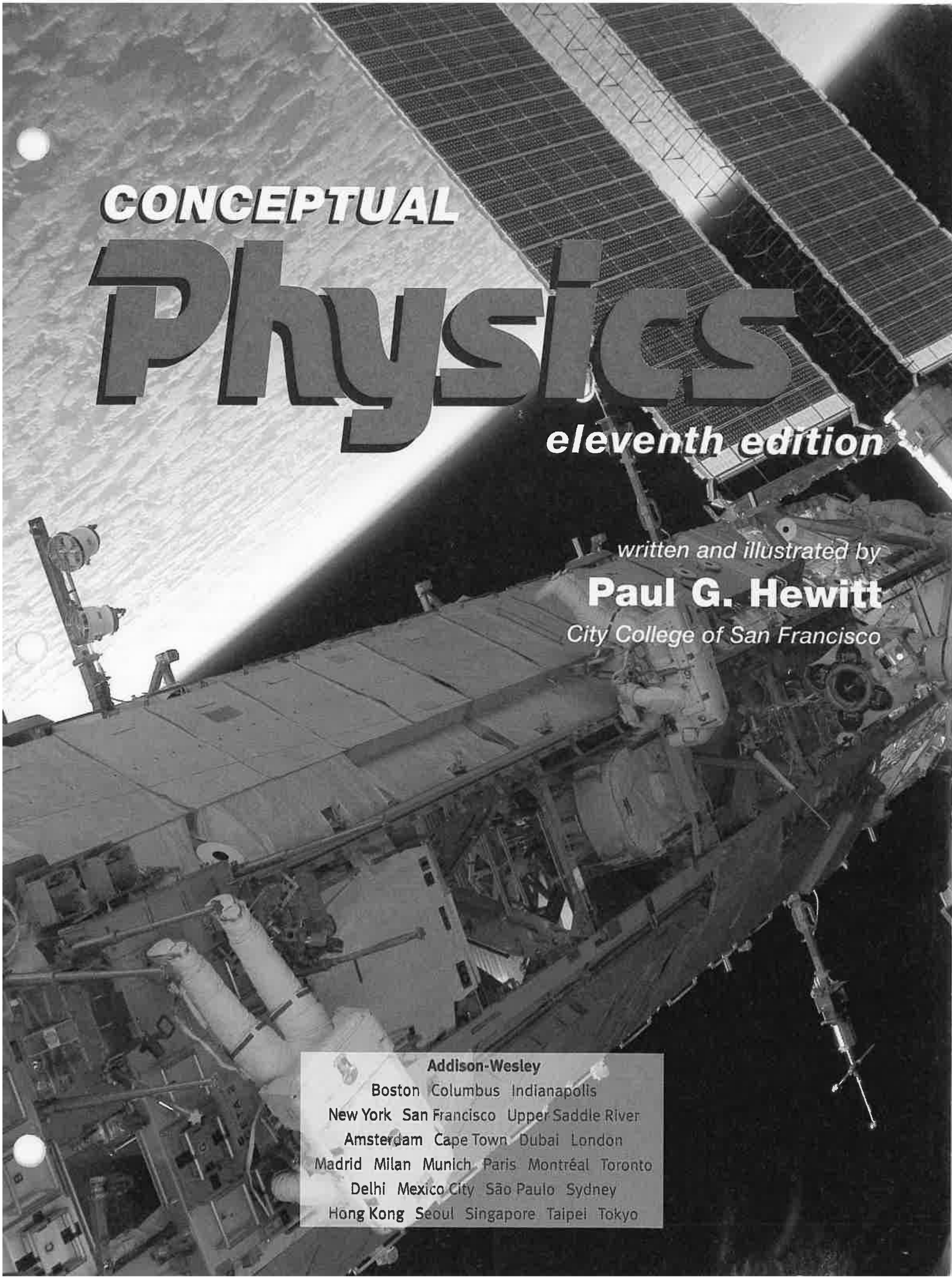
CONCEPTUAL Physics

eleventh edition

written and illustrated by
Paul G. Hewitt
City College of San Francisco



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

Contents in Brief

Contents in Detail

THE CONCEPTUAL PHYSICS Photo Album

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

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

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

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

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

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

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

Family photos begin with the touching photo on page 72 of son Paul and his daughter Grace. On page 79 is another photo that links touching to Newton's third law; my brother Steve with his daughter Gretchen at their coffee farm in Costa Rica. Steve's son Travis is seen on page 144, and his oldest daughter Stephanie on page 215. My son Paul is again shown on pages 287 and 319. Daughter-in-law Ludmila Hewitt holds crossed Polaroids on page 523. The endearing girl on page 202 is my daughter Leslie Abrams, earth-science co-author of *Conceptual Physical Science* textbooks. This colorized photo of Leslie has been a trademark of *Conceptual Physics* since the Third Edition. A more recent photo of her with husband Bob is on page 456. Their children, Megan and Emily, along with son Paul's children, make up the colorful set of photos on page 477. Granddaughter Emily is on page 520, and as mentioned, Megan on page 381. Photos of my late son James are on pages 140, 371, and 503. He left me my first grandson, Manuel, seen on pages 219 and 360. Manuel's grandmom, my wife Millie, who passed away in 2004, bravely holds her hand above the active pressure cooker on page 287. Brother Dave (no, not a twin) and his wife Barbara demonstrate atmospheric pressure on page 251. Their son Dave is on page 418, and grandson John Perry Hewitt is on page 259. Sister Marjorie Hewitt Suchocki, an author and emeritus theologian at Claremont School of Theology, illustrates reflection on page 489. Marjorie's son, John Suchocki, author of *Conceptual Chemistry,* now in its fourth edition, and chemistry co-author of the *Conceptual Physical Science* textbooks, walks fearlessly across hot coals on page 300 (for emphasis, David Willey does the same on page 310). Talented nephew John is also a vocalist and guitarist known as John Andrew in his popular CDs, seen with his guitar on pages 351 and 443. The group listening to music on page 375 are part of John's and Tracy's wedding party; from left to right, late Butch Orr, niece Cathy Candler (on page 124), bride and groom, niece Joan Lucas (on page 35), sister Marjorie, Tracy's parents Sharon and David Hopwood, teachers Kellie Dippel and Mark Werkmeister, and myself.

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

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

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

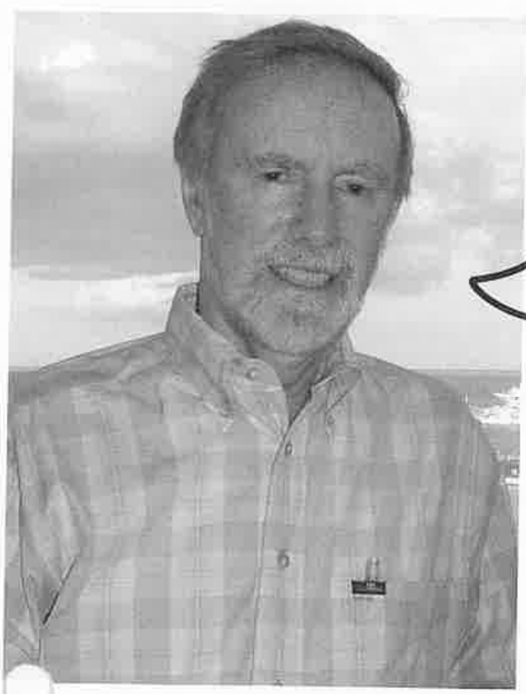
The inclusion of these people who are so dear to me makes *Conceptual Physics* all the more my labor of love.

To the Student

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

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

Enjoy your physics!



Paul G. Hewitt

To the Instructor

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

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

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

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

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

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

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

Chapter 5 continues with Newton's third law. The end of the chapter treats the parallelogram rule for combining vectors—first force vectors and then velocity vectors. It also introduces vector components. More on vectors is found in Appendix D, and especially in the Practice Book.

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

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

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

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

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

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

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

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

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

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

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

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

The **Laboratory Manual** that accompanies this edition provides a great variety of activities and lab exercises. Available for purchase.

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

The **Instructor Manual** for the textbook and *Laboratory Manual,* like previous ones, features demonstrations and suggested lectures for every chapter. It includes answers to the end-of-chapter material as cited above. If you're new to teaching this course, you'll likely find it enormously useful. It sums up the "what-works" in my quarter-century of teaching.

The **Instructor Resource DVD** provides a wealth of presentation tools to help support your instruction. It includes more than 100 video clips of my favorite classroom demonstrations, more than 130 interactive applets developed specifically to help you illustrate particularly tricky concepts, a full set of lecture outlines for each chapter in PowerPoint, and chapter-by-chapter weekly in-class quizzes in PPT for use with Classroom Response Systems (easy-to-use wireless polling systems that allow you to pose questions in class, have each student vote, and then display and discuss results in real time). The IR DVD also provides all the art and photos from the book (in high-resolution jpeg format), the Test Bank, Next-Time Questions, and the Instructor Manual in editable Word format.

For out-of-class help for your students, a critically acclaimed website found at http://www.physicsplace.com provides a wealth of study resources. The Physics Place is the most educationally advanced, most highly rated by students, and most widely used website available for students taking this course. The website includes students' favorite interactive online tutorials (covering topics that many of you requested), and a library of Interactive Figures (key figures from each chapter in the book that are better understood through interactive experimentation owing to reasons of scale, geometry, time evolution, or multiple representation). Through the website students can also access the Pearson eText, an online version of the text with highlighting, notes, and search functions, as well as media linked directly from the text. Videos, quizzes, flashcards, a glossary, and a wealth of other chapter-specific study aids are also provided.

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

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

What's New in This Edition

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

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

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

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

Acknowledgments

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

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

For valued suggestions carried over from previous editions, I thank my friends Dean Baird, Howie Brand, George Curtis, Marshall Ellenstein, Mona El Tawil-Nassar, Herb Gottlieb, Jim Hicks, Peter Hopkinson, John Hubisz, David Kagan, Dan Johnson, Juliet Layugan, Paul McNamara, Fred Myers, Kenn Sherey, Chuck Stone, Diane Riendeau, Pablo Robinson, Lawrence Weinstein, and Phil Wolf. 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 photos, in addition to my wife I thank Bob Abrams, Dean Baird, Keith Bardin, Howie Brand, Mark Clark, Anne Cox, Ken Ford, Burl Grey, my brother Dave Hewitt, my son Paul Hewitt, Ludmila Hewitt, Ron Hipschman, Suzanne Lyons, Will Maynez, Eric Muller, Fred Myers, Milo Patterson, Jay Pasachoff, Diane Reindeau, Roger Rassool, John Suchocki, and David Willey.

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

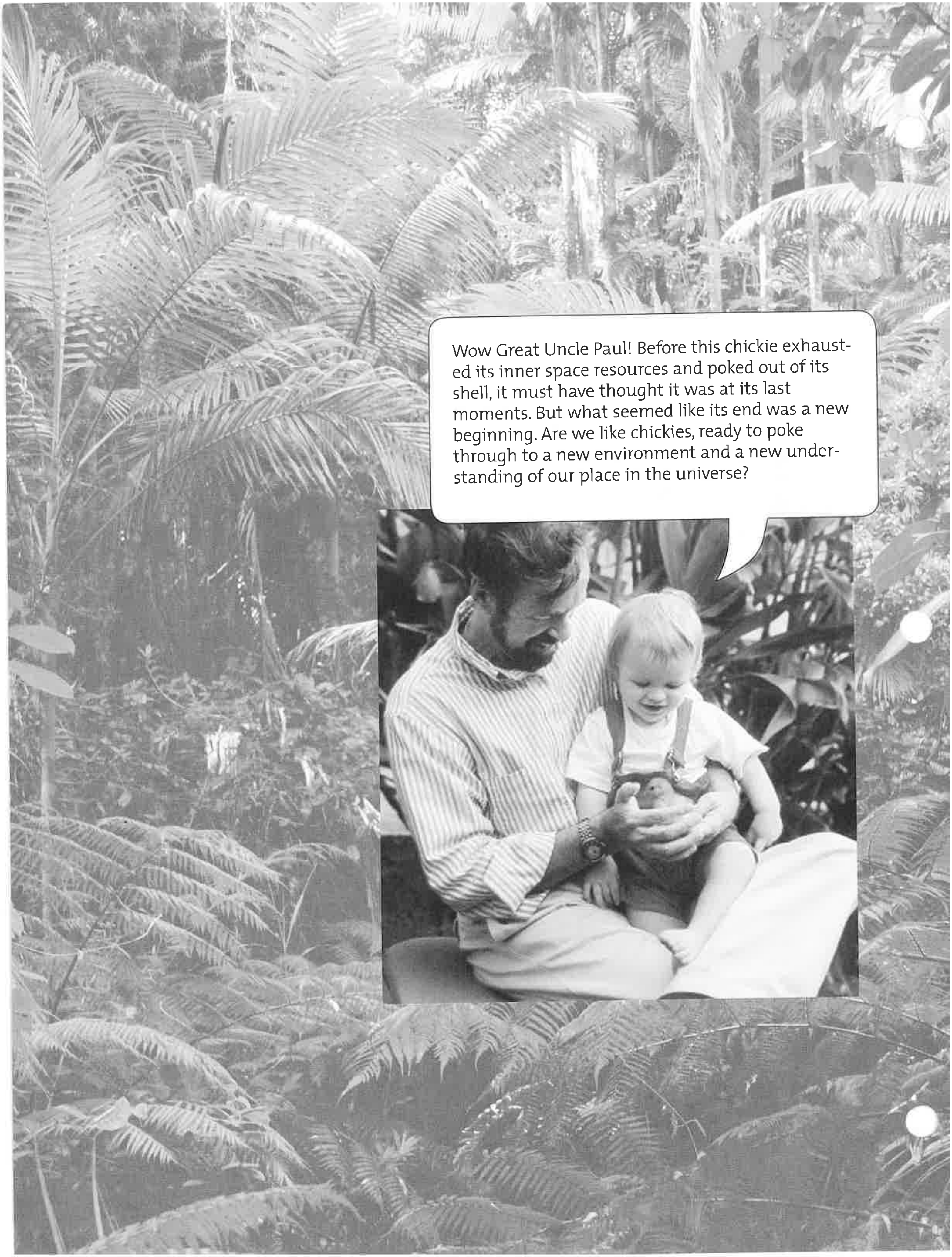
For the *Problem Solving in Conceptual Physics* ancillary, co-authored with Phil Wolf, we both thank Tsing Bardin, Howie Brand, George Curtis, Ken Ford, Herb Gottlieb, Jim Hicks, David Housden, Chelcie Liu, Evan Jones, Fred Myers, Stan Schiocchio, Diane Riendeau, and David Williamson for valuable feedback.

I am particularly grateful to my wife, Lillian Lee Hewitt, for her assistance in all phases of book-and-ancillary preparation. I'm grateful to my niece Gretchen Hewitt Rojas for keyboarding help. Thanks go to my lifelong friend Ernie Brown for designing the physics logo and for chapter headers in the new problems book.

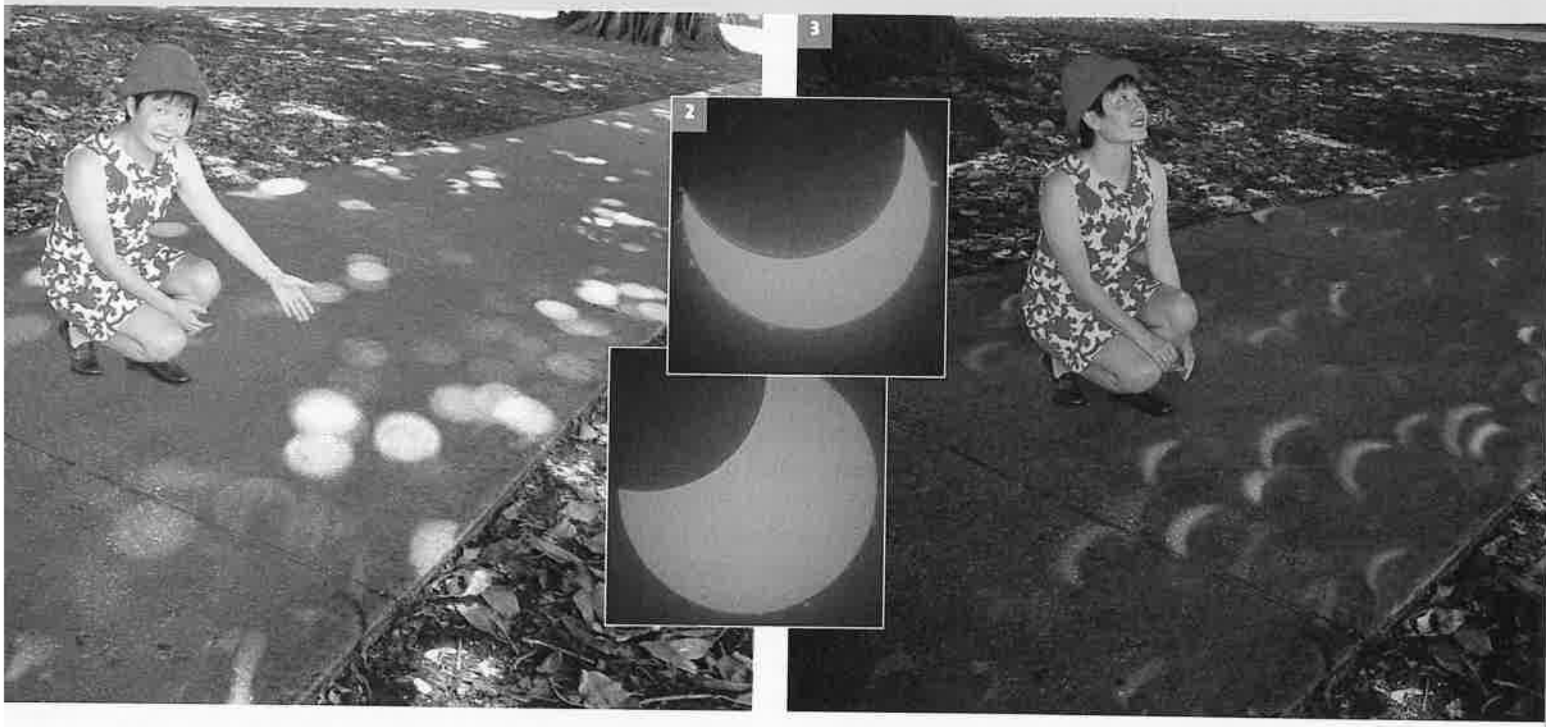
For their dedication to this edition, I am grateful to the staff at Addison Wesley in San Francisco. I am especially thankful to Chandrika Madhavan and Editor-in-Chief

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

Paul G. Hewitt
St. Petersburg, Florida


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

1 About Science



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

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

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

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

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, when people first discovered regularities and relationships in nature, such as star patterns in the night sky and weather patterns—when the rainy season started or when the days grew longer. From these regularities, people learned to make predictions that gave them some control over their surroundings.

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

Scientific Measurements

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

HOW ERATOSTHENES MEASURED THE SIZE OF EARTH

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

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

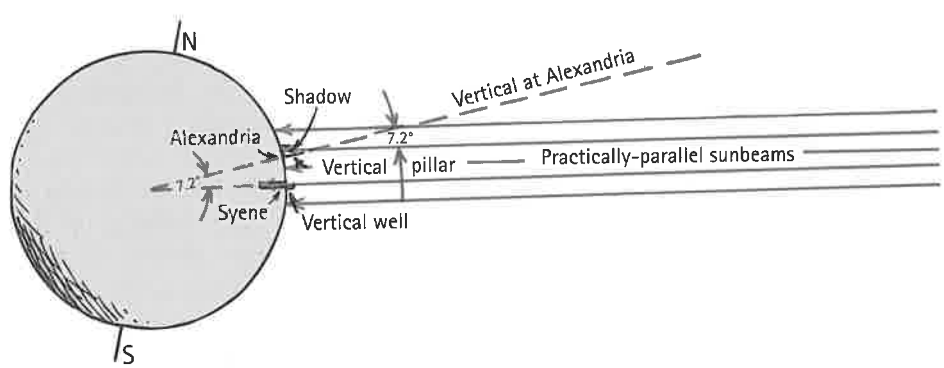


FIGURE 1.1

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

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

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

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

SIZE OF THE MOON

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

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

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

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

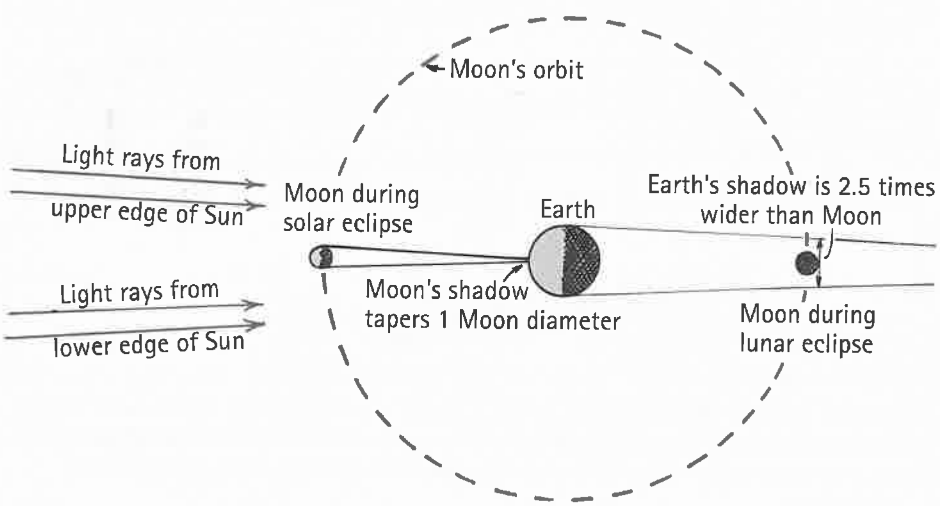


FIGURE 1.2

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

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

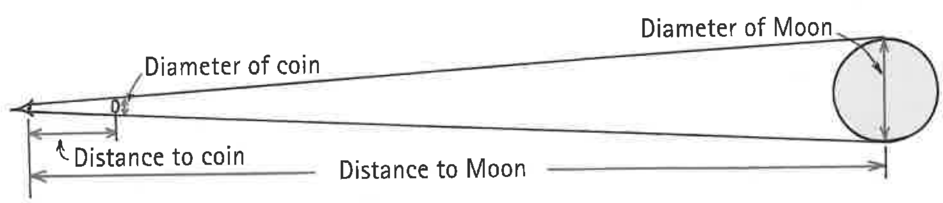
shadow—but just barely. The Moon's shadow tapers almost to a point at Earth's surface, evidence that the taper of the Moon's shadow at this distance is 1 Moon diameter. So during a lunar eclipse Earth's shadow, covering the same distance, must also taper 1 Moon diameter. Taking the tapering of the Sun's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

FIGURE 1.3

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

DISTANCE TO THE MOON

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



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

FIGURE 1.4

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

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

DISTANCE TO THE SUN

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

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

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

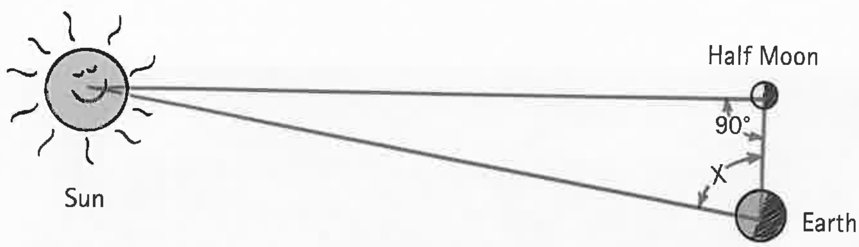


FIGURE 1.5

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

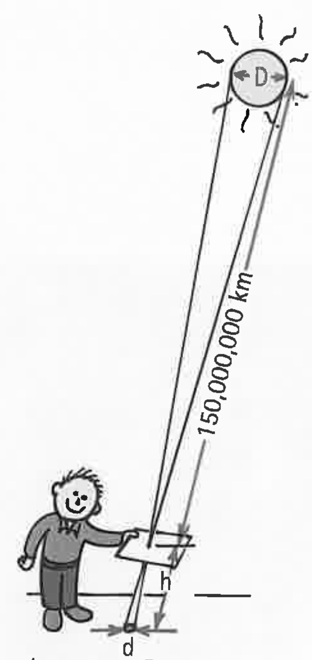
A rule of trigonometry states that, if you know all the angles in a right triangle plus the length of any one of its sides, you can calculate the length of any other side. Aristarchus knew the distance from Earth to the Moon. At the time of the half Moon he also knew one of the angles, 90°. All he had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

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

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

SIZE OF THE SUN

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



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

FIGURE 1.6

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

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

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

FIGURE 1.7
Renoir accurately painted the spots of sunlight on his subjects' clothing and surroundings—images of the Sun cast by relatively small openings in the leaves above.

FIGURE 1.8
The crescent-shaped spots of sunlight are images of the Sun when it is partially eclipsed.

Mathematics—The Language of Science

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

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

Scientific Methods

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

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

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

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

The Scientific Attitude

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

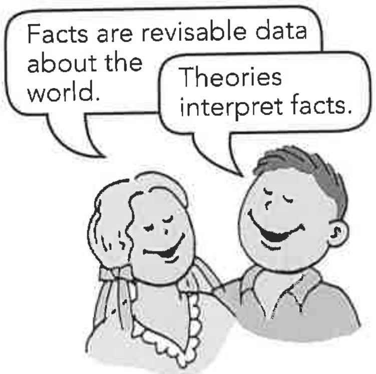
Science is a way of knowing about the world and making sense of it.

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

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

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

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



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

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

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

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

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

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

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

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

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

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

CHECK POINT

Which of these is a scientific hypothesis?

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

Check Your Answer

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

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

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

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

CHECK POINT

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

Check Your Answer

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

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

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

Science, Art, and Religion

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

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

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

Pseudoscience

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

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

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

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

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

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

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

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

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

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

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

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

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

Science and Technology

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

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

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

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

Risk Assessment

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

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

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

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

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

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

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

No wars are fought over science.

Physics—The Basic Science

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

Physics is more than a part of the physical sciences. It is the *basic* science. It's about the nature of basic things such as motion, forces, energy, matter, heat, sound, light, and the structure of atoms. Chemistry is about how matter is put together, how atoms combine to form molecules, and how the molecules combine to make up the many kinds of matter around us. Biology is more complex and involves matter that is alive. So underneath biology is chemistry, and underneath chemistry is physics. The concepts of physics reach up to these more complicated sciences. That's why physics is the most basic science.

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

CHECK POINT

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

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

Check Your Answer

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

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

In Perspective

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

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

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

We live in an exciting time!

SUMMARY OF TERMS

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

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

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

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

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

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

Pseudoscience Fake science that pretends to be real science.

REVIEW QUESTIONS

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

Scientific Measurements

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

Mathematics—The Language of Science

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

Scientific Methods

10. Outline some features of the scientific method.

The Scientific Attitude

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

Science, Art, and Religion

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

Science and Technology

19. Clearly distinguish between science and technology.

Physics—The Basic Science

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

PROJECTS

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

EXERCISES

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