# CONCEPTUAL
# Physics

## THIRTEENTH EDITION

Paul G. Hewitt

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# SOME SIGNIFICANT DATES IN THE HISTORY OF PHYSICS

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

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# PERIODIC TABLE OF THE ELEMENTS

**Group**

**Period**

| Group | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 | 10 | 11 | 12 | 13 | 14 | 15 | 16 | 17 | 18 |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| **1** | 1 H 1.0079 | | | | | | | | | | | | | | | | | 2 He 4.003 |
| **2** | 3 Li 6.941 | 4 Be 9.012 | | | | | | | | | | | 5 B 10.811 | 6 C 12.011 | 7 N 14.007 | 8 O 15.999 | 9 F 18.998 | 10 Ne 20.180 |
| **3** | 11 Na 22.990 | 12 Mg 24.305 | | | | | | | | | | | 13 Al 26.982 | 14 Si 28.086 | 15 P 30.974 | 16 S 32.066 | 17 Cl 35.453 | 18 Ar 39.948 |
| **4** | 19 K 39.098 | 20 Ca 40.078 | 21 Sc 44.956 | 22 Ti 47.88 | 23 V 50.942 | 24 Cr 51.996 | 25 Mn 54.938 | 26 Fe 55.845 | 27 Co 58.933 | 28 Ni 58.69 | 29 Cu 63.546 | 30 Zn 65.39 | 31 Ga 69.723 | 32 Ge 72.61 | 33 As 74.922 | 34 Se 78.96 | 35 Br 79.904 | 36 Kr 83.8 |
| **5** | 37 Rb 85.468 | 38 Sr 87.62 | 39 Y 88.906 | 40 Zr 91.224 | 41 Nb 92.906 | 42 Mo 95.94 | 43 Tc 98 | 44 Ru 101.07 | 45 Rh 102.906 | 46 Pd 106.42 | 47 Ag 107.868 | 48 Cd 112.411 | 49 In 114.82 | 50 Sn 118.71 | 51 Sb 121.76 | 52 Te 127.60 | 53 I 126.905 | 54 Xe 131.29 |
| **6** | 55 Cs 132.905 | 56 Ba 137.327 | 57 La 138.906 | 72 Hf 178.49 | 73 Ta 180.948 | 74 W 183.84 | 75 Re 186.207 | 76 Os 190.23 | 77 Ir 192.22 | 78 Pt 195.08 | 79 Au 196.967 | 80 Hg 200.59 | 81 Tl 204.383 | 82 Pb 207.2 | 83 Bi 208.980 | 84 Po 209 | 85 At 210 | 86 Rn 222 |
| **7** | 87 Fr 223 | 88 Ra 226.025 | 89 Ac 227.028 | 104 Rf 265 | 105 Db 268 | 106 Sg 270 | 107 Bh 269 | 108 Hs 277 | 109 Mt 276 | 110 Ds 281 | 111 Rg 280 | 112 Cn 285 | 113 Nh 284 | 114 Fl 289 | 115 Mc 289 | 116 Lv 293 | 117 Ts 294 | 118 Og 294 |

**Lanthanides**

| 58 Ce 140.115 | 59 Pr 140.908 | 60 Nd 144.24 | 61 Pm 145 | 62 Sm 150.36 | 63 Eu 151.964 | 64 Gd 157.25 | 65 Tb 158.925 | 66 Dy 162.5 | 67 Ho 164.93 | 68 Er 167.26 | 69 Tm 168.934 | 70 Yb 173.04 | 71 Lu 174.967 |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|

**Actinides**

| 90 Th 232.038 | 91 Pa 231.036 | 92 U 238.029 | 93 Np 237 | 94 Pu 244 | 95 Am 243 | 96 Cm 247 | 97 Bk 247 | 98 Cf 251 | 99 Es 253 | 100 Fm 257 | 101 Md 259 | 102 No 259 | 103 Lr 256 |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|

☐ Metal
☐ Metalloid
☐ Nonmetal

Atomic masses are averaged by isotopic abundance on the Earth's surface, expressed in atomic mass units. Conventional IUPAC atomic masses are provided as recommended by G. Kaptay in *J. Min. Metall. Sect. BMetall. 48 (1) B (2012)153 159*. For radioactive elements, this is commonly the whole number nearest the most stable isotope of that element. The elements here are color coded to indicate metal, metalloid, or nonmetal. But please recognize that the heaviest elements, such as 104 and greater, are highly unstable existing only for a fraction of a second within a laboratory setting. Any metallic properties they might exhibit are not discernible.

*Conceptual Physics* began as a compilation of Paul Hewitt's classroom lectures at City College of San Francisco—published in 1971 by Little, Brown and Company as its first college science textbook. Successive editions testify to its success, each occurring, on average, at four-year intervals. Covers for the first three editions honored Erwin Muller's historic micrograph of atoms at the tip of a sharp needle. The fourth edition cover is the author's photo of interference colors reflected by oily water. The author's son James tossed grains of rice into a pond next to the Exploratorium to create wave interference for the photo on the fifth edition cover. Up to this point, all photos and Paul's hand-drawn illustrations were black and white. A second color was added for the sixth edition. Subsequent editions sported full-color art and photos. Not shown are the covers for editions six through nine. The sixth edition featured a blend of bubble-chamber particle tracks and flowing water, the seventh featured lightning bolts as viewed through a diffraction grating, the eighth of the aurora borealis, and the ninth of Hawaiian lava flow. Covers that are shown pick up with edition ten, of elementary particle tracks blended with sky and water, edition eleven with solar cells on the ISS, the only edition that shows humans. A close-up of solar cells on Earth is on the cover of the twelfth edition. Not indicated, are the increases in cover size from 7" × 9" for the first three editions to the present 8½" × 11". This array of textbook covers marks a half century of physics presented as a study of nature's rules—relevant at all times.
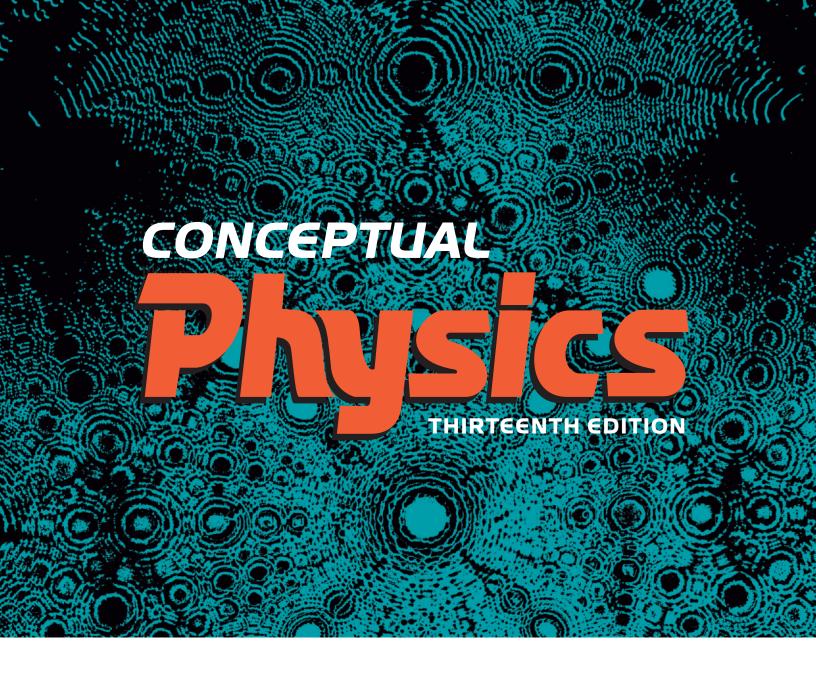
| | |
|---|---|
| **1900** | **Planck** introduces the quantum idea. |
| **1905** | **Einstein** introduces the light corpuscle (photon) concept. |
| **1905** | **Einstein** advances the special theory of relativity. |
| **1911** | **Rutherford** reveals the nuclear atom. |
| **1913** | **Bohr** gives a quantum theory of the hydrogen atom. |
| **1915** | **Einstein** advances the general theory of relativity. |
| **1923** | **Compton's** experiments confirm the existence of the photon. |
| **1924** | **de Broglie** advances the wave theory of matter. |
| **1925** | **Goudsmit** and **Uhlenbeck** establish the spin of the electron. |
| **1925** | **Pauli** states the exclusion principle. |
| **1926** | **Schrödinger** develops the wave theory of quantum mechanics. |
| **1927** | **Heisenberg** proposes the uncertainty principle. |
| **1928** | **Dirac** blends relativity and quantum mechanics in a theory of the electron. |
| **1929** | **Hubble** discovers the expanding universe. |
| **1932** | **Anderson** discovers antimatter in the form of the positron. |
| **1932** | **Chadwick** discovers the neutron. |
| **1934** | **Fermi** proposes a theory of the annihilation and creation of matter. |
| **1938** | **Meitner** and **Frisch** interpret results of **Hahn** and **Strassmann** as nuclear fission. |
| **1939** | **Bohr** and **Wheeler** give a detailed theory of nuclear fission. |
| **1942** | **Fermi** builds and operates the first nuclear reactor. |
| **1945** | **Oppenheimer's** Los Alamos team creates a nuclear explosion. |
| **1947** | **Bardeen**, **Brattain**, and **Shockley** develop the transistor. |
| **1956** | **Reines** and **Cowan** identify the antineutrino. |
| **1957** | **Feynman** and **Gell-Mann** explain weak interactions with a "left-handed" neutrino. |
| **1960** | **Maiman** invents the laser. |
| **1965** | **Penzias** and **Wilson** discover background radiation in the universe left over from the Big Bang. |
| **1967** | **Bell** and **Hewish** discover pulsars, which are neutron stars. |
| **1969** | **Gell-Mann** suggests quarks as the building blocks of nucleons. |
| **1977** | **Lederman** and his team discover the bottom quark. |
| **1981** | **Binning** and **Rohrer** invent the scanning tunneling microscope. |
| **1987** | **Bednorz** and **Müller** discover high-temperature superconductivity. |
| **1995** | **Cornell** and **Wieman** create a "Bose–Einstein condensate" at 20 billionths of a degree. |
| **1998** | **Perlmutter, Schmidt,** and **Riess** discover the accelerated expansion of the universe. |
| | |
| **2000** | **Pogge** and **Martini** provide evidence for supermassive black holes in other galaxies. |
| **2000** | Fermilab group identifies the tau neutrino, the last member of the lepton particle group. |
| **2003** | Scientists studying radiation in space put the age of the universe at 13.7 billion years. |
| **2004** | **Geim** and **Novoselov** discover graphene, a one-atom-thick form of carbon. |
| **2005** | **Gerald Gabrielse** measures the magnetism of the electron to 1 part in a trillion. |
| **2006** | U.S.–Russian team identifies elements number 116 and 118. |
| **2012** | CERN laboratory announces the discovery of the long-sought Higgs boson. |
| **2015** | LIGO team detects gravitational waves from coalescing black holes. |
| **2018** | Jarillo-Herrero discovers superconductivity in graphene. |
| **2019** | Event Horizon Telescope obtains first image of a supermassive black hole. |
| **2020** | The catalog of exoplanets (planets orbiting other stars) grows to more than 4,330. |

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## THIRTEENTH EDITION

*written and illustrated by*

## Paul G. Hewitt

*City College of San Francisco*

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Cover Image by Dr. Erwin Mueller/Science

*To my everything—my wife Lillian*

# Contents in Brief

# Contents in Detail

# Conceptual Physics
# Photo Album

Conceptual Physics is a very personal book, reflected in its many photographs of family, along with friends and colleagues worldwide. Many of these people are identified in chapter-opening photos, and, with some exceptions, I'll not repeat their names here. Family and friends whose photos are Part Openers, however, are listed. The book opens on page 1 with great-nephew Evan Suchocki sitting on my lap pondering life's opportunities with his pet chick.

Part One opens on page 23 with little Ian Evans, son of teacher friends Bart and Jill Evans. Part Two opens on page 237 with little Georgia Hernandez, my delightful great-great-niece. Part Three opens on page 325 with four-year-old Francesco Ming Giovannuzzi, grandson of friend Tsing Bardin, page 280. Part Four opens on page 405 with Abby Dijamco, daughter of my last CCSF teaching assistant, dentist Stella Dijamco. In Part Five on page 461 is my great-great-nephew Richard Hernandez, older brother to Georgia. Part Six opens on page 549 with my granddaughter Gracie Hewitt at age four. Part Seven opens with another granddaughter, Kara Mae Hurrell, as a four-year-old tot in a pot on page 687. Part Eight opens on page 751 with young London Dixon, the daughter of my physician's medical assistant, April Dixon.

The two friends most influential in my transition from a life of sign painting to a life of physics are Burl Grey, page 33, and Jacque Fresco, pages 152, 153. For success as an author I credit my friend and physics mentor, Ken Ford, pages 426, 752, to whom previous editions have been dedicated. Longtime best friend Huey Johnson, known as Dan, page 384, has also been personally influential.

Family photos include my first wife, Millie, on page 350. My eldest daughter is Jean Hurrell, page 261, and with her children Marie and Kara Mae on page 499, and both granddaughters shown separately on pages 67 and 102. Jean's husband Phil tinkers with electricity on page 488. My son Paul is with his daughter Grace, page 84, and doing some thermodynamics on page 389. Gracie plays music on page 446 and further speculates about science on page 549.

Son Paul's former wife Ludmila is shown with Polaroids on page 636, and their son Alex skateboards on pages 104, 170. My daughter Leslie at age 16 is on page 249, a colorized photo that has been a trademark of Conceptual Physics since the third edition. Since then Leslie has been my earth-science coauthor of the Conceptual Physical Science textbooks. A more recent photo with her husband Bob Abrams, page 550. Their children, Megan and Emily, are on pages 349 and 210. A grand slam grandchildren photo is on page 579. My late son James is on page 171 with his best friend Robert Baruffaldi, also his cousin. Other photos of James are on pages 450 and 613. James left me my first grandson, Manuel, pages 268, 331, 436.

Millie's relatives include nephew Mike Luna, page 232. Grand-niece Angela Hendricks, page 656, is a teacher and amateur photographer who graciously supplied photos of her cousins Georgia Hernandez and her older brother Richard Hernandez on pages 294, 321, 426, 446 and 461, and her own child Hudson, page 294. Hudson also appears with his dad Jake Hendricks on page 97. Grand-niece Alejuandra Luna leans on Newton's third law, page 102. Great nephew Isaac Jones uses a sparkler, page 329, as his dad Terrence used back in the sixth and seventh editions. Terrence Jones is now on page 326.

A year after Millie's passing in 2004, I married my friend of many years, Lillian Lee. Lillian has wonderfully assisted me in all steps of textbook production, including ancillaries. Of the many photos of Lil throughout this edition, I'll mention two favorites: One with her pet bird Sneezlee on page 580, and the photo with me illustrating the essence of Newton's third law—you cannot touch without being touched—on page 92. Lillian's dad, Wai Tsan Lee, shows magnetic induction on page 517, and mom, Siu Bik Lee, making excellent use of solar energy on page 360 and with solar images on page 611. Lillian's niece Serena Sinn excels in sports, page 126. Lil's nephew Erik Wong with his sister Allison nicely illustrate thermodynamics on page 395.

Photos of my siblings begin with my sister Marjorie, author and theologian emerita at Claremont School of Theology in Claremont, California, illustrating reflection on page 596. Marjorie's daughter, occupational therapist Cathy Candler, page 157, and her son Garth Orr, page 260. Marjorie's daughter Joan Lucas's two children, SpaceX engineer Mike Lucas, page 772, and lawyer Alexandra Lucas, page 550. Marjorie's multitalented son, John Suchocki, page 366, the creator of Conceptual Academy, a chemistry professor and author, and my coauthor of the *Conceptual Physical Science* and *Conceptual Integrated Science* textbooks; he's also a singer-songwriter known as John Andrew strumming his guitar, pages 406, 533. The group listening to music, page 454, is of John and Tracy's Hawaii long-ago wedding party. My brother Dave and his wife Barbara pump water on page 309. Their electrician son Davey is on page 505, and the yum photos of solar cells, page 360, and the GPS unit, page 782, is courtesy of their daughter Dotty Jean Allen. My youngest brother Steve and his daughter Gretchen are shown on page 100. Steve's son, Navy pilot Travis is on page 176, and Steve's teacher daughter Stephanie on pages 619 and 782.

Photos of City College of San Francisco physics-instructor friends open several chapters and are named there. Others include Diana Lininger Markham, pages 152, 182. Fred Cauthen, pages 146, 540. Norman Whitlatch, page 454. Dave Wall, page 550. Roger King, pages 354, 688. Jill Evans, pages, 64, 140, and 488, and Chelcie Liu, page 44.

Suppliers of physics equipment are friends David and Christine Vernier of Vernier Software, page 126, Paul Stokstad of PASCO, page 152, and Peter Rea of Arbor Scientific, page 215.

The following people are personal American friends in order of appearance: Judith Brand, whose skillful edits grace this entire edition, page 2. David Vasquez, pages 2, 143. Will Maynez, pages 24, 116, 341, and 504. Sue Johnson, Huey Johnson's wife, p 44. Lab Manual author Dean Baird, pages 44, 45, 366, 557, 562, and 583. Paul Doherty, pages 84, 85, 550. David Kagan, pages 84, 688. Howie Brand from college days, pages 104, 384. David Manning, pages 120, 177, 304, and his daughter Brady, page 59. Bob Miner, page 129, his wife Ana, page 24, and

Ana's daughter Estefania, page 368. Tenny Lim, page 133, draws her bow, a photo that has appeared in every book since the sixth edition. Tenny again on pages 184, 185. Young Andrea Wu, page 150. Marshall Ellenstein, pages 158, 302, 622, 623. Alexei Cogan, page 169. Alan Davis with son William, page 184, and William again, page 512, and a photo taken by his mom Fe, page 589. Chuck Stone, page 213. John Hubisz, page 260. Ray Serway, page 280. Evan Jones, page 304. Fred Myers, pages 304, 305, 512, 592, 712. Helen Yan, pages 346, 347, 622. Dennis McNelis, page 353, and his grandson Myles Dooley, page 423. Exploratorium physicist Ron Hipschman on pages 184, 366, 367, 373, 644. Childhood best friend Paul Ryan is on page 378. Huey and Sue Johnson's grandson Bay Johnson, page 452. Ryan Patterson, page 436. Elan Lavie, page 462. Kirby Perchbacher, pages 286 and 462. Karen Jo Matsler, pages 542 and 592. Bruce Novak, page 554, and his mom Greta Novak on page 302. Charlie Spiegel, page 559. Suzanne Lyons and children Simone and Tristan, page 572. Carlos Vasquez, page 572. Jeff Wetherhold, page 572. Bree Barnett Dreyfuss, page 622. Phil Wolf, page 666. Brad Huff, page 692. Stanley Micklavzina, page 704, Walter Steiger, page 717. Brenda Skoczelas, page 752. Mike and Jane Jukes, pages 780 and 796.

The physics community is global. International friends in order of appearance: My protégé Einstein Dhayal (India), pages 2, 530. Cedric and Anne Linder (Sweden), pages 24, 25. Carl Angell (Norway), page 44. Derek Muller (Canada), pages 104, 105. Peter Hopkinson (Canada), pages 122, 592. Bilal Gunes (Turkey), page 152. Ed van den Berg (Netherlands), page 184, and his wife Daday, page 488. Tomas Brage (Sweden), page 184, and with Barbara Brage, page 384. Ole Anton and Aage Mellem (Norway), page 326. Anette Zetterberg (Sweden), page 326, and husband P. O. page 384, with son Johan on page 304. Johan's wife Sara Bloomberg on page 282. Z. Tugba Kahyaoglu (Turkey), pages 462, 530. Mona El Tawil-Nassar (Egypt), page 480. David Housden (New Zealand), page 502. Roger Rasool (Australia), pages 704 and 716.

These are photographs of people very dear to me, which makes *Conceptual Physics* all the more a labor of love.

# To the Student

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

I enjoy physics, and you will too — because you'll understand it. If you get hooked and take a follow-up course, then you can focus on mathematical problems. Go for comprehension of concepts now, and if computation follows, it will be with understanding.

Enjoy your physics!

Paul G. Hewitt

# To the Instructor

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

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

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

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

$$\mathsf{s} = \mathsf{s}_0 + \delta \ni$$
$$\mathsf{s} = \mathsf{s}_0 \ni + \tfrac{1}{2} \delta \ni^2$$
$$\mathsf{s}^2 = \mathsf{s}_0^2 + 2\delta \mathsf{s}$$
$$\mathsf{s}_a = \tfrac{1}{2}(\mathsf{s}_0 + \mathsf{s})$$

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

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

Chapter 5 continues with Newton's third law. Many third-law examples via vectors and their components should bring clarity to this commonly misunderstood law of motion. More on vectors is found in Appendix D and especially in the *Practice Book*.