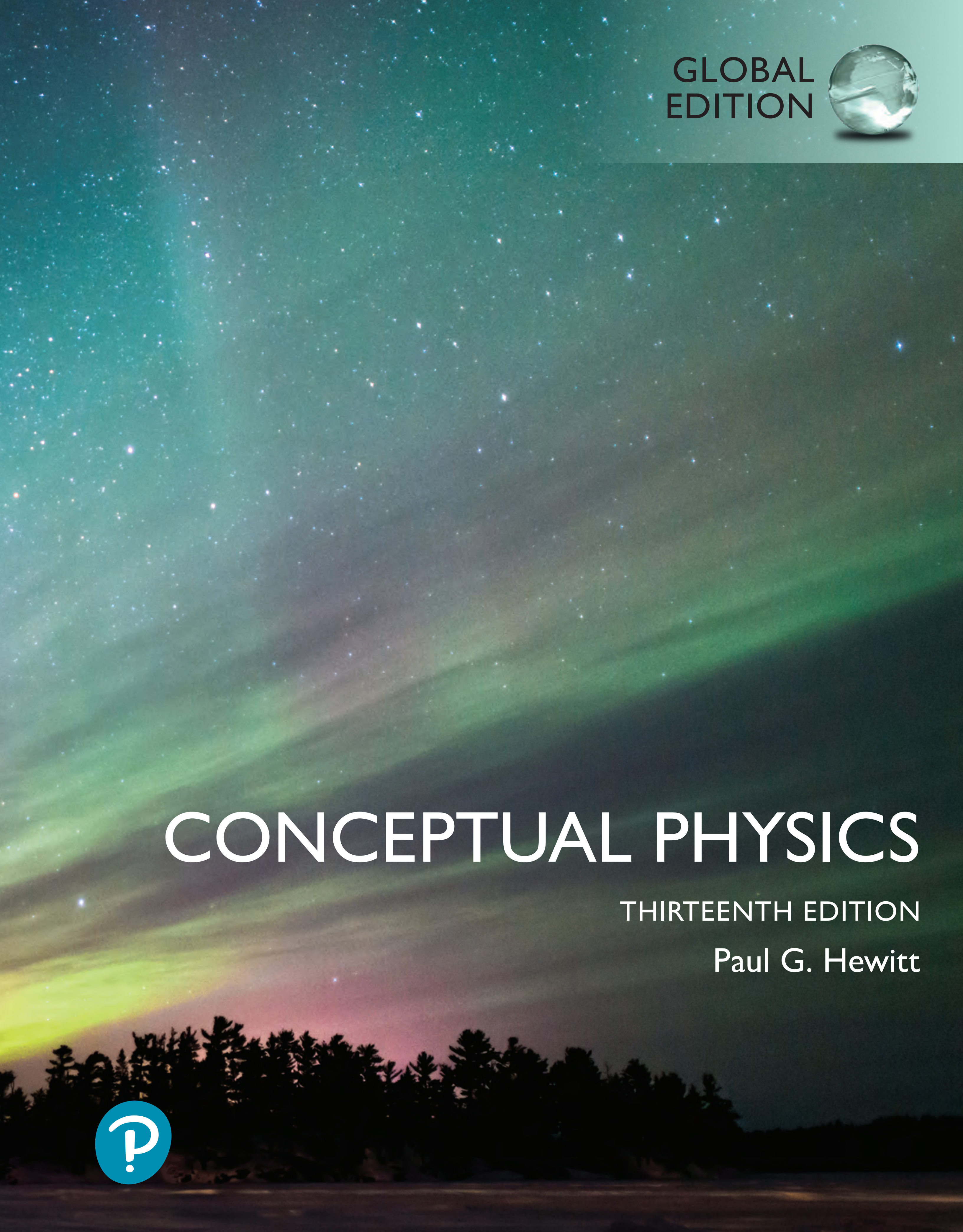

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Paul G. Hewitt

CONCEPTUAL
Physics

THIRTEENTH EDITION
GLOBAL EDITION

written and illustrated by

Paul G. Hewitt

City College of San Francisco

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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.

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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:

$$\varsigma = \varsigma_0 + \delta\backepsilon$$

$$\varsigma = \varsigma_0\backepsilon + \tfrac{1}{2}\delta\backepsilon^2$$

$$\varsigma^2 = \varsigma_0^2 + 2\delta\varsigma$$

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

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.

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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.

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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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Contributors:

Mark Gino Aliperio, *De La Salle University*
Pankaj Mohanty, *University of Johannesburg*
Mukesh Kumar, *University of the Witwatersrand*
Wayne Rowlands, *Swinburne University of Technology*
Abhishek Pandey, *University of the Witwatersrand*

Reviewers:

Ertugrul Demir, *Yeditepe Üniversitesi*
Iyabo Usman, *University of the Witwatersrand*
Joydeep Chowdhury, *Jadavpur University*
Susan Jacobs, *University of Johannesburg*
Kenneth Hong Chong Ming, *National University of Singapore*

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

1.1 Scientific Measurements
- How Eratosthenes Measured the Size of Earth
- Size of the Moon
- Distance to the Moon
- Distance to the Sun
- Size of the Sun
- Mathematics—The Language of Science

1.2 Scientific Methods
- The Scientific Attitude
- Dealing with Misconceptions

1.3 Science, Art, and Religion

1.4 Science and Technology

1.5 Physics—The Basic Science

1.6 In Perspective

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.

ADDITIONAL RESOURCES
Videos
Screencasts

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.

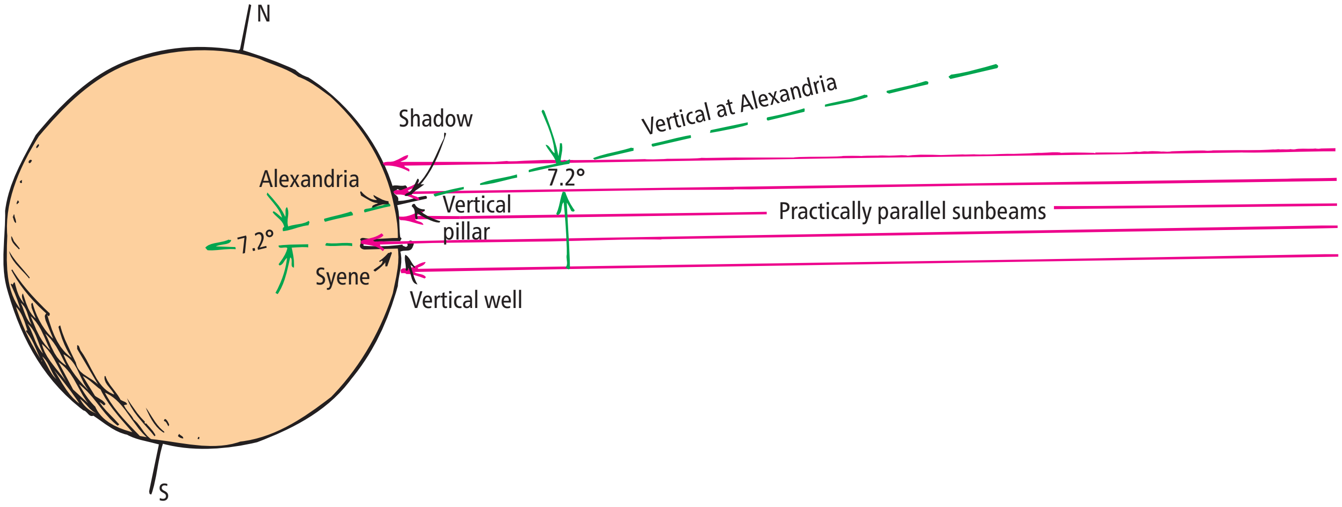


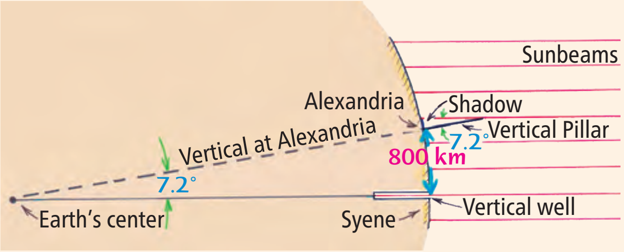
FIGURE 1.1

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 km) = 40,000 km, very close to the currently accepted value of Earth's circumference.

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 km) = 25,000 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.

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.

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.

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.

The shadows cast by any pair of vertical structures in sunlight, spaced a known distance apart, provide sufficient information for calculating Earth's circumference.

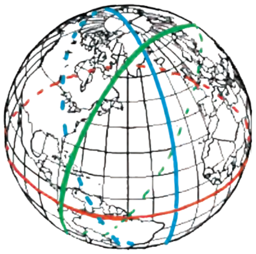


FIGURE 1.2
Three great circles, one at the equator (red), one along a line of longitude (blue), and another in a random direction (green).

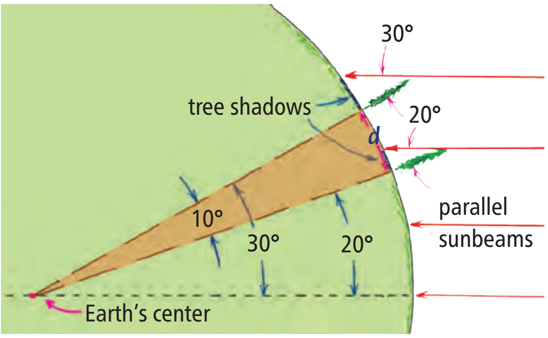


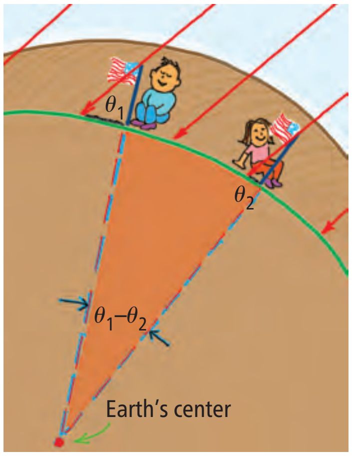
FIGURE 1.3
The two-tree arc *d* subtends an angle of 10° at Earth's center (shown by brown "wedge").

How many 10° segments of Earth make up a full 360° circumference of Earth? The answer is $360^\circ/10^\circ = 36$. 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.)

Eratosthenes' simultaneous readings were enabled by a shadow near a line of longitude on the summer solstice. With a smartphone he could have calculated Earth's size on any day along any of Earth's great circles, even the equator.



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!

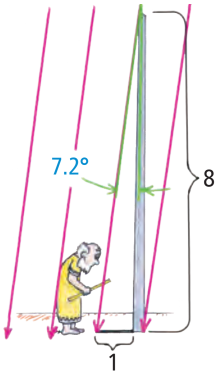


FIGURE 1.4
Two routes to the same solution.

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

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[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.

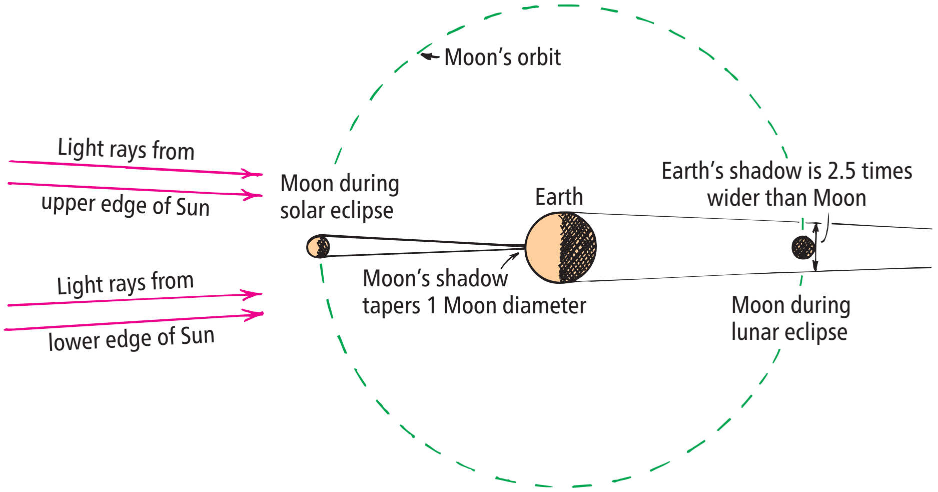


FIGURE 1.5
During a lunar eclipse, Earth's shadow is observed to be 2.5 times as wide as the Moon's diameter. Because of the Sun's large size, Earth's shadow must taper. The amount of taper is evident during a solar eclipse, where the Moon's shadow tapers a whole Moon diameter from Moon to Earth. So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

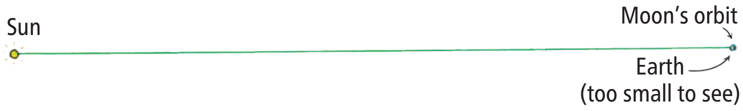


FIGURE 1.6
Correct scale of solar and lunar eclipses, which shows why a perfect lineup of the Sun, Moon, and Earth doesn't occur monthly. (Eclipses are even rarer because the Moon's orbit is tilted about 5° from the plane of Earth's orbit about the Sun.)

Distance to the Moon

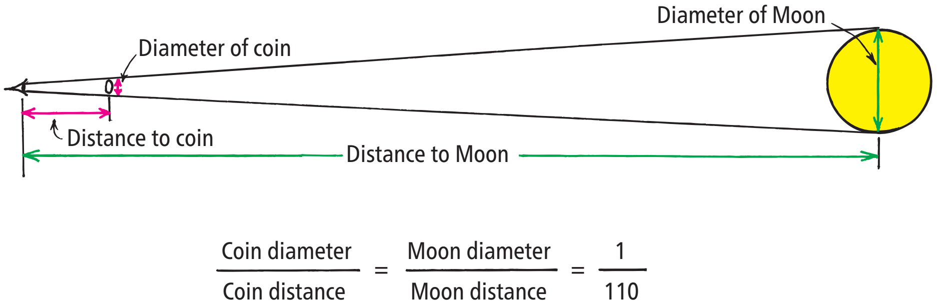
Tape a small coin, such as a dime, to a window and view it with one eye so that it just blocks out the full Moon. This occurs when your eye is about 110 coin diameters away from the coin. Then the ratio *coin diameter/coin distance* is about 1/110. Geometrical reasoning from similar triangles shows this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

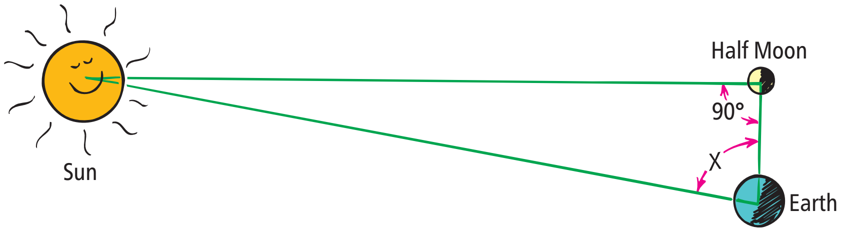


FIGURE 1.8
When the Moon appears exactly half full, the Sun, Moon, and Earth form a right triangle (not to scale). The hypotenuse is the Earth–Sun distance. By simple trigonometry, the hypotenuse of a right triangle can be found if you know the size of either nonright angle and the length of one side. 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.

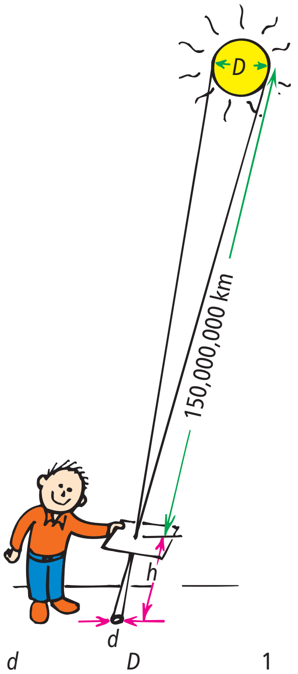
Today we know the Sun is an average of 150,000,000 kilometers from Earth. It is somewhat closer to Earth in early January (146,000,000 km) and somewhat farther away in early July (152,000,000 km).

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