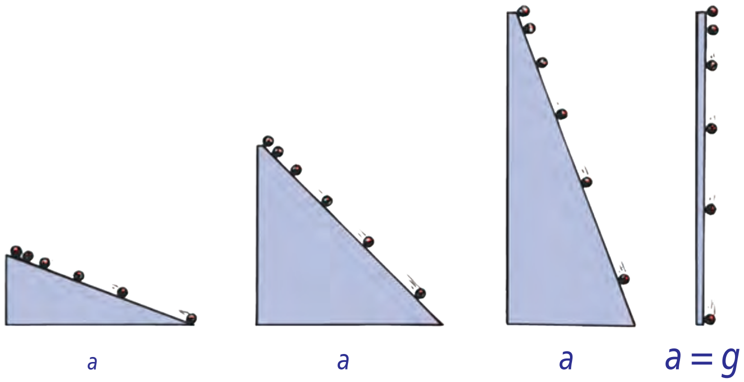


FIGURE 3.6
The steeper the slope of the incline, the greater the acceleration of the ball. What is the ball's acceleration if it falls vertically?

velocity of the ball at any given time after being released from rest is simply equal to its acceleration multiplied by the time:[3]

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

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 equal to the acceleration multiplied by the number of seconds it has been accelerating.

Galileo found that acceleration down each incline was constant for each incline, with 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 ignored, 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.

3.4 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.** Table 3.2 shows the instantaneous speeds 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). Again, we see 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

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	$10t$

[3]Note that this relationship follows from the definition of acceleration. For a ball starting from rest, $a = \Delta v/\Delta t$ can be written $a = v/t$ and then rearranged (multiplying both sides of the equation by t) to $v = at$.

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:

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

The instantaneous velocity v of an object falling from rest[4] 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.

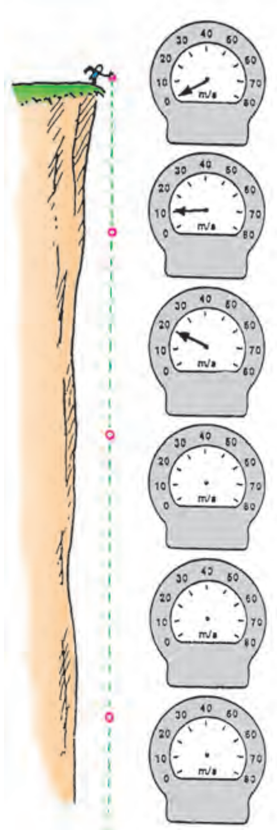


FIGURE 3.7
Pretend that a falling rock is equipped with a speedometer. In each successive second of fall, you'd find the rock's speed increasing by the same amount: 10 m/s. Sketch in the missing speedometer needle at $t = 3$ s, 4 s, and 5 s. (Table 3.2 shows the speeds we would read at various seconds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

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 ANSWERS

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 the object's 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 the object is moving upward or downward, its acceleration is 10 m/s^2 the whole time.

[4] If, instead of being dropped from rest, the object is thrown downward at speed v_o, the speed v after any elapsed time t is $v = v_o + at = v_o - gt$, with the positive direction upward.

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 the ball 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 is 4 seconds. We'll now treat how far it travels up and down.

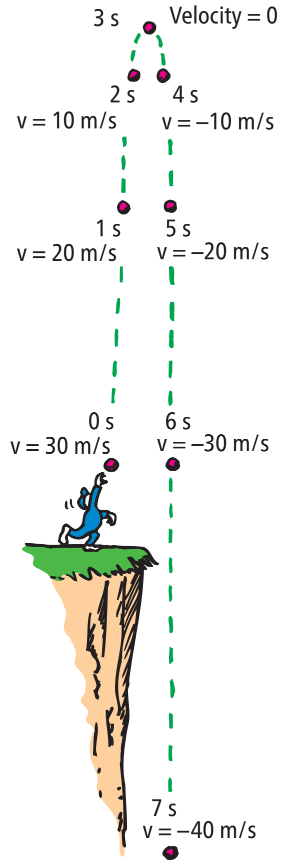


FIGURE 3.8
The rate at which the velocity changes each second is the same.

How Far

How *far* an object falls is entirely 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

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

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

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

in which d is the distance something falls when the time of fall in seconds is substituted for t and squared.[5] 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; 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 the total 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 successive seconds, it will fall through ever-increasing distances because its speed is continuously increasing.

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

[5]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.)

CHECK POINT

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

a. What is its speed on striking the ground?

b. What is its average speed during the 1/2 second?

c. How high is the ledge from the ground?

CHECK YOUR ANSWERS

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

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

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

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

Or equivalently,

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

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

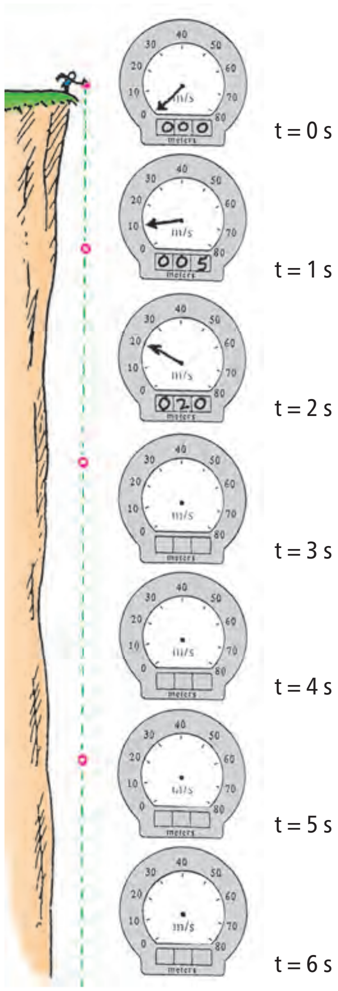


FIGURE 3.9
Pretend that a falling rock is equipped with a speedometer and an odometer. Each second, the speed readings increase by 10 m/s and the distance readings by $\frac{1}{2}gt^2$. Can you complete the speedometer positions and odometer readings?

Let's return to the rock equipped with a speedometer (Figure 3.9). For the first two seconds of free fall we see the readings for both speed and distance. Distances shown are 5 meters then 20 meters for the first two seconds of fall, which follow the $d = \frac{1}{2}gt^2$ rule. Can you figure the speed and distance readings from three to six seconds?

It is a common observation that many objects fall with unequal accelerations. A leaf, a feather, and 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 $d = \frac{1}{2}gt^2$ can be used to obtain a very good approximation for most objects falling in air from an initial position of rest.

Take some time to investigate Figure 3.11, which summarizes the essence of this chapter. In a nutshell, the distinction between speed and velocity is shown by car travel and airplane travel from San Francisco. Note how changes in speed affect acceleration by a car speeding up and slowing down, and then circling at a constant speed while accelerating around a circular track. A roller-coaster ride encompasses all. Acceleration is easiest to understand with the simple case of falling bodies.

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

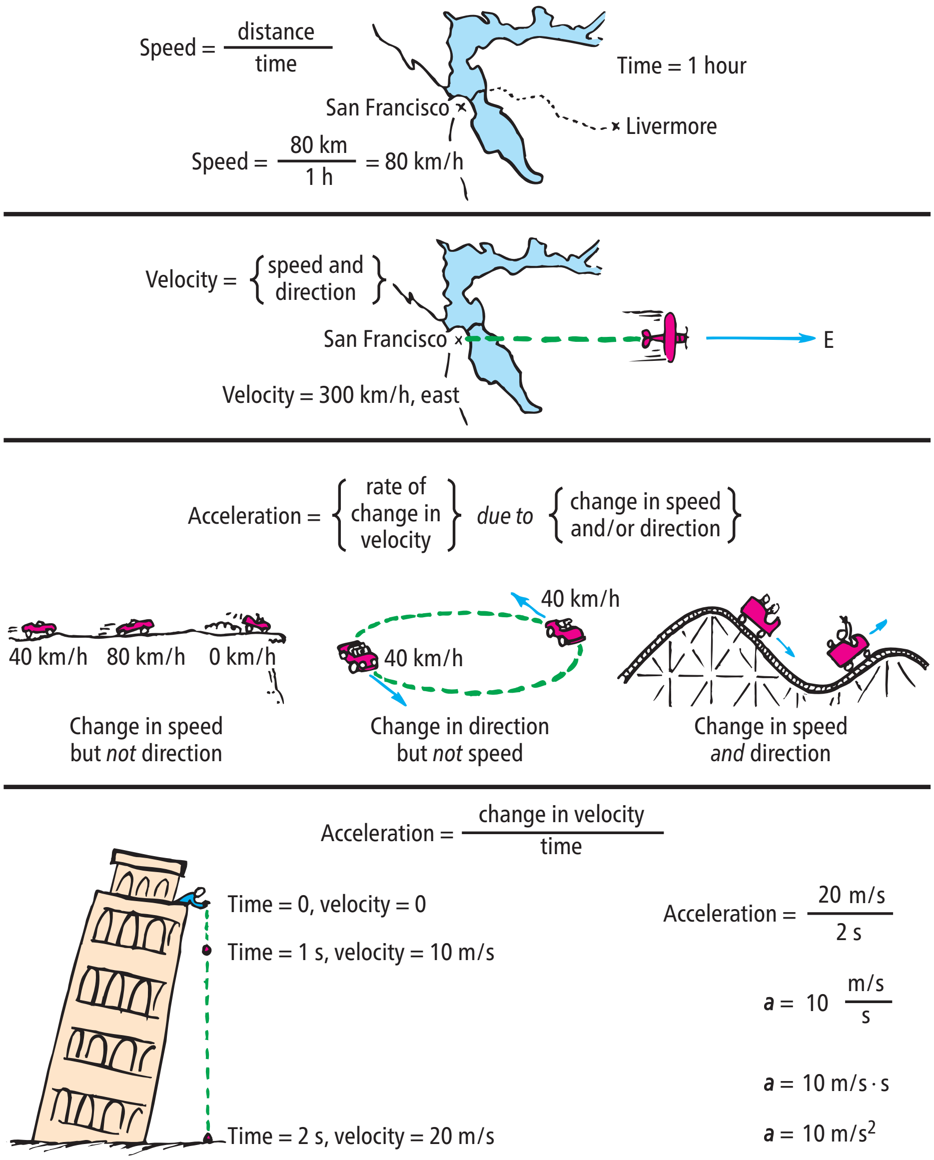
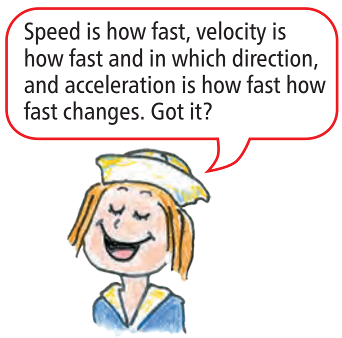


FIGURE 3.11
Motion analysis.

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 $d = \frac{1}{2}gt^2$. It is important to understand that 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. It is important to understand that acceleration is the rate at which velocity itself changes.



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 from 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 the greatest basketball stars can't raise their body 1.25 meters high, although they *can* 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. As soon as 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 the sum of rising and falling times. While you are 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

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

No basketball player is known to have attained a standing vertical jump of 1.25 meters. Setting d as 1.25 meters and using the more precise value of 9.8 m/s^2 for g, we solve for t, half the hang time, and 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 (since this is the time for one way of the up-and-down round trip) and we get a record-breaking hang time of 1 second.

We're discussing vertical motion from a standing position here. Running jumps are a different story. When a foot bounds from the floor when running, liftoff speed can be increased. Aha, the increased liftoff speed extends hang time. Either way, whether jumping from rest or running, the jumper's horizontal velocity while airborne remains constant and only the vertical "component" of velocity undergoes change. We will return to this when we treat projectile motion in Chapter 10. Interesting physics!

3.5 Velocity Vectors

Whereas 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. Speed is a scalar quantity and velocity is a vector quantity.

Acceleration is also a vector quantity. Acceleration always acts in the direction of net force. In Figure 3.12, notice the relative directions of the red acceleration vectors and blue velocity vectors as a car speeds up, slows down, and changes directions. We see that acceleration and velocity sometimes, but not always, act in the same direction.

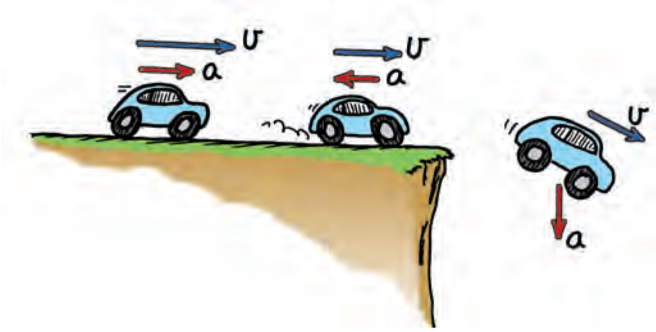


FIGURE 3.12
When you accelerate in the direction of your velocity, you speed up; when you accelerate against your velocity, you slow down; when you accelerate at an angle to your velocity, you change direction.

Vector thinking is important in swimming across a river, for there are two components of velocity to consider: your swimming velocity and the velocity of water flow in the river. To swim across, your swimming motion takes you straight to the opposite bank, but the current carries you along the direction of the river. The combination leads to a diagonal path downriver rather than to the point straight across.

The same is true of an airplane flying in a crosswind. An airplane flying at 120 km/h with no wind will cover 120 km in a one-hour flight. But if it is caught in a 90-km/h crosswind it will be blown off its intended course at an angle (Figure 3.13). The velocity vectors shown in the figure are scaled so that 1 cm represents 30 km/h. Thus, the 120-km/h velocity of the airplane is shown by the 4-cm vector, and the 90-km/h crosswind is shown by the 3-cm vector. The diagonal of the constructed rectangle measures 5 cm, which represents the resulting 150 km/h. So the airplane moves at 150 km/h relative to the ground in a direction rotated 37° from its intended direction.

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."

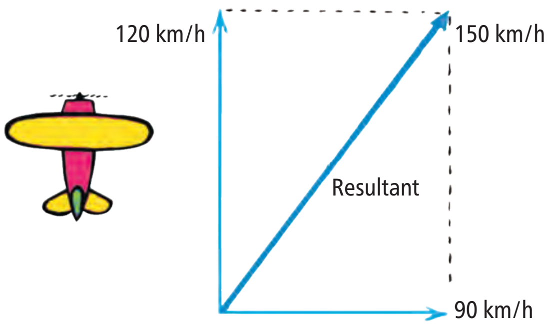


FIGURE 3.13
The 90 km/h crosswind blows the 120-km/h airplane off course at 150 km/h.

CHECK POINT

Suppose you swim at a steady speed of 4 m/s in still water. If you attempt to swim directly across a river that flows at 4 m/s, how fast will you be swimming relative to the shore?

CHECK YOUR ANSWER

Similar to the airplane blown off course, your path across the stream will be the diagonal of a square consisting of a pair of 4-m/s vectors at right angles to each other. Your resulting velocity will be $\sqrt{2}$ times the length of each 4-m/s side. So relative to the shore your swimming speed will be $\sqrt{2} \times 4\ \text{m/s} = 5.7\ \text{m/s}$.

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!

Chapter 3 Review

For instructor-assigned homework, go to:

www.masteringphysics.com

SUMMARY OF TERMS (KNOWLEDGE)

Speed How fast an object 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 An object's speed and direction of motion.

Vector quantity A quantity that has both magnitude and direction.

Scalar quantity A quantity that has only a magnitude, not a 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.

READING CHECK QUESTIONS (COMPREHENSION)

3.1 Speed

1. Differentiate between average speed and instantaneous speed.
2. What kind of speed is registered by an automobile speedometer—average speed or instantaneous speed?
3. What is the average speed, in kilometers per hour, of a car that covers a distance of 10 kilometers in 10 minutes?
4. How far do you travel moving an average speed of 80 km/h for 30 min?
5. As you read the words on this page in your chair, how fast are you moving relative to the chair? Relative to the Sun?

3.2 Velocity

6. Why is velocity a vector quantity?
7. Can an object moving with constant velocity move in a curved path?
8. If a car moving at a steady speed rounds a corner at 60 km/h, does it maintain a constant speed? Maintain a constant velocity? Defend your answers.

3.3 Acceleration

9. A car's velocity increases from 40 to 50 km/h in 10 s when it is moving along a straight path. What is its acceleration?
10. What is the acceleration of a car that maintains a constant velocity of 120 km/h for 10 s?
11. When are you more aware of motion in a vehicle—when it is moving steadily in a straight line or when it is accelerating?
12. 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?
13. What did Galileo discover about a ball's gain in speed when rolling down an inclined plane? What did he discover about the ball's acceleration?
14. What is the relationship between velocity and acceleration? If the acceleration of a ball is 3 m/s^2, what is its velocity 2 seconds after starting from rest?
15. How much acceleration occurs for a ball on an inclined plane raised to be vertical?

3.4 Free Fall

16. How many forces act on a freely falling object?
17. How much air resistance acts on a freely falling object?
18. What is the relationship between instantaneous velocity and *g* for a freely falling body?
19. What is the speed acquired by a freely falling object 2 seconds after being dropped from a rest position? Will your answer change if the object was not at rest?
20. The acceleration of free fall is about 10 m/s^2. Why does the unit second appear twice?
21. What is the direction of acceleration for a body thrown upward?
22. What is the relationship between distance traveled and time for a uniformly accelerated body?
23. What is the distance fallen for a ball in free fall 1 s after being dropped from a rest position? What is the distance for a 5-s drop?
24. How does friction affect the free fall of an object?
25. Consider these values: 10 m, 10 m/s, and 10 m/s^2. Which value is a measure of speed, which of distance, and which of acceleration?

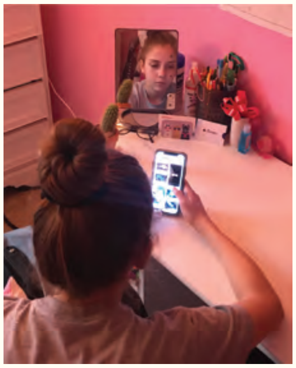
3.5 Velocity Vectors

26. How do speed and velocity differ?
27. Why will you swim faster directly across a river if the river flows at right angles to your intended path?
28. A bird flies at a particular speed in a crosswind that has the same speed. What part of a rectangle formed by velocity vectors represents the resultant speed?

THINK AND DO (HANDS-ON APPLICATIONS)

29. Your grandfather is interested in your educational progress. Without using equations, explain to him the difference between velocity and speed.

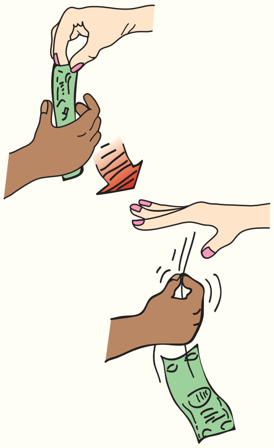
30. Use your smartphone to time how long it takes for a ball (or any object) to fall a given height. Do several trials and average the times. Use $d = \frac{1}{2}gt^2$ to see how close your answer matches the given height. Rearrange the equation to $g = 2d/t^2$ and see how close you get to 10 m/s^2 (or 9.8 m/s^2).



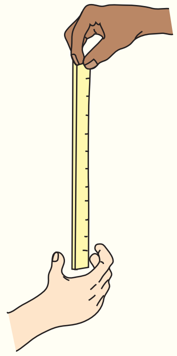
31. Test the accuracy of your *pedometer*, the step counter found in your smartphone or watch. Using a tape measure or meterstick, measure your stride—the distance between your feet when you step. Next, go for a walk while using the map app on your smartphone or watch and measure the distance of your walk. Then multiply the number of steps on your pedometer by your stride length. Did it match the distance that you measured?

32. Try this with your friends. Hold a dollar bill so that the midpoint hangs between a friend's fingers and challenge them to catch it by snapping their fingers shut when you release it. Your friend won't be able to catch it!

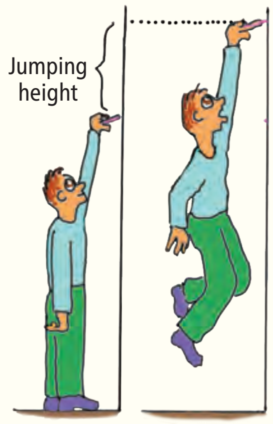
    Explanation: From $d = \frac{1}{2}gt^2$, the bill will fall a distance of 8 centimeters (half the length of the bill) in a time of 1/8 second, but the time required for the necessary impulses to travel from their eye to their brain to their fingers is at least 1/7 second.



33. Compare your reaction time with a friend's reaction time by catching a ruler that is dropped between your fingers. Have a friend hold the ruler as shown and you snap your fingers as soon as you see the ruler released. The number of centimeters that pass through your fingers depends on your reaction time. You can express this in fractions of a second by rearranging $d = \frac{1}{2}gt^2$. Expressed for time, $t = \sqrt{2d/g} = 0.045\sqrt{d}$, where d is in centimeters.



34. Stand flatfooted next to a wall. Make a mark on the wall at the highest point you can reach. Then jump vertically and make another mark. The distance between the two marks is your vertical jumping distance. Use this data to calculate your personal hang time.



PLUG AND CHUG (EQUATION FAMILIARIZATION)

These are "plug-in-the-number" one-step substitution type activities to familiarize you with the equations of the chapter. They are less challenging than Think and Solves.

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

35. A man walks 3.0 meters in 1.2 seconds. Calculate the speed at which he is walking.

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

36. Show that the average speed of a tortoise that covers a distance of 10 cm in 10 s is 0.01 m/s.

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

37. Calculate the acceleration of a car that starts from rest and reaches 120 km/h in 15 s.

38. Calculate the acceleration of a mongoose when it increases its velocity from rest to 21 m/s in 3 s.

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

39. If the average speed of a man is 0.9 m/s, then calculate the distance he covers in 10 s.

$$\textbf{Free-fall distance from rest: } d = \tfrac{1}{2}gt^2$$

40. Show that a freely falling rock drops a distance of 20 m when it falls from rest for 2 s.

THINK AND SOLVE (MATHEMATICAL APPLICATION)

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

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

43. A ball is tossed with enough speed straight up so that it is in the air for 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?

44. You toss a ball straight up with an initial speed of 20 m/s. How much time does it take to reach its maximum height (ignoring air resistance)?

45. Surprisingly, very few athletes can jump more than 2 feet (0.6 m) straight up. Use $d = \frac{1}{2}gt^2$ 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.

46. An airplane with an airspeed of 120 km/h lands on a runway where the wind speed is 40 km/h.
    (a) What is the landing speed of the plane if the wind is head on?
    (b) If the wind is a tailwind, coming from behind the airplane?
    (c) What would be the landing speed of the 120-km/h plane landing in a headwind of 120 km/h?

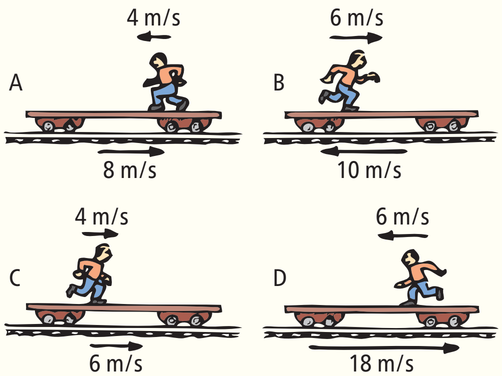
47. What is the speed over the ground of a mosquito flying 2 m/s relative to the air against a 2 m/s headwind?

48. What is the speed over the ground of a mosquito flying 2 m/s relative to the air caught in a 2 m/s right-angle crosswind?

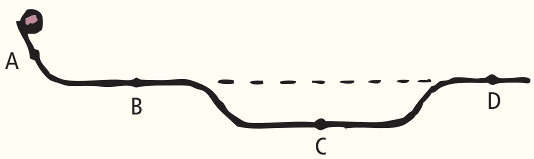
49. Show that the speed of a bird that flies 10 km/h in a crosswind of 10 km/h is about 14 km/h.

THINK AND RANK (ANALYSIS)

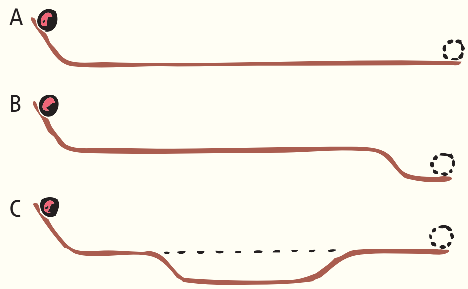
50. Jogging Jake runs along a train flatcar that moves at the velocities shown in positions A–D. Rank the velocity of Jake relative to a stationary observer on the ground from fastest to slowest. (Call the direction to the right positive.)



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

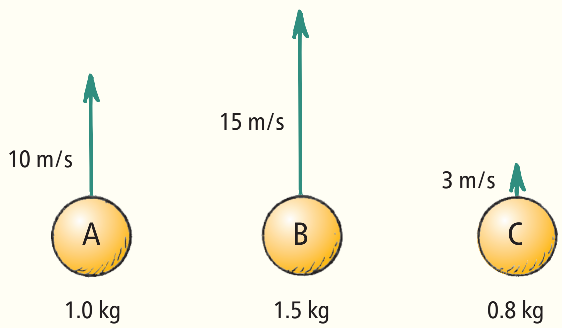


52. A ball is released at the left end of these different tracks bent from equal-length pieces of channel iron.



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

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



(a) Rank the speeds of the balls 1 s after being thrown from fastest to slowest.

(b) Rank the accelerations of the balls 1 s after being thrown from greatest to least. (Or are the accelerations the same?)

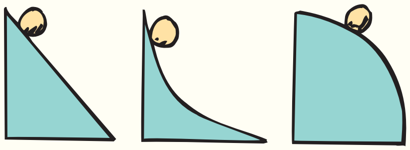
THINK AND EXPLAIN (SYNTHESIS)

54. Susan Burger can paddle a canoe in still water at 9 km/h. How successful will she be canoeing:
(a) upstream, and
(b) downstream in a river that flows at 9 km/s?
55. 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.
56. Reckless Rick is driving along the road at 80 km/h and bumps into Hapless Harry, who is directly in front of him and is driving at 88 km/h. What is the speed of the collision?
57. Does the speedometer of a car indicate its average speed or its instantaneous speed?
58. If you are driving at a constant speed on a hill that has serpentine curves, when you turn your car, (a) does its velocity change, and (b) do you accelerate in this process?
59. Name the parameters that tell you (a) how fast you can go and (b) how fast you can get fast.
60. A deer accelerates to a speed of 30 km/h, and a buck accelerates to a speed of 40 km/h. Can you comment on which animal underwent maximum acceleration? Justify your answer.
61. What is the acceleration of a car that moves at a steady velocity of 100 km/h for 10 s? Explain your answer noting this is a question in reading as well as physics.
62. Which is greater, accelerating 25 km/h to 30 km/h or 96 km/h to 100 km/h, both occurring during the same time? Defend your answer.
63. Suppose that a freely falling object were equipped with a speedometer. By how much would its reading in speed increase with each second of fall?
64. Suppose that the freely falling object were equipped with a speedometer and an odometer. Would the readings of the distance fallen each second indicate equal or different falling distances for successive seconds?
65. For an object in free fall, how does its acceleration vary with the distance it travels?
66. Extend Tables 3.2 and 3.3 to include times of fall of 6 to 10 s, assuming no air resistance.
67. A metallic bob is made to fall freely from the top of the Eiffel Tower (300 m). Compute its acceleration:
(a) after 100 meters fall from the starting point and
(b) 100 meters before reaching the ground.
68. How will air drag affect the readings on the falling speedometer?
69. Compare the acceleration of a ball tossed straight upward with a ball simply dropped, neglecting air resistance.
70. 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? What is the time required for rising compared to falling?
71. Billy Bob stands at the edge of a cliff (in Figure 3.8) and 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?
72. Billy Bob stands at the edge of a cliff and throws a ball nearly straight up at a certain speed and another ball nearly straight down with the same initial speed. If air resistance DOES affect the speed of the balls, which ball will have the greater speed when it strikes the ground below?
73. Why would it be dangerous to go outdoors on rainy days if there were no air resistance?
74. When you drive forward and apply your brakes, you have a positive velocity and negative acceleration. Cite a driving situation where you experience a negative velocity and a positive acceleration.
75. Why would a person's hang time be considerably greater on the Moon?
76. Why does a stream of water from a faucet get narrower as it falls?
77. If vertically falling rain makes 45-degrees slanted streaks on the side-door windows of a moving vehicle, how does the speed of the vehicle compare with the speed of the falling rain?

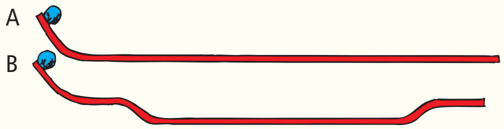
THINK AND DISCUSS (EVALUATION)

78. If you throw a ball vertically upward against gravity, comment on the directions of the velocity and acceleration.
79. For a linear motion, what does it indicate if the direction of acceleration is opposite to that of the velocity?
80. You observe the speedometer of the car while your mother is driving. If you notice that the speedometer reading remains at 80 km/h while driving on a highway, what would you say about the car's acceleration?
81. Correct your friend who says, "The racing car rounded the curve at a constant velocity of 100 km/h."
82. Can the speed of a ball be zero while its acceleration is not zero? Cite a common example to your classmates.
83. Give an example of something that undergoes acceleration while moving at constant speed. Can something undergo acceleration while traveling at constant velocity? Discuss with your classmates.

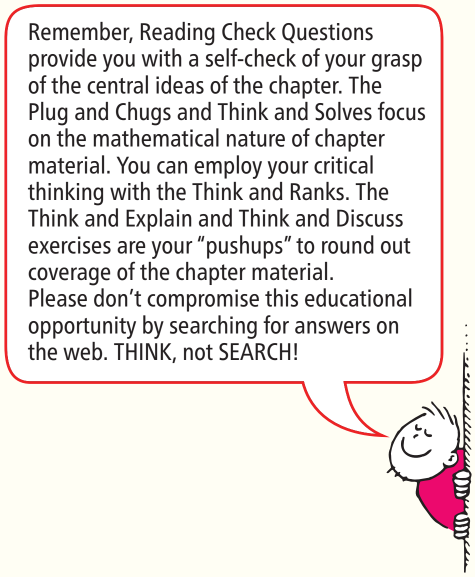
84. On which of these hills does the ball roll down with increasing speed and decreasing acceleration along the path? (Use this example if you wish to explain the difference between speed and acceleration.)



85. Which of the three balls on the hilltop shown in the above art start to roll simultaneously, and which will reach the bottom first? Discuss your explanation.
86. Be picky and correct your friend who says, "in free fall, air resistance is more effective in slowing a kilogram of fur than a 1-kilogram bar of iron."
87. If you drop a ball and air resistance is not a factor, its acceleration toward the ground is 10 m/s^2. Would its acceleration after throwing the ball downward be greater than 10 m/s^2? Why or why not?
88. Why might the acceleration of an object thrown downward through the air be appreciably less than 10 m/s^2? Discuss your reason with your classmates.
89. Suppose a car is heading north. Considering the traffic, the car slowed down, causing deceleration. Comment on the direction of acceleration of the car.
90. Madison tosses a ball straight upward, and Anthony drops a ball. Your discussion partner says both balls undergo the same acceleration. What is your response?
91. Two balls are released simultaneously from rest at the left end of equal-length tracks A and B as shown.
    (a) Which ball reaches the end of its track first?
    (b) On which track is the average speed greater?
    (c) Why is the speed of the ball at the end of the tracks the same?



92. We studied idealized cases of balls rolling down smooth planes and objects falling with no air resistance. A classmate complains that all this attention focused on idealized cases is worthless because idealized cases simply don't occur in the everyday world. What positive response can be made for studying ideal cases in nature?
93. Make up a multiple choice question that would check a classmate's understanding of the distinction between speed and velocity.
94. Make up a multiple choice question that would check a classmate's understanding of the distinction between velocity and acceleration.



CHAPTER THREE Multiple-Choice Practice Exam

Choose the BEST answer to each of the following:

1. If an object moves along a straight-line path at constant speed, then it must be
   (a) accelerating.
   (b) acted on by a force.
   (c) both of these.
   (d) neither of these.

2. The average speed of a ball rolling along a horizontal track will be increased if the track has a
   (a) small upward hump along it.
   (b) downward dip along it.
   (c) both the same if the hump and dip are opposites of each other.
   (d) not enough information

3. A mosquito flying at 2 m/s encounters a 2-m/s breeze blowing in the opposite direction, giving it a resulting speed over the ground of
   (a) 0 m/s.
   (b) 3 m/s.
   (c) 4 m/s.
   (d) 6 m/s.

4. Neglecting air resistance, when you toss a ball upward, by about how much does its upward speed decrease each second?
   (a) 10 m/s
   (b) 10 m/s^2
   (c) The answer depends on the initial speed.
   (d) None of these

5. The acceleration of a block of ice sliding down an inclined plane
   (a) increases with time.
   (b) decreases with time.
   (c) is practically constant.
   (d) need more information

6. During each second of free fall, the speed of a dropped object
   (a) increases by the same amount.
   (b) changes by increasing amounts.
   (c) remains constant.
   (d) doubles.

7. A freely falling object has a speed of 40 m/s at one instant. Exactly 1 s later its speed will be
   (a) the same.
   (b) 10 m/s.
   (c) 45 m/s.
   (d) greater than 45 m/s.

8. Mike stands at the edge of a cliff and throws one ball straight up and another ball straight down, both with the same speed. Neglecting air resistance, which ball hits the ground below with the greater speed?
   (a) The one thrown upward
   (b) The one thrown downward
   (c) neither, both hit with the same speed
   (d) need more information

9. Nellie steps off the edge of a table and lands on the floor below in ¼ second. The height of the table top above the floor is about
   (a) 1/3 m.
   (b) 1/2 m.
   (c) 3/4 m.
   (d) 1 m.

10. The vertical height attained by a basketball player who achieves a hang time of a full 1 s is about
    (a) 0.8 m.
    (b) 1 m.
    (c) 1.2 m.
    (d) 2.5 m.

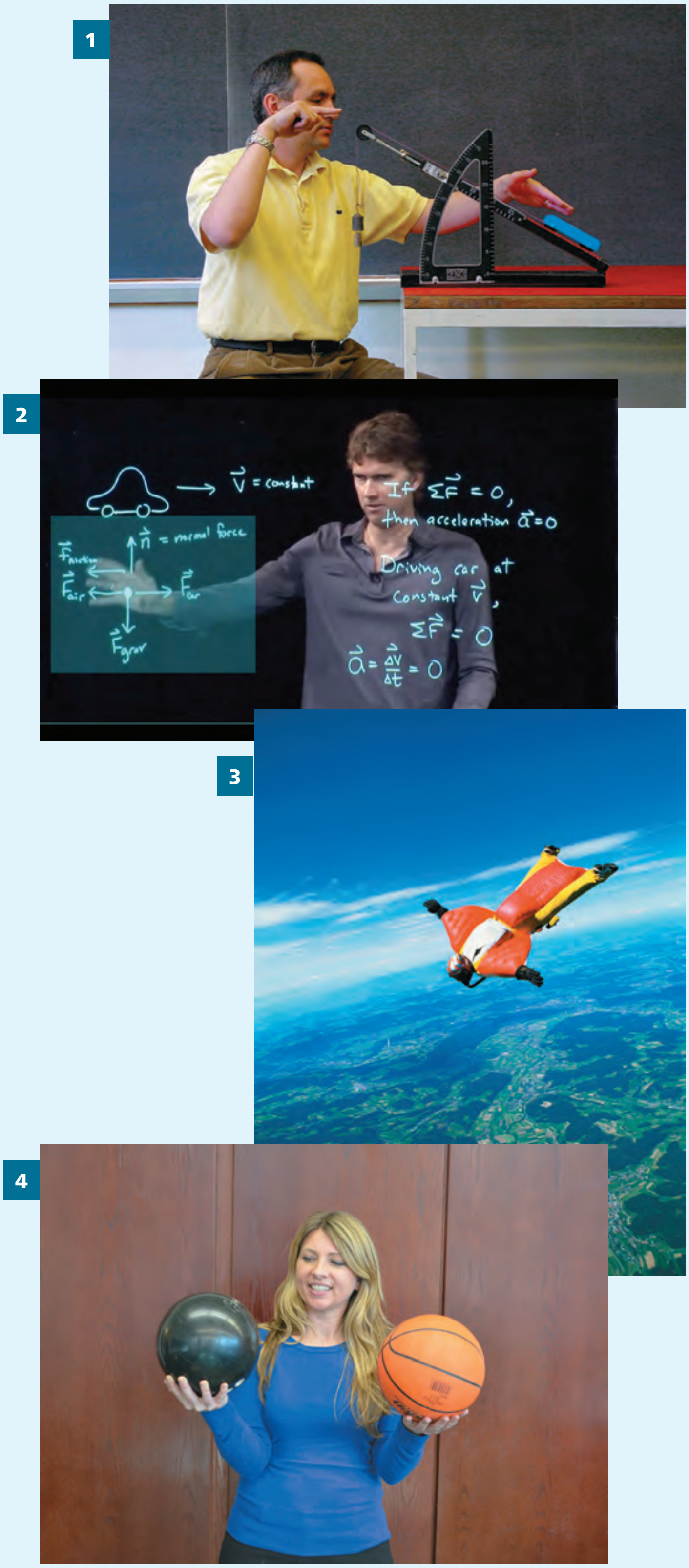
Answers and Explanations to Multiple-Choice Practice Exam

1. (d): Constant speed in a straight line means no net force and no acceleration in accord with the equilibrium rule. Only if the object were accelerating would a force be acting. So choice (d) is the answer. **2. (b):** The ball gains speed moving downward into the dip and loses the gain moving upward. Even so, everywhere in the dip its speed exceeds the speed along the horizontal part of the track. The upward hump decreases average speed. Hence the average speed along the entire track is increased by the presence of the dip. **3. (a):** The two speeds are relative to the ground; 2 m/s minus 2 m/s $=$ 0. The mosquito "hovers" at rest above the ground. **4. (a):** Without air resistance, the acceleration of the ball everywhere along its path is g, 10 m/s^2, which means the ball's change in speed is 10 m/s for each second, whatever its initial speed. So the correct answer is (a). Other choices are incorrect. Note that choice (b) is not a speed, but an acceleration, as evidenced by the second squared. **5. (c):** Speed or velocity changes with time, but not acceleration. If the ramp is friction-free without curves or obstructions, acceleration will be constant. **6. (a):** In free fall the acceleration of an object is a constant g, which tells us speed constantly changes by 10 m/s each second. So (a) is the correct answer. Choice (c) may incorrectly confuse acceleration g, a constant, with speed v that changes with time. Choice (b) would apply to falling distance, not speed. Choice (d) indicates a wild guess, ouch! **7. (d):** A freely-falling body near Earth's surface gains a speed of 10 m/s for each second of fall. One second after reaching a speed of 40 m/s, the speed would be 50 m/s, which isn't a choice. Choice (d), however, says "greater than 45 m/s," which is true, making choice (d) the best answer. **8. (c):** The speeds at ground level are the same, because when the ball thrown upward returns to its starting level, it will have its same initial speed as when thrown, which will also be the same speed as when thrown downward. So either way, both hit the ground below at the same speed, but at different times.
9. (a): Distance fallen from rest at a constant acceleration of 10 m/s^2 over a specific time is given by $d = \frac{1}{2}gt^2 = \frac{1}{2}\,(10\text{ m/s}^2)(1/4)^2 = 0.31$ m $\approx$ 1/3 m. This is a straight plug in using that equation. **10. (c):** Hang-time is calculated from $d = \frac{1}{2}gt^2$. For a full 1-s jump, time up $=$ time down, which is ½ s *either way. Then* $d = \frac{1}{2}gt^2 = \frac{1}{2}(10\text{ m/s}^2)(\frac{1}{2})^2 = 1.25$ m, close enough to 1.2 m that makes choice (c) the best answer.

CHAPTER FOUR

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** Matt Anderson invented this impressive Learning Glass to teach while facing his students. **3** Wingsuit flyers do what flying squirrels have always done, but faster. **4** Jill Evans asks her class why the heavier ball, when dropped, doesn't fall faster than the lighter ball.

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's second law links the fundamental concepts of acceleration and force to Galileo's concept of *mass,* given by the famous equation $a = F/m$. Interestingly, Isaac Newton first became famous not for his laws of motion or even for his law of universal gravitation. His fame began with his study of light, finding that white light was composed of the colors of the rainbow.

Isaac Newton was born prematurely on Christmas Day, 1642, and he 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; as a young teen, he was taken out of school to help manage his mother's farm. He had little interest in farming, 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 graduate from the University of Cambridge, without particular distinction.

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. Legend tells us that seeing an apple fall to the ground led him to consider the force of gravity extending to the Moon and beyond. He formulated and applied the law of universal gravitation to solving the centuries-old mysteries of planetary motion and ocean tides, which we'll return to in Chapter 9.

At the age of 26 Newton 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. It wasn't until Newton was 42 years of age that he included his three laws of motion in what is generally acknowledged as the greatest scientific book ever written, *Philosophiae Naturalis Principia Mathematica*.

When Newton was 46, his energies turned somewhat from science and he was elected to a one-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. He was also a member of 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 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. He was knighted by Queen Anne in 1705.

Newton died at the age of 84 and was buried in Westminster Abbey along with England's monarchs and heroes. His laws of motion provided the foundation for the Apollo Program, which 282 years later put humans on the Moon. His first law was the law of inertia, as we saw in Chapter 2. In this chapter we treat his second law of motion.

4.1 Forces

Quite simply, a **force** is a push or pull. The nature of a force may be gravitational, electromagnetic, or one of the interactions that occur between particles at the nuclear level. In Chapters 9 and 10 we'll focus on gravitational forces. In Part 5 we'll study electromagnetic forces, and in Parts 6 and 7 we'll treat the forces within the atomic nucleus. At a deep level, the simple act of kicking a ball involves all these forces. We'll skip over that depth for now and instead treat forces simply as common-sense pushes and pulls, which were good enough for Newton and will be quite adequate as we learn about Newton's three laws of motion.

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FIGURE 4.1
Kick the ball and it accelerates.

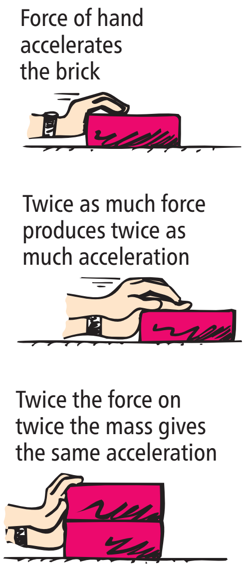

FIGURE 4.2
Acceleration is directly proportional to force.

Consider a hockey puck at rest on ice. Hit the puck (apply a force), and it briefly accelerates. When the hockey stick is no longer pushing it—that is, when no unbalanced forces act on the puck—it moves at constant velocity. Apply another force by striking the puck again, and again the motion changes. Unbalanced forces acting on an object cause the object to accelerate. Likewise for kicking a ball (Figure 4.1).

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 that an object's acceleration is directly proportional to the net force acting on it, and we write

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

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

CHECK POINT

1. **A jumbo jet cruises at a 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?**
2. **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?**
3. **If you push with the same increased force on the same crate 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. The acceleration is zero because the velocity is constant. Zero acceleration means zero net force, which means that the force of air resistance must be equal and opposite to the thrusting force of 100,000 N. The two horizontal forces cancel each other and motion of the aircraft continues unchanged. (Note we don't need to know the velocity of the jet. All we need to know is that velocity is constant, our clue that both acceleration and net force are zero.)
2. The crate will have four times as much acceleration.
3. The crate will have less acceleration because friction will reduce the net force.

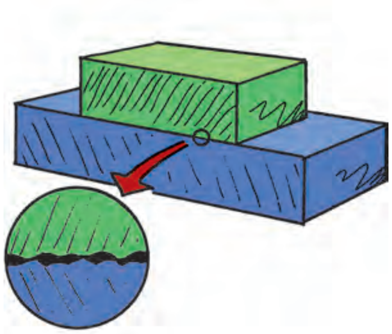

FIGURE 4.3
Friction results from surface irregularities and mutual attractions (stickiness) between atoms in the surfaces of sliding objects.

4.2 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 (Figure 4.3). 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 the direction that opposes 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 table at rest on a level floor. But if you push it a bit and it doesn't move, a force of friction between the table legs and the floor is produced (Figure 4.4). Still at rest, this tells you that the force of friction is equal and opposite to your push. The table is in static equilibrium. If you push a bit harder, the clinging force of friction may give way and the table slides.[1] If you push it horizontally at a steady speed in a straight-line path, it is in dynamic equilibrium. Your greater push is matched by greater friction. If you push harder and the table gains speed as it slides, then maximum friction exists between the table legs and the floor.

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. A pushed crate requires more force to get it going than 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 the friction is static friction, with more grab than sliding friction. But once the tires start to slide, the friction force is reduced—not a good thing. An antilock brake system keeps the tires below the threshold of breaking loose into a slide.

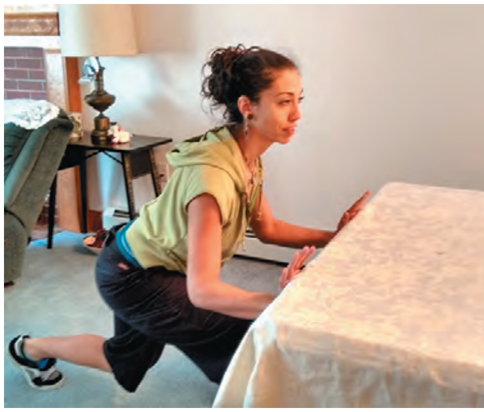

FIGURE 4.4
When Marie's push is as great as the force of friction between the table and the floor, the net force on the table is zero and it slides at an unchanging speed.

CHECK POINT

1. **Marie exerts a 100-N horizontal force on a table on the floor, and it doesn't slide. This indicates that 100 N isn't great enough to make the table slide. How does the friction force between the table and the floor compare with Marie's push?**
2. **She then pushes a little harder—say, with an extra 10 N—and the table still doesn't slide. How much friction acts on the table?**
3. **She pushes still harder, and the table moves. Once in motion, she finds that a push of 115 N is sufficient to keep the table sliding at a constant velocity. How much friction then acts on the table?**
4. **What net force acts on the sliding table when pushed with 125 N while the friction with the floor is 115 N?**
5. **In the above cases, when does *static friction* occur, and when does *sliding friction* occur? When does *no* friction occur?**

CHECK YOUR ANSWERS

1. The force of friction is 100 N in the opposite direction, which opposes motion that would occur otherwise. The fact that the table is at rest is evidence that $\Sigma F = 100\text{ N} - 100\text{ N} = 0$, static equilibrium.
2. The friction increases from 100 N to 110 N; again illustrating that $\Sigma F = 110\text{ N} - 110\text{ N} = 0$, static equilibrium.

[1]Even though it may not seem so yet, most of the concepts in physics are not really complicated. But friction is different; 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).

3. The friction acting on the table is 115 N, because constant-velocity motion means that $\Sigma F = 115\text{ N} - 115\text{ N} = 0$, dynamic equilibrium.
4. The net force is 10 N, because $\Sigma F = 125\text{ N} - 115\text{ N}$. In this case, the crate accelerates.
5. When the table is pushed and remains motionless, the force at the floor is *static friction*, which keeps it from sliding. When the table does slide, *sliding friction* occurs, whether velocity changes or it stays constant. No friction occurs when the table is at rest and no horizontal pushes act on it. A friction force occurs only when sliding or when an attempt to slide occurs.

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.

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 on a tire is 100 newtons at low speed, to a close approximation it is 100 newtons at a higher speed. The friction force may be greater when the tire is at rest and on the verge of sliding, but, once sliding, the friction force remains approximately the same.

More interesting still, friction does not depend on the area of contact. For a narrower tire the same weight is concentrated on a smaller area with no change in the amount of friction. 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. The 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.

Friction is not restricted to solids sliding or tending to slide 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 you ride a bicycle or ski downhill. Air resistance increases with increasing speed. A falling sack will reach a constant velocity when the air resistance balances the force due to gravity on the sack.

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.

CHECK POINT

What net force does a sliding crate experience when you exert a force of 110 N and the 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). The crate accelerates.

4.3 Mass and Weight

The acceleration imparted to an object depends not only on applied forces and friction forces but also on the inertia of the object, its resistance to changes in its motion. 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*. Our current understanding of mass delves into its source, the recently discovered Higgs boson. (Intriguing, indeed, and we'll touch on that in Chapter 32.) For now you'll first want to understand mass in its simplest sense—as a measure of the inertia of a material object. The greater the mass of an object, the greater its inertia.

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:** ***Usually the force upon an object due to gravity.***

We say *usually* in the definition of weight because an object can have weight when gravity is not a factor, such as occurs in a rotating space station. In any event, near Earth's surface and in the absence of acceleration, mass and weight are directly proportional to each other.[2]

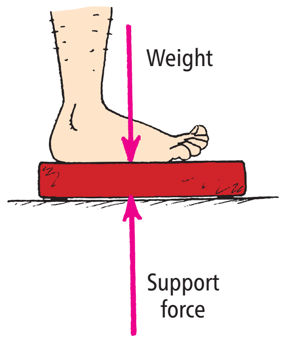

FIGURE 4.6
At equilibrium on a weighing scale, weight (*mg*) is balanced by an upward support force.

CHECK POINT

1. **Does a 2-kg iron block possess twice as much inertia as a 1-kg iron block? Twice as much mass as a 1-kg iron block? Twice as much volume as a 1-kg iron block? Twice as much weight as a 1-kg iron block weighed in the same location?**
2. **Does a 2-kg iron block possess twice as much inertia as a 1-kg bunch of bananas? Twice as much mass as 1-kg of bananas? Twice as much volume as 1 kg of bananas? Twice as much weight as a 1 kg of bananas when weighed in the same location?**
3. **How does the mass of a bar of gold vary with location?**

CHECK YOUR ANSWERS

1. The answer is yes to all of these questions. A 2-kg block of iron has twice as many iron atoms, and therefore twice the amount of inertia, mass, and weight. The blocks consist of the same material, so the 2-kg block also has twice the volume.
2. Two kilograms of anything has twice the inertia and twice the mass of 1 kg of anything else. Because mass and weight are proportional in the same location, 2 kg of anything will weigh twice as much as 1 kg of anything. Except for volume, the answer to all the questions is yes. Volume and mass are proportional only for the same material—for the same *density* (the same mass per volume). The density of iron is much greater than the density of bananas, so 2 kg of more-compact iron occupies less volume than 1 kg of bananas.
3. It varies not at all! The bar consists of the same number of atoms no matter what the location. Although its weight may vary with location, its mass is the same everywhere. That's why mass rather than weight is preferred in scientific studies.

[2]In Chapter 8 we'll discuss how the support force provided by rotation produces a *simulated gravity*, in which an astronaut in a rotating space habitat experiences weight.

The weight of an object of mass m due to gravity equals mg, where g is the constant of proportionality and has the value 10 N/kg (more precisely, 9.8 N/kg). Equivalently, g is the acceleration due to gravity, 10 m/s^2 (the unit N/kg is equivalent to m/s^2).

The direct proportion of mass to weight tells us that 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—their masses.

CHECK POINT

If you were a passenger in the International Space Station and were confronted with two cans, one filled with refried beans and the other empty, how could you determine which is full and which is empty?

CHECK YOUR ANSWER

Shake the cans back and forth! Or move both in any way, and you'll immediately judge which one has a greater resistance to changes in motion. The can of refried beans is harder to shake, so it has more inertia, which is to say it has more mass.

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 (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 that have weaker gravity than Earth. On the Moon's surface, for example, where the gravitational force on things is only one-sixth as strong as on Earth, a 1-kilogram brick weighs about 1.6 newtons (or 0.36 pound). On planets with stronger gravity,

[3]So 2.2 lb equal 9.8 N, or 1 N is approximately equal to 0.22 lb—about the weight of a small 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.