GLOBAL EDITION

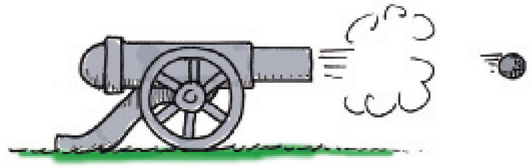
Conceptual Physics

TWELFTH EDITION

Paul G. Hewitt

ALWAYS LEARNING

PEARSON



A Conceptual Approach to Physics—Now with MasteringPhysics®!

Since defining this course 30 years ago, Paul Hewitt's best-selling text continues as the benchmark by which all others are judged. In **Conceptual Physics with MasteringPhysics®, Twelfth Edition,** Paul Hewitt integrates a compelling text and the most advanced media to make physics interesting, understandable, and relevant for non-science majors. The **Twelfth Edition** will delight students with informative and fun Hewitt-Drew-It screencasts, updated content, applications, and new learning activities in **MasteringPhysics**.

NEW! A new interior design provides an attractive, fresh, and accessible new look, updating a classic text to be even more student friendly.

NEW! Over 200 QR codes throughout the book allow students to use a mobile device to instantly watch Paul Hewitt's video demonstrations and Hewitt-Drew-It screencasts to prepare for lecture and gain a better conceptual understanding of physics.

NEW! Updated applications are available for digital technology, environment, and energy. These topics are at the forefront of everyone's consciousness these days and an intelligent awareness of their scientific foundations will give rise to better decision making in the political arena.

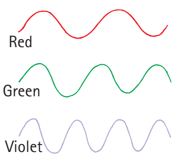


FIGURE 26.5
INTERACTIVE FIGURE

Relative wavelengths of red, green, and violet light. Violet light has nearly twice the frequency of red light and half the wavelength.

different wavelengths—waves of low frequencies have long wavelengths, and waves of high frequencies have short wavelengths. For example, since the speed of the wave is 300,000 km/s, an electric charge oscillating once per second (1 Hz) will produce a wave with a wavelength of 300,000 km. This is because only one wavelength is generated in 1 second. If the frequency of oscillation were 10 Hz, then 10 wavelengths would be formed in 1 second, and the corresponding wavelength would be 30,000 km. A frequency of 10,000 Hz would produce a wavelength of 30 km. So, the higher the frequency of the vibrating charge, the shorter the wavelength of radiant energy.[3]

We tend to think of space as empty, but only because we cannot see the montages of electromagnetic waves that permeate every part of our surroundings. We see some of these waves, of course, as light. These waves constitute only a microportion of the electromagnetic spectrum. We are unconscious of radio and cellphone waves, which engulf us every moment. Free electrons in every piece of metal on Earth's surface continuously dance to the rhythms of these waves. They jiggle in unison with the electrons being driven up and down along their transmitting antennae. A radio or television receiver is simply a device that sorts and amplifies these tiny currents. There is radiation everywhere. Our first impression of the universe is one of matter and void, but actually the universe is a dense sea of radiation occupied only occasionally by specks of matter.

SCREENCAST: Speed of Light

CHECK POINT

Are we correct to say that a radio wave is a low-frequency light wave? And that a radio wave is also a sound wave?

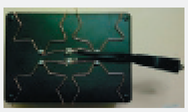
CHECK YOUR ANSWERS

Yes and no. Both a radio wave and a light wave are electromagnetic waves emitted by vibrating electrons; radio waves have lower frequencies than light waves, so a radio wave may be considered to be a low-frequency light wave (and a light wave, similarly, may be considered to be a high-frequency radio wave). But a sound wave is a mechanical vibration of matter and is fundamentally different from an electromagnetic wave. So a radio wave is definitely not a sound wave.

FRACTAL ANTENNAS

For quality reception of electromagnetic waves, a conventional antenna has to be about one-quarter wavelength long. That's why, in early mobile devices, antennas had to be pulled out before the device was used. Nathan Cohen, a professor at Boston University, was troubled by a rule in Boston at the time that prohibited the use of large external antennas on buildings. So he fashioned a small antenna by folding aluminum foil into a compact fractal shape (a Van Koch figure—check *fractals* on the Internet). It worked. He then engineered and patented many practical fractal antennas, as did Carles Puente, an inventor in Spain. Both formed fractal-antenna companies.

Fractals are fascinating shapes that can be split into parts, each of which is (or approximates) a reduced copy of the whole. In any fractal, similar shapes appear at all levels of magnification. Common fractals in nature include snowflakes, clouds, lightning bolts, shorelines, and even cauliflower and broccoli.



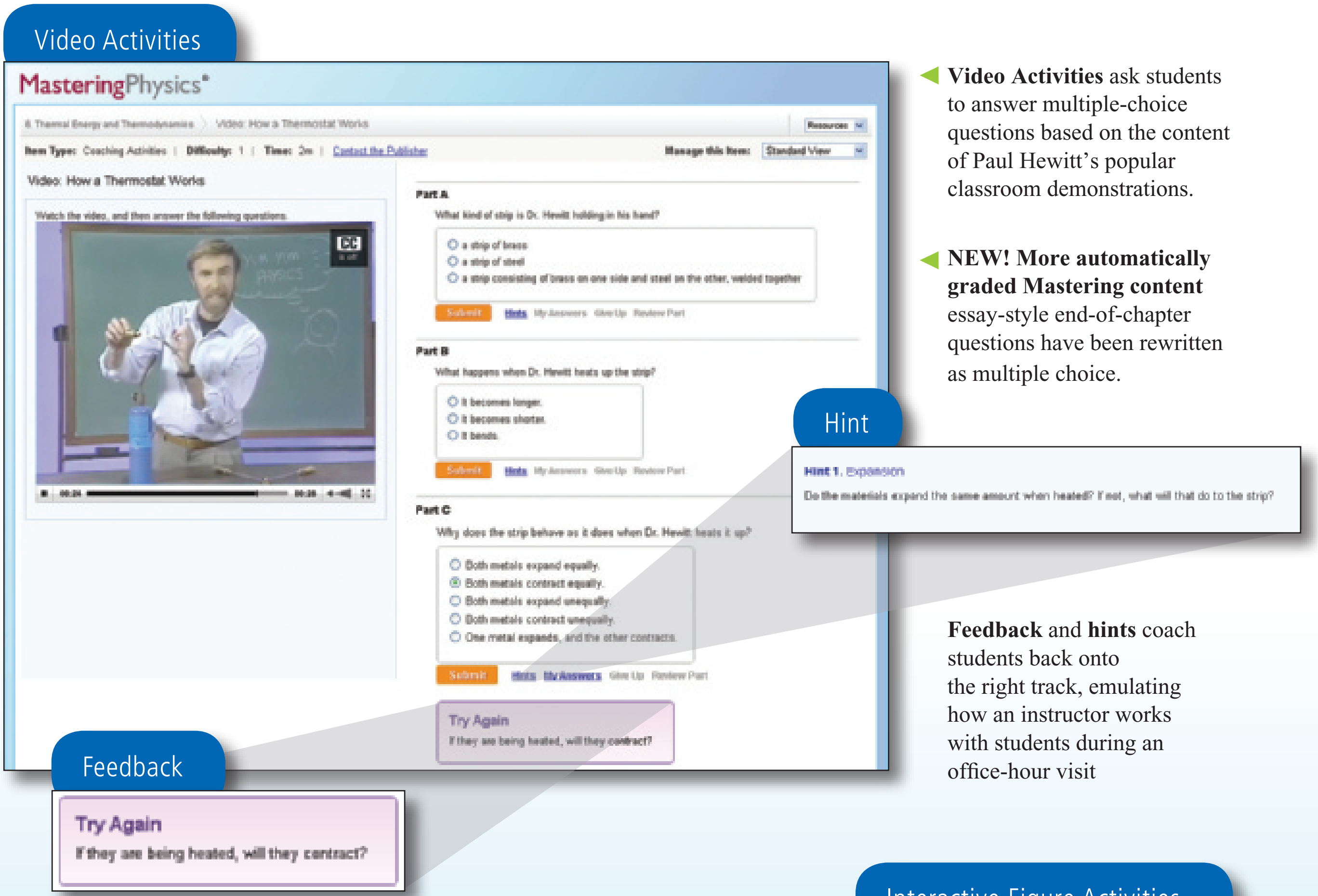
The fractal antenna, like other fractals, has a shape that repeats itself. Because of its folded self-similar design, a fractal antenna can be compressed and fit into the body of the device—it can also simultaneously operate at different frequencies. Hence the same antenna can be used for mobile-phone conversations and for GPS navigation.

How nice that these devices fit in your pocket. Cheers for compact fractal antennas!

[3] The relationship is $c = f\lambda$, where c is the wave speed (constant), f is the frequency, and λ is the wavelength.

Outstanding Content Accompanied by Unparalleled Tutoring

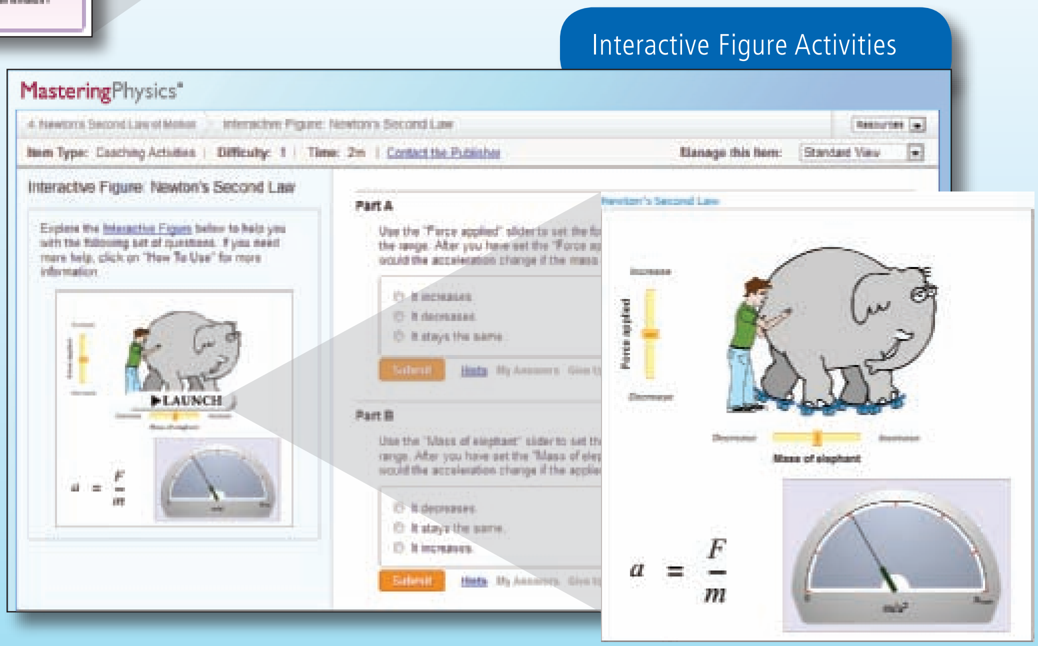
The Mastering system provides tutorials and coaching activities covering content relevant to the conceptual physics course and motivates students to learn outside of class and arrive prepared for lecture.



◀ **Video Activities** ask students to answer multiple-choice questions based on the content of Paul Hewitt's popular classroom demonstrations.

◀ **NEW! More automatically graded Mastering content** essay-style end-of-chapter questions have been rewritten as multiple choice.

Feedback and **hints** coach students back onto the right track, emulating how an instructor works with students during an office-hour visit

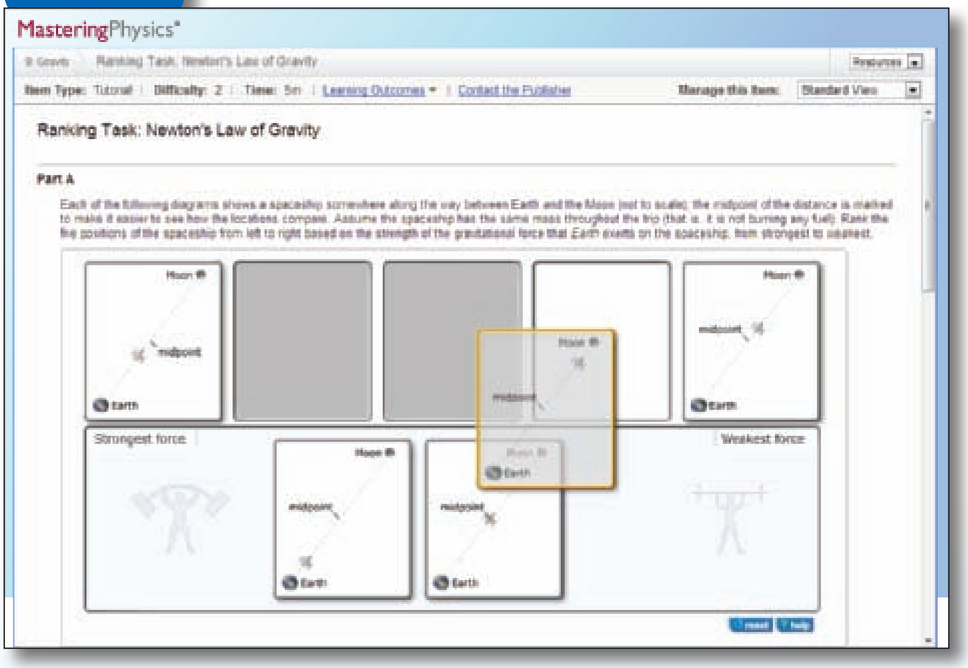


Interactive Figure Activities ▶ help students master important topics by interacting with key figures, bringing principles to life. Hints and specific wrong answer feedback help guide students toward understanding the scientific principles.

Survey data show that the immediate feedback and tutorial assistance in MasteringPhysics motivate students to do more homework. The result is that students learn more and improve their test scores.

MasteringPhysics®
www.masteringphysics.com

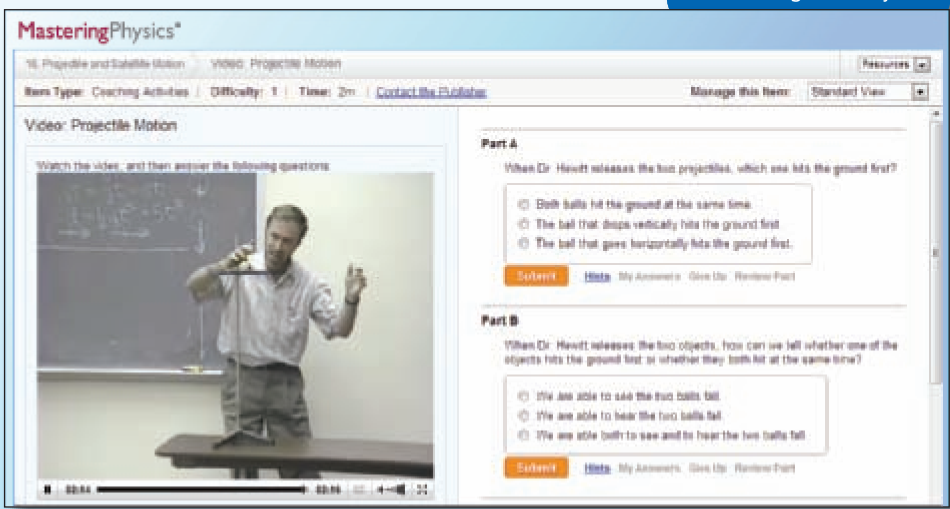
Tutorials

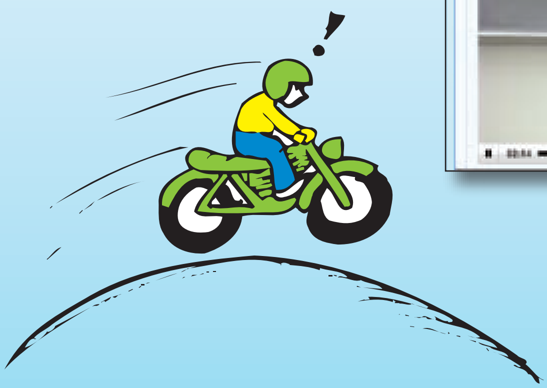


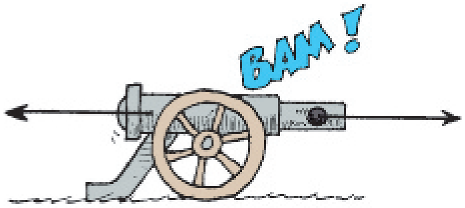
Assignable, in-depth tutorials guide students through the toughest topics with individualized coaching. These self-paced tutorials coach students with hints and feedback specific to individual misconceptions. Tutorials respond to a wide variety of typical wrong answers that students might enter at any step.

Coaching Activity

Coaching Activities have students interact with content, and available hints and/or feedback promote comprehension of the concepts.







Student Results

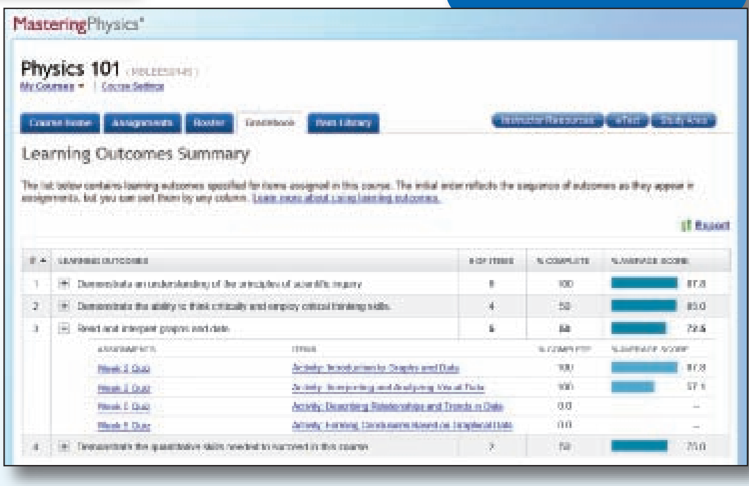
MasteringPhysics is the leading online homework, tutorial, and assessment product designed to improve results by helping students quickly master concepts. Students benefit from self-paced tutorials featuring specific wrong-answer feedback, hints, and a huge variety of educationally effective content to keep them engaged and on track. Robust diagnostics and unrivaled gradebook reporting allow instructors to pinpoint the weaknesses and misconceptions of a student or class to provide timely intervention.

NEW! Learning Catalytics™ is a "bring your own device" student engagement, assessment, and classroom intelligence system. With Learning Catalytics you can:

- Assess students in real time, using open-ended tasks to probe student understanding.
- Understand immediately where students are and adjust your lecture accordingly.
- Improve your students' critical-thinking skills.
- Access rich analytics to understand student performance.
- Add your own questions to make Learning Catalytics fit your course exactly.
- Manage student interactions with intelligent grouping and timing.

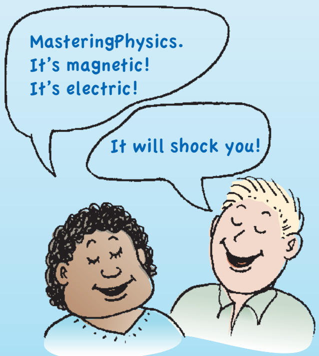
Learning Outcomes

A learning objective has been added to help the students focus on the most important concepts in each chapter. These learning outcomes are associated with content in MasteringPhysics®, allowing the work of tracking student performance against course learning outcomes to be done automatically.

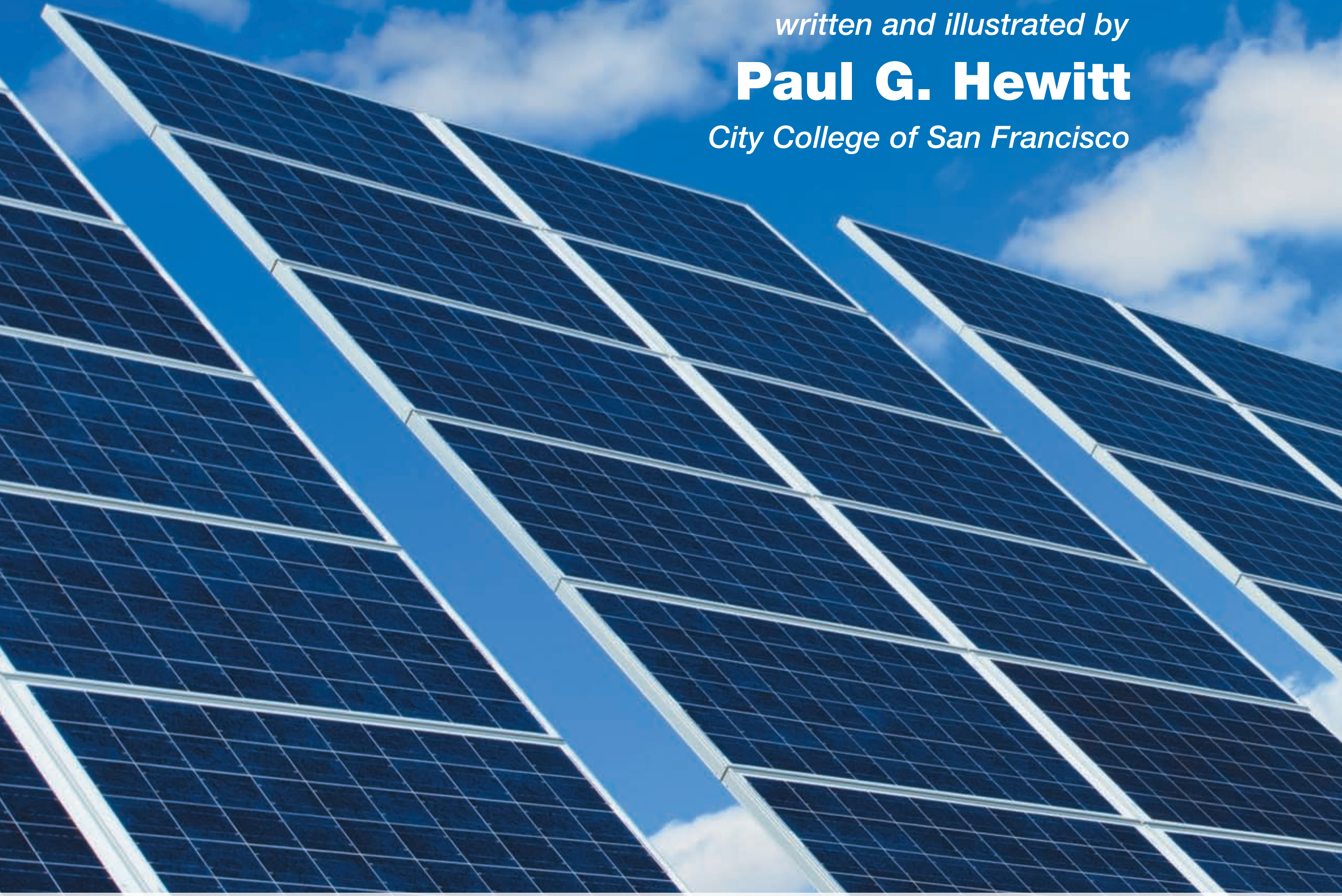


Gradebook Diagnostics

The Gradebook Diagnostics screen allows you to quickly and easily identify vulnerable students, difficult problems, and your students' most common misconceptions.



CONCEPTUAL Physics



CONCEPTUAL Physics

Twelfth Edition
Global Edition

written and illustrated by

Paul G. Hewitt

City College of San Francisco

PEARSON

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To my grandchildren, Manuel, Alexander, Megan, Grace, and Emily
and to all students who struggle to learn physics

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, who overlap with colleagues and friends worldwide. Many of these people are identified in chapter-opening photos, and with some exceptions I'll not repeat their names here. Family and friends whose photos are Part Openers, however, are listed here. We begin on page 26, where great-nephew Evan Suchocki (pronounced "su-hock-ee" with a silent c) holds a pet chickie on my lap.

Part One opens on page 45 with Charlotte Ackerman, the daughter of friends Duane Ackerman and Ellen Hum. Part Two opens with Andrea Wu (also on pages 157 and 518), daughter of my friend in Hawaii, Chiu Man Wu (page 348). Part Three opens on page 270 with four-year-old Francesco Ming Giovannuzzi from Florence, Italy, grandson of friends Keith and Tsing Bardin (page 271). Part Four on page 381 shows Abby Dijamco, daughter of my last CCSF teaching assistant, dentist Stella Dijamco. In Part Five, on page 431, is my granddaughter Megan, daughter of Leslie and Bob Abrams. Part Six, page 511, opens with Lillian's nephew, Christopher Lee. Part Seven, page 478, shows William Davis, son of friends Alan and Fe Davis. My granddaughter Grace Hewitt begins Part Eight on page 683.

City College of San Francisco friends and colleagues open several chapters and are named there. Photos that are figures include Will Maynez, the designer and builder of the air track displayed on page 126, and again burning a peanut on page 324. Diana Lininger Markham is shown on pages 55 and 185. Fred Cauthen drops balls on page 153.

Physics instructor friends from other colleges and universities include Evan Jones playing with Bernoulli on page 290 and showing LED lighting on page 599. Egypt's Mona El Tawil-Nassar adjusts capacitor plates on page 449. Sanjay Rebello from Kansas State University, Manhattan, is shown on page 164. Hawaii's Walter Steiger is on page 653. Chuck Stone of Colorado School of Mines, Golden, shows an energy ramp on page 211.

Physics high school teacher friends include retired Marshall Ellenstein, who swings the water-filled bucket on page 172, walks barefoot on broken glass on page 289, and poses with Richard Feynman on page 570. Other physics teachers from Illinois are Ann Brandon, riding on a cushion of air on page 294, and Tom Senior, making music on page 429.

Family photos begin with wife Lillian and me, showing that you cannot touch without being touched on page 107. Another updated photo that links touching to Newton's third law shows my brother Stephen with his daughter Gretchen on page 113. Stephen's son Travis is on page 180, and his oldest daughter Stephanie on pages 256, 569, and 715. My son Paul is shown on pages 331 and 366.

Daughter-in-law Ludmila Hewitt holds crossed Polaroids on page 582. The endearing girl on page 241 is my daughter Leslie Abrams, earth-science coauthor of the *Conceptual Physical Science* textbooks. This colorized photo of Leslie has been a trademark of *Conceptual Physics* since the Third Edition. A more recent photo with her husband Bob is on page 512. Their children, Megan and Emily (page 580), along with son Paul's children, Alex (page 116) and Grace (page 417), make up the colorful set of photos on page 536. Photos of my late son James are on pages 176, 420, and 562. He left me my first grandson, Manuel, seen on pages 260 and 409. Manuel's grandmom, my wife Millie, who passed away in 2004, bravely holds her hand above the active pressure cooker on page 332. Brother David and his wife Barbara demonstrate atmospheric pressure on page 295. Their son, also David, an electrician, is on page 471, and grandson John Perry Hewitt is on page 302. Sister Marjorie Hewitt Suchocki, author and emeritus theologian at Claremont School of Theology, illustrates reflection on page 548. Marjorie's son, John Suchocki, author of *Conceptual Chemistry*, Fifth Edition, and chemistry coauthor of the *Conceptual Physical Science* textbooks, is also a singer-songwriter, known as John Andrew; he strums his guitar on page 498. The group listening to music on page 425 is part of John's and Tracy's wedding party: from left to right, late Butch Orr, niece Cathy Candler (page 162 and her son Garth Orr on page 252), bride and groom, niece Joan Lucas (page 65), sister Marjorie, Tracy's parents Sharon and David Hopwood, teachers Kellie Dippel and Mark Werkmeister, and me.

Photos of Lillian's family include her dad (my father-in-law), Wai Tsan Lee, showing magnetic induction on page 483, and her mom (my mother-in-law), Siu Bik Lee, making good use of solar power on page 341. My nephew and niece, Erik and Allison Wong, dramatically illustrate thermodynamics on page 372.

Personal friends who were my former students begin with Tenny Lim, a rocket engineer at the Jet Propulsion Lab in Pasadena, drawing her bow on page 141. This photo has appeared in every book since the Sixth Edition. She is seen with her husband Mark Clark on Segways on page 170. Another of my protégés is rocket-scientist Helen Yan, who is involved in satellite imaging sensoring for Lockheed Martin in Sunnyvale, in addition to teaching physics part-time at CCSF (page 147), and again posing with Richard Feynman and Marshall Ellenstein on page 570. On page 176 Cliff Braun is at the far left of my son James in Figure 8.50, with nephew Robert Baruffaldi at the far right. Alexei Cogan demonstrates the center of gravity on page 169, and the karate gal on page 121 is Cassy Cosme.

Three dear friends from school days are Howard Brand on page 116, Dan Johnson on page 362, and his wife Sue on page 65 (the first rower in the racing shell). Dan and Sue Johnson's grandson Bay plays the piano on page 422. Other cherished friends are Ryan Patterson, resonating on page 409, and Paul Ryan, who drags his finger through molten lead on page 357. My science influence from the sign-painting days is Burl Grey, shown on page 56 (with a sample sign-painting discussion on page 52), and Jacques Fresco is on page 159. Dear friend Dennis McNelis is eating pizza on page 335. Larry and Tammy Tunison wear radiation badges on page 647 (Tammy's dogs are on page 346). Greta Novak floats on very dense water on page 289, and her son Bruce Novak displays two versions of the color spectrum on page 515. Duane Ackerman's daughter Emily looks through novel lenses on page 563. Peter Rea of Arbor Scientific is on page 213. Paul Stokstad of PASCO is shown on page 158, and David and Christine Vernier of Vernier Software are on page 135.

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 Twelfth Edition is identical to that in the previous edition. New to this edition are expanded personality profiles at the beginning of every chapter, highlighting a scientist, teacher, or historical figure who complements the chapter material. Each chapter begins with a photo montage of educators, and sometimes their children, who bring life to the learning of physics.

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

Part One, "Mechanics," begins with Chapter 2, which, as in the previous edition, presents a brief historical overview of Aristotle and Galileo, progressing to Newton's first law and to mechanical equilibrium. Force vectors are introduced, primarily for forces that are parallel to one another. Vectors are extended to velocity in the following Chapter 3, and Chapter 5 treats both force and velocity vectors and their components.

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

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

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

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

Chapter 4, "Newton's Second Law of Motion," where the concepts of velocity and acceleration find their application.

Chapter 5 continues with Newton's third law. 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 previous chapters are employed with momentum but not with energy.

Chapter 7, "Energy," is a longer chapter, rich with everyday examples and current energy concerns. Energy is central to mechanics, so this chapter has the greatest amount of chapter-end material (80 exercises). Work, energy, and power also get generous coverage in the *Practice Book*.

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

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

Parts Three through Eight continue, like earlier parts, with enriched examples of current technology. New lighting with CFLs and LEDs in Chapter 23 has added 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 as in the previous edition. Odd-numbered answers and solutions to *all* chapter-end material are given at the end of the book.

As in 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 **Reading Check Questions** that summarize the main points of the chapter. Students can find the answers to these questions, word for word, in the reading. The **Plug and Chug** exercises are for familiarity with equations. As introduced in previous editions, many good comments have come from the **Think and Rank** exercises. Critical thinking is required in comparing quantities in similar situations. Getting an answer is not enough; the answer must be compared with others and a ranking from most to least is asked for. I consider this the most worthwhile offering in the chapter-end material.

Think and Explain exercises are the nuts and bolts of conceptual physics. Many require critical thinking, while some are designed to connect concepts to familiar situations. Most chapters also have **Think and Discuss** sections (which are tailored for student discussion). More math-physics challenges are found in the sets of **Think and Solve** exercises. These problems are much less numerous than Think and Explains and Think and Ranks. Many more problems are available in the student supplement, **Problem Solving in Conceptual Physics**, coauthored with Phil Wolf. While problem solving is not the main thrust of a conceptual course, Phil and I, like most physics instructors, nevertheless love solving problems. In a novel and student-friendly way, our supplement features problems that are more physics than math, nicely extending *Conceptual Physics*—even to student-friendly algebraic courses that feature problem solving. Problem solutions are included in the Instructor Resources area of MasteringPhysics.

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

The **Laboratory Manual** coauthored with Dean Baird that accompanies this edition provides a great variety of activities and lab exercises. The polishing that Dean gives this material is extraordinary.

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

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

The **Instructor Resources** are a wealth of presentation tools to help support your instruction. In a word, they are *sensational!* They include "everything you could ask for as a teaching resource," including lecture outlines for each chapter in PowerPoint and chapter-by-chapter weekly in-class quizzes in PowerPoint. The **Instructor Resources** also provide 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.

Last but not least is **MasteringPhysics**. . . .

MasteringPhysics®

Innovative, targeted, and effective online learning media is easily integrated into your course using MasteringPhysics to assign tutorials, quizzes, and other activities as out-of-class homework or projects that are automatically graded and recorded. Simple icons throughout the text highlight key tutorials, interactive figures, and other online resources available in the Mastering study area. The instructor resources are also available for download. A chapter section guide in the study area summarizes the media available to you and your students, chapter by chapter.

For more information on the support ancillaries, see http://www.pearsonglobaleditions.com/hewitt or contact your Pearson representative.

SCREENCAST: Conservation of Momentum

New Features in This Edition

The greatest addition to this edition are the 147 **Hewitt-Drew-It screencasts** that have been featured on YouTube since 2012. QR codes throughout the book link the student to these tutorial lessons that have been created by me and embellished by my wife. We feel that these lessons are our most recent and important contribution to making physics correct and understandable. They nicely complement the chapter material of this edition. Simply scan the QR codes in the book with your smartphone or electronic device and a QR code reader app. After scanning the code, you will be able to view the Hewitt-Drew-It screencasts online. (Note: Data usage charges may apply.)

The profiles of physicists and physics educators in the previous edition are still included, with new people added throughout. By learning more about the people behind the chapter content, the reader gets a more personalized flavor of physics.

More on force and velocity vectors and climate change is in this edition. New updates to current-day physics are found throughout the book. New boxes include 3-D printing, GPS operation, and the Higgs boson.

The chapter-end material has been reorganized, with consecutive numbering to assist in making assignments.

I regard this as the best physics book I have ever written.

Acknowledgments

I remain enormously grateful to Kenneth Ford for checking accuracy and for his many insightful suggestions. Many years ago, I admired one of Ken's books, *Basic Physics*, which first inspired me to write *Conceptual Physics*. Today I am honored that he has devoted so much of his time and energy to making this edition a beautiful book. Errors invariably appear after manuscript is submitted, so I take full responsibility for any errors that have survived his scrutiny.

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Paul G. Hewitt
St. Petersburg, Florida

Global Edition

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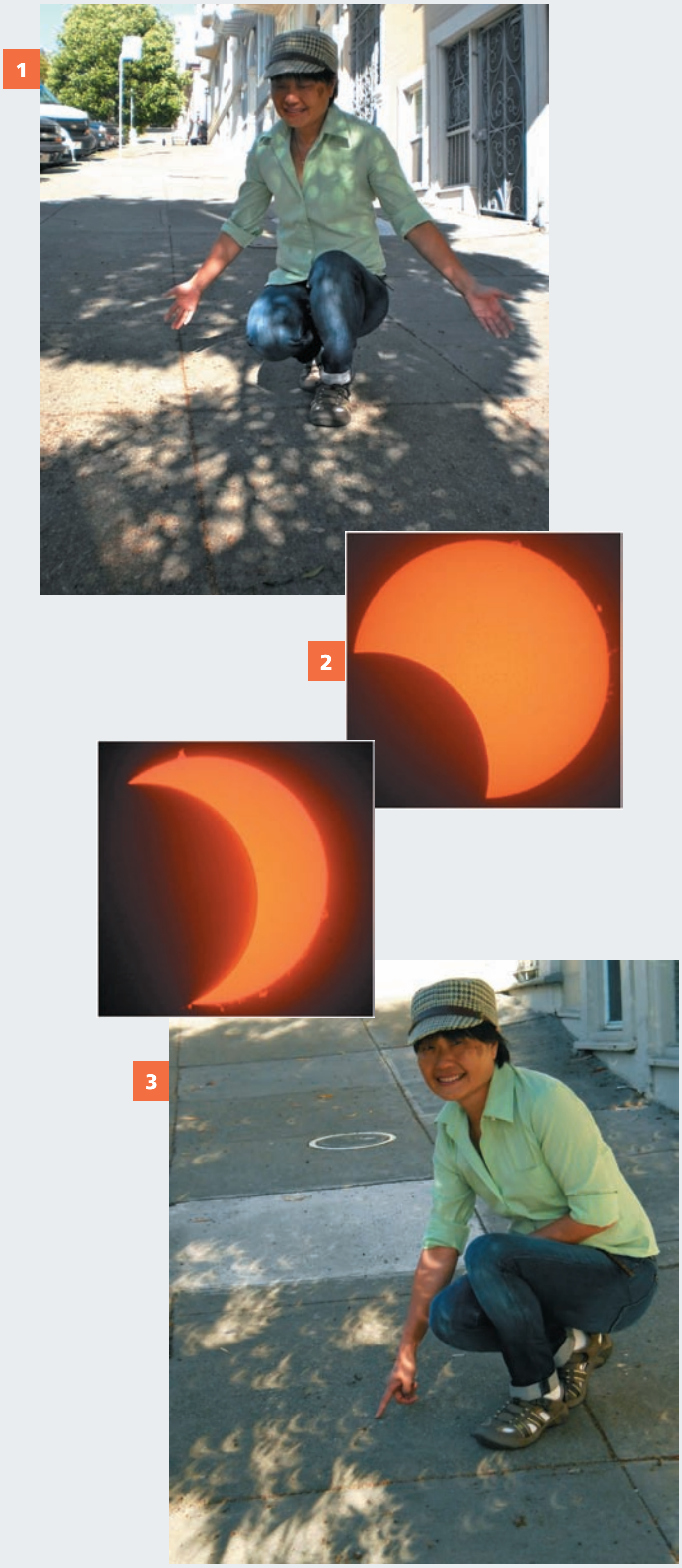
Wow Great Uncle Paul! Before this chickie exhausted its inner space resources and poked out of its shell, it must have thought it was at its last moments. But what seemed like its end was a new beginning. Are we like chickies, ready to poke through to a new environment and a new understanding of our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

1

CHAPTER 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** A full view of the Sun is blocked as the Moon progresses in front of the Sun. **3** The circular spots become crescents during the 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 (2000 years ago with no computers and no artificial satellites—using only good thinking, geometry, and simple measurements). In this chapter you will see how he accomplished this.

1.1 Scientific Measurements

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

How Eratosthenes Measured the Size of Earth

The size of Earth was first measured in Egypt by Eratosthenes in about 235 BC. He calculated the circumference of Earth in the following way. He knew that the Sun is highest in the sky at noon on the day of the summer solstice (which occurs around June 21 on today's calendars). At this time, a vertical stick casts its shortest shadow. If the Sun is directly overhead, a vertical stick casts no shadow at all. Eratosthenes learned from library information that the Sun was directly overhead at noon on the day of the summer solstice in Syene, a city south of Alexandria (where the Aswan Dam stands today). At this particular time, sunlight shines directly down a deep well in Syene and is reflected back up again. Eratosthenes reasoned that, if the Sun's rays were extended into Earth at this point, they would pass through the center. Likewise, a vertical line extended into Earth at Alexandria (or anywhere else) would also pass through Earth's center.

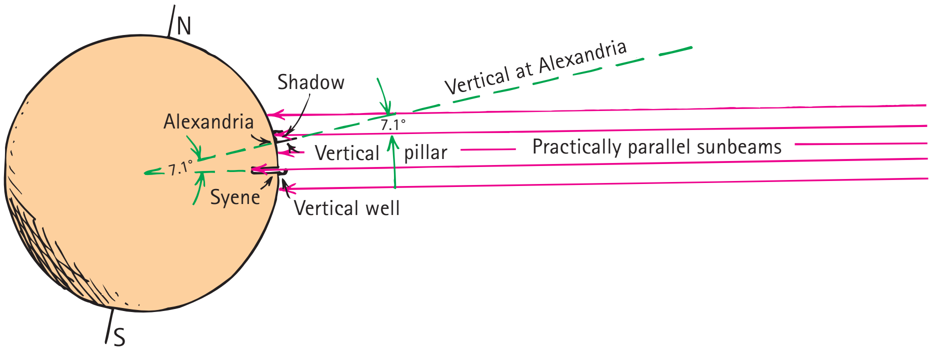


FIGURE 1.1
When the Sun is directly overhead at Syene, it is not directly overhead in Alexandria, 800 km north. When the Sun's rays shine directly down a vertical well in Syene, they cast a shadow of a vertical pillar in Alexandria. The verticals at both locations extend to the center of Earth, and they 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.

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 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 taller than its shadow, the radius of Earth must be 8 times greater than the distance between Alexandria and Syene.

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

Size of the Moon

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

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

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

  Science made great headway in Greece in the 4th and 3rd centuries BC, and spread throughout the Mediterranean world. Scientific advance came to a near halt in Europe when the Roman Empire fell in the 5th century AD. Barbarian hordes destroyed almost everything in their paths as they overran Europe. Reason gave way to religion, which plunged Europe into the Dark Ages. During this time, the Chinese and Polynesians were charting the stars and the planets and Arab nations were developing mathematics and learning about the production of glass, paper, metals, and various chemicals. Greek science was re-introduced 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. In the 15th century art and science were beautifully blended by Leonardo da Vinci. Scientific thought was furthered in the 16th century with the advent of the printing press.