ELEVENTH EDITION

COLLEGE PHYSICS

SERWAY ✦ VUILLE

EDITION

11

College Physics

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We dedicate this book to our wives, children, grandchildren, relatives, and friends who have provided so much love, support, and understanding through the years, and to the students for whom this book was written.

Contents Overview

PART 1 Mechanics

Topic 1 Units, Trigonometry, and Vectors 1
Topic 2 Motion in One Dimension 31
Topic 3 Motion in Two Dimensions 59
Topic 4 Newton's Laws of Motion 80
Topic 5 Energy 121
Topic 6 Momentum, Impulse, and Collisions 161
Topic 7 Rotational Motion and Gravitation 190
Topic 8 Rotational Equilibrium and Dynamics 224
Topic 9 Fluids and Solids 267

PART 2 Thermodynamics

Topic 10 Thermal Physics 320
Topic 11 Energy in Thermal Processes 349
Topic 12 The Laws of Thermodynamics 382

PART 3 Vibrations and Waves

Topic 13 Vibrations and Waves 423
Topic 14 Sound 457

PART 4 Electricity and Magnetism

Topic 15 Electric Forces and Fields 495
Topic 16 Electrical Energy and Capacitance 527
Topic 17 Current and Resistance 566
Topic 18 Direct-Current Circuits 590
Topic 19 Magnetism 620
Topic 20 Induced Voltages and Inductance 656
Topic 21 Alternating- Current Circuits and Electromagnetic Waves 688

PART 5 Light and Optics

Topic 22 Reflection and Refraction of Light 723
Topic 23 Mirrors and Lenses 750
Topic 24 Wave Optics 782
Topic 25 Optical Instruments 814

PART 6 Modern Physics

Topic 26 Relativity 838
Topic 27 Quantum Physics 864
Topic 28 Atomic Physics 886
Topic 29 Nuclear Physics 908
Topic 30 Nuclear Energy and Elementary Particles 932

APPENDIX A: Mathematics Review A.1
APPENDIX B: An Abbreviated Table of Isotopes A.14
APPENDIX C: Some Useful Tables A.19
APPENDIX D: SI Units A.21
ANSWERS: Quick Quizzes, Example Questions, and Odd-Numbered Conceptual Questions and Problems A.23
Index I.1

Contents

ABOUT THE AUTHORS viii
PREFACE ix
ENGAGING APPLICATIONS xxi
MCAT TEST PREPARATION GUIDE xxiii

PART 1 Mechanics

Topic 1 Units, Trigonometry, and Vectors 1

1.1 Standards of Length, Mass, and Time 1
1.2 The Building Blocks of Matter 3
1.3 Dimensional Analysis 4
1.4 Uncertainty in Measurement and Significant Figures 6
1.5 Unit Conversions for Physical Quantities 9
1.6 Estimates and Order-of-Magnitude Calculations 11
1.7 Coordinate Systems 13
1.8 Trigonometry Review 14
1.9 Vectors 16
1.10 Components of a Vector 18
1.11 Problem-Solving Strategy 22
Summary 24

Topic 2 Motion in One Dimension 31

2.1 Displacement, Velocity, and Acceleration 31
2.2 Motion Diagrams 41
2.3 One-Dimensional Motion with Constant Acceleration 42
2.4 Freely Falling Objects 48
Summary 53

Topic 3 Motion in Two Dimensions 59

3.1 Displacement, Velocity, and Acceleration in Two Dimensions 59
3.2 Two-Dimensional Motion 61
3.3 Relative Velocity 69
Summary 73

Topic 4 Newton's Laws of Motion 80

4.1 Forces 80
4.2 The Laws of Motion 82
4.3 The Normal and Kinetic Friction Forces 92
4.4 Static Friction Forces 96
4.5 Tension Forces 98
4.6 Applications of Newton's Laws 100
4.7 Two-Body Problems 106
Summary 111

Topic 5 Energy 121

5.1 Work 121
5.2 Kinetic Energy and the Work–Energy Theorem 126
5.3 Gravitational Potential Energy 129
5.4 Gravity and Nonconservative Forces 135
5.5 Spring Potential Energy 137
5.6 Systems and Energy Conservation 142
5.7 Power 144
5.8 Work Done by a Varying Force 149
Summary 151

Topic 6 Momentum, Impulse, and Collisions 161

6.1 Momentum and Impulse 161
6.2 Conservation of Momentum 166
6.3 Collisions in One Dimension 169
6.4 Glancing Collisions 176
6.5 Rocket Propulsion 178
Summary 181

Topic 7 Rotational Motion and Gravitation 190

7.1 Angular Velocity and Angular Acceleration 190
7.2 Rotational Motion Under Constant Angular Acceleration 194
7.3 Tangential Velocity, Tangential Acceleration, and Centripetal Acceleration 195
7.4 Newton's Second Law for Uniform Circular Motion 201
7.5 Newtonian Gravitation 206
Summary 215

Topic 8 Rotational Equilibrium and Dynamics 224

8.1 Torque 224
8.2 Center of Mass and Its Motion 228
8.3 Torque and the Two Conditions for Equilibrium 234
8.4 The Rotational Second Law of Motion 238
8.5 Rotational Kinetic Energy 246
8.6 Angular Momentum 249
Summary 253

Topic 9 Fluids and Solids 267

9.1 States of Matter 267
9.2 Density and Pressure 268
9.3 Variation of Pressure with Depth 272
9.4 Pressure Measurements 276
9.5 Buoyant Forces and Archimedes' Principle 277
9.6 Fluids in Motion 283
9.7 Other Applications of Fluid Dynamics 289
9.8 Surface Tension, Capillary Action, and Viscous Fluid Flow 292
9.9 Transport Phenomena 300
9.10 The Deformation of Solids 304
Summary 310

PART 2 Thermodynamics

Topic 10 Thermal Physics 320

10.1 Temperature and the Zeroth Law of Thermodynamics 320
10.2 Thermometers and Temperature Scales 321
10.3 Thermal Expansion of Solids and Liquids 326
10.4 The Ideal Gas Law 332
10.5 The Kinetic Theory of Gases 337
Summary 343

Topic 11 Energy in Thermal Processes 349

11.1 Heat and Internal Energy 349
11.2 Specific Heat 351
11.3 Calorimetry 353
11.4 Latent Heat and Phase Change 355
11.5 Energy Transfer 361
11.6 Climate Change and Greenhouse Gases 372
Summary 374

Topic 12 The Laws of Thermodynamics 382

12.1 Work in Thermodynamic Processes 382
12.2 The First Law of Thermodynamics 386
12.3 Thermal Processes in Gases 389

12.4 Heat Engines and the Second Law of Thermodynamics 397
12.5 Entropy 406
12.6 Human Metabolism 412
Summary 415

PART 3 Vibrations and Waves

Topic 13 Vibrations and Waves 423

13.1 Hooke's Law 423
13.2 Elastic Potential Energy 426
13.3 Concepts of Oscillation Rates in Simple Harmonic Motion 431
13.4 Position, Velocity, and Acceleration as Functions of Time 434
13.5 Motion of a Pendulum 437
13.6 Damped Oscillations 440
13.7 Waves 441
13.8 Frequency, Amplitude, and Wavelength 444
13.9 The Speed of Waves on Strings 445
13.10 Interference of Waves 447
13.11 Reflection of Waves 448
Summary 449

Topic 14 Sound 457

14.1 Producing a Sound Wave 457
14.2 Characteristics of Sound Waves 458
14.3 The Speed of Sound 459
14.4 Energy and Intensity of Sound Waves 461
14.5 Spherical and Plane Waves 464
14.6 The Doppler Effect 466
14.7 Interference of Sound Waves 471
14.8 Standing Waves 473
14.9 Forced Vibrations and Resonance 477
14.10 Standing Waves in Air Columns 478
14.11 Beats 482
14.12 Quality of Sound 484
14.13 The Ear 485
Summary 487

PART 4 Electricity and Magnetism

Topic 15 Electric Forces and Fields 495

15.1 Electric Charges, Insulators, and Conductors 495
15.2 Coulomb's Law 498
15.3 Electric Fields 503
15.4 Electric Field Lines 507
15.5 Conductors in Electrostatic Equilibrium 510
15.6 The Millikan Oil-Drop Experiment 512
15.7 The Van de Graaff Generator 513
15.8 Electric Flux and Gauss' Law 514
Summary 519

Topic 16 Electrical Energy and Capacitance 527

16.1 Electric Potential Energy and Electric Potential 527
16.2 Electric Potential and Potential Energy of Point Charges 534
16.3 Potentials, Charged Conductors, and Equipotential Surfaces 537
16.4 Applications 539
16.5 Capacitors 541
16.6 Combinations of Capacitors 544
16.7 Energy in a Capacitor 550
16.8 Capacitors with Dielectrics 552
Summary 558

Topic 17 Current and Resistance 566

17.1 Electric Current 566
17.2 A Microscopic View: Current and Drift Speed 569
17.3 Current and Voltage Measurements In Circuits 571
17.4 Resistance, Resistivity, and Ohm's Law 572
17.5 Temperature Variation of Resistance 576
17.6 Electrical Energy and Power 577
17.7 Superconductors 580
17.8 Electrical Activity in the Heart 582
Summary 585

Topic 18 Direct-Current Circuits 590

18.1 Sources of emf 590
18.2 Resistors in Series 591
18.3 Resistors in Parallel 594
18.4 Kirchhoff's Rules and Complex DC Circuits 599
18.5 *RC* Circuits 602
18.6 Household Circuits 606
18.7 Electrical Safety 607
18.8 Conduction of Electrical Signals by Neurons 609
Summary 611

Topic 19 Magnetism 620

19.1 Magnets 620
19.2 Earth's Magnetic Field 622
19.3 Magnetic Fields 624
19.4 Motion of a Charged Particle in a Magnetic Field 627
19.5 Magnetic Force on a Current-Carrying Conductor 629
19.6 Magnetic Torque 632
19.7 Ampère's Law 635
19.8 Magnetic Force Between Two Parallel Conductors 638
19.9 Magnetic Fields of Current Loops and Solenoids 640
19.10 Magnetic Domains 643
Summary 645

Topic 20 Induced Voltages and Inductance 656

20.1 Induced emf and Magnetic Flux 656
20.2 Faraday's Law of Induction and Lenz's Law 659
20.3 Motional emf 665
20.4 Generators 668
20.5 Self-Inductance 672
20.6 *RL* Circuits 675
20.7 Energy Stored in Magnetic Fields 678
Summary 679

Topic 21 Alternating-Current Circuits and Electromagnetic Waves 688

21.1 Resistors in an AC Circuit 688
21.2 Capacitors in an AC Circuit 691
21.3 Inductors in an AC Circuit 693
21.4 The *RLC* Series Circuit 694
21.5 Power in an AC Circuit 698
21.6 Resonance in a Series *RLC* Circuit 700
21.7 The Transformer 701
21.8 Maxwell's Predictions 703
21.9 Hertz's Confirmation of Maxwell's Predictions 704
21.10 Production of Electromagnetic Waves by an Antenna 705
21.11 Properties of Electromagnetic Waves 707
21.12 The Spectrum of Electromagnetic Waves 711
21.13 The Doppler Effect for Electromagnetic Waves 714
Summary 715

PART 5 Light and Optics

Topic 22 Reflection and Refraction of Light 723

22.1 The Nature of Light 723
22.2 Reflection and Refraction 724
22.3 The Law of Refraction 728
22.4 Dispersion and Prisms 733
22.5 The Rainbow 736

22.6 Huygens' Principle 736
22.7 Total Internal Reflection 738
Summary 742

Topic 23 Mirrors and Lenses 750

23.1 Flat Mirrors 750
23.2 Images Formed by Spherical Mirrors 753
23.3 Images Formed by Refraction 760
23.4 Atmospheric Refraction 763
23.5 Thin Lenses 764
23.6 Lens and Mirror Aberrations 772
Summary 773

Topic 24 Wave Optics 782

24.1 Conditions for Interference 782
24.2 Young's Double-Slit Experiment 783
24.3 Change of Phase Due to Reflection 787
24.4 Interference in Thin Films 788
24.5 Using Interference to Read CDs and DVDs 792
24.6 Diffraction 793
24.7 Single-Slit Diffraction 795
24.8 Diffraction Gratings 797
24.9 Polarization of Light Waves 800
Summary 807

Topic 25 Optical Instruments 814

25.1 The Camera 814
25.2 The Eye 815
25.3 The Simple Magnifier 819
25.4 The Compound Microscope 821
25.5 The Telescope 823
25.6 Resolution of Single-Slit and Circular Apertures 826
25.7 The Michelson Interferometer 830
Summary 832

PART 6 Modern Physics

Topic 26 Relativity 838

26.1 Galilean Relativity 838
26.2 The Speed of Light 839
26.3 Einstein's Principle of Relativity 841
26.4 Consequences of Special Relativity 842
26.5 Relativistic Momentum 849
26.6 Relative Velocity in Special Relativity 850
26.7 Relativistic Energy and the Equivalence of Mass and Energy 852
26.8 General Relativity 856
Summary 859

Topic 27 Quantum Physics 864

27.1 Blackbody Radiation and Planck's Hypothesis 864
27.2 The Photoelectric Effect and the Particle Theory of Light 866
27.3 X-Rays 869
27.4 Diffraction of X-Rays by Crystals 871
27.5 The Compton Effect 874
27.6 The Dual Nature of Light and Matter 875
27.7 The Wave Function 878
27.8 The Uncertainty Principle 879
Summary 881

Topic 28 Atomic Physics 886

28.1 Early Models of the Atom 886
28.2 Atomic Spectra 887
28.3 The Bohr Model 889
28.4 Quantum Mechanics and the Hydrogen Atom 893
28.5 The Exclusion Principle and the Periodic Table 897
28.6 Characteristic X-Rays 899
28.7 Atomic Transitions and Lasers 901
Summary 903

Topic 29 Nuclear Physics 908

29.1 Some Properties of Nuclei 908
29.2 Binding Energy 911
29.3 Radioactivity 912
29.4 The Decay Processes 916
29.5 Natural Radioactivity 921
29.6 Nuclear Reactions 922
29.7 Medical Applications of Radiation 924
Summary 927

Topic 30 Nuclear Energy and Elementary Particles 932

30.1 Nuclear Fission 932
30.2 Nuclear Fusion 936
30.3 Elementary Particles and the Fundamental Forces 939
30.4 Positrons and Other Antiparticles 940
30.5 Classification of Particles 940
30.6 Conservation Laws 942
30.7 The Eightfold Way 945
30.8 Quarks and Color 945
30.9 Electroweak Theory and the Standard Model 947
30.10 The Cosmic Connection 949
30.11 Unanswered Questions in Cosmology 951
30.12 Problems and Perspectives 953
Summary 954

APPENDIX A: Mathematics Review A.1

APPENDIX B: An Abbreviated Table of Isotopes A.14

APPENDIX C: Some Useful Tables A.19

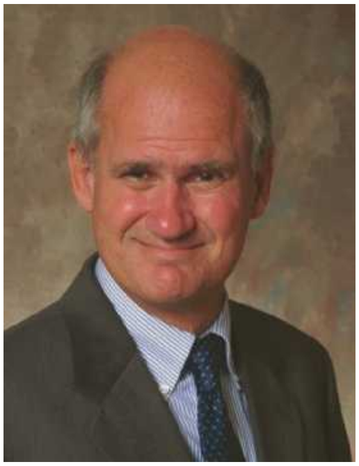
APPENDIX D: SI Units A.21

Answers: Quick Quizzes, Example Questions, and Odd-Numbered Conceptual Questions and Problems A.23

Index I.1

About the Authors

Raymond A. Serway received his doctorate at Illinois Institute of Technology and is Professor Emeritus at James Madison University. In 2011, he was awarded an honorary doctorate degree from his alma mater, Utica College. He received the 1990 Madison Scholar Award at James Madison University, where he taught for 17 years. Dr. Serway began his teaching career at Clarkson University, where he conducted research and taught from 1967 to 1980. He was the recipient of the Distinguished Teaching Award at Clarkson University in 1977 and the Alumni Achievement Award from Utica College in 1985. As Guest Scientist at the IBM Research Laboratory in Zurich, Switzerland, he worked with K. Alex Müller, 1987 Nobel Prize recipient. Dr. Serway was also a visiting scientist at Argonne National Laboratory, where he collaborated with his mentor and friend, the late Sam Marshall. Early in his career, he was employed as a research scientist at the Rome Air Development Center from 1961 to 1963 and at the IIT Research Institute from 1963 to 1967. Dr. Serway is also the coauthor of *Physics for Scientists and Engineers*, ninth edition; *Principles of Physics: A Calculus-Based Text*, fifth edition; *Essentials of College Physics*, *Modern Physics*, third edition; and the high school textbook *Physics*, published by Holt, Rinehart and Winston. In addition, Dr. Serway has published more than 40 research papers in the field of condensed matter physics and has given more than 60 presentations at professional meetings. Dr. Serway and his wife Elizabeth enjoy traveling, playing golf, fishing, gardening, singing in the church choir, and especially spending quality time with their four children, nine grandchildren, and a great grandson.



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Preface

College Physics is written for a one-year course in introductory physics usually taken by students majoring in biology, the health professions, or other disciplines, including environmental, earth, and social sciences, and technical fields such as architecture. The mathematical techniques used in this book include algebra, geometry, and trigonometry, but not calculus. Drawing on positive feedback from users of the tenth edition, analytics gathered from both professors and students, as well as reviewers' suggestions, we have refined the text to better meet the needs of students and teachers. In addition, the text now has a fully-integrated learning path in MindTap.

This textbook, which covers the standard topics in classical physics and twentieth-century physics, is divided into six parts. Part 1 (Topics 1–9) deals with Newtonian mechanics and the physics of fluids; Part 2 (Topics 10–12) is concerned with heat and thermodynamics; Part 3 (Topics 13 and 14) covers wave motion and sound; Part 4 (Topics 15–21) develops the concepts of electricity and magnetism; Part 5 (Topics 22–25) treats the properties of light and the field of geometric and wave optics; and Part 6 (Topics 26–30) provides an introduction to special relativity, quantum physics, atomic physics, and nuclear physics.

Objectives

The main objectives of this introductory textbook are twofold: to provide the student with a clear and logical presentation of the basic concepts and principles of physics and to strengthen their understanding of them through a broad range of interesting, real-world applications. To meet those objectives, we have emphasized sound physical arguments and problem-solving methodology. At the same time we have attempted to motivate the student through practical examples that demonstrate the role of physics in other disciplines. Finally, with the text fully integrated into MindTap, we provide a learning path that keeps students on track for success.

Changes to the Eleventh Edition

The text has been carefully edited to improve clarity of presentation and precision of language. We hope that the result is a book both accurate and enjoyable to read. Although the overall content and organization of the textbook are similar to the tenth edition, numerous changes and improvements have been made in preparing the eleventh edition. Some of the new features are based on our experiences and on current trends in science education. Other changes have been incorporated in response to comments and suggestions offered by users of the tenth edition. The features listed here represent the major changes made for the eleventh edition.

MindTap® for Physics

MindTap®

MindTap for Physics is the digital learning solution that helps instructors engage and transform today's students into critical thinkers. Through paths of dynamic assignments and applications that instructors can personalize, real-time course analytics, and an accessible reader, MindTap helps instructors turn cookie-cutter assignments into cutting-edge learning pathways and elevate student engagement beyond memorization into higher-level thinking.

Developed and designed in response to years of research, MindTap leverages modern technology and a powerful answer evaluation system to address the unmet needs of students and educators. The MindTap Learning Path groups the most engaging digital learning assets and activities together by week and topic, including readings and automatically graded assessments, to help students master each learning objective. MindTap for Physics assessments incorporate assorted just-in-time learning tools such as displayed solutions, solution videos for selected problems, targeted readings, and examples from the textbook. These just-in-time tools are embedded directly adjacent to each question to help students maintain focus while completing automatically graded assessments.

Easy to use, efficient and informative, MindTap provides instructors with the ability to personalize their course with dynamic online learning tools, videos and assessments. An assignable Pre-Course Assessment (PCA) provides a student diagnostic pre-test and personalized improvement plans to help students' foundational math skills outside of class time.

Interactive Video Vignettes encourage an active classroom where students can address their alternate conceptions outside of the classroom. Interactive Video Vignettes include online video analysis and interactive individual tutorials to address learning difficulties identified by PER (Physics Education Research).

Organization by Topics

Our preparatory research for this edition showed that successful students don't just *read* physics, they *engage with* physics. The MindTap platform is designed as an integrated, active educational experience that incorporates diverse media and has assessment-based applied knowledge at its very core. While integrating *College Physics* into MindTap, we realized that students were using the textbook as a resource while working on their online homework, rather than as a narrative source. As we continued creating a variety of media, just-in-time-help, and other material to support our activity-based pedagogy, it became clear we were building learning paths and designing assessments around specific *topics*, guided by the fundamental learning objectives of those topics. Consequently, we switched from "chapters" to "topics" to emphasize the textbook's new place as part of an active, fully-integrated online MindTap experience.

Vector Rearrangement

The topic of vectors has been moved to Topic 1 with other preliminary material. This rearrangement allows students to get comfortable with vectors and how they are used in physics well before they're needed for solving problems.

Revision of Topic 4 (Newton's Law of Motion)

A revision to the discussion of Newton's laws of motion will ease students' entry into this difficult topic and increase their success. Here, the common contact forces are introduced early, including the normal force, the kinetic friction force, tension forces, and the static friction force. After finishing these new sections, students will already know how to calculate these forces in the most common contexts. Then, when encountering applications, they will suddenly find that many difficult, two-dimensional problems will reduce to one dimension, because the second dimension simply gives the normal and friction forces that they already understand.

The System Approach Extended to Rotating Systems

The most difficult problems in first-year physics are those involving both the second law of motion and the second law of motion for rotation. Following an insight by one of the authors (Vuille) while teaching an introductory class, it turns out that these problems, involving up to four equations and four unknowns, can often be easily solved with one equation and one unknown! Vuille has put this technique in Topic 8 (Rotational Equilibrium and Dynamics). Not found in any other first-year textbook, this technique greatly reduces the learning curve in that topic by turning the hardest problem type into one of the easiest.

New Conceptual Questions

One hundred and twenty-five of the conceptual questions in the text (25% of the total amount) are new to this edition; they have been developed to be more systematic and clicker-friendly.

New End-of-Topic Problems

Hundreds of new problems have been developed for this edition, taking into account statistics on problem usage by past users.

Textbook Features

Most instructors would agree that the textbook assigned in a course should be the student's primary guide for understanding and learning the subject matter. Further, the textbook should be easily accessible and written in a style that facilitates instruction and learning. With that in mind, we have included the following pedagogical features to enhance the textbook's usefulness to both students and instructors.

Examples Each example constitutes a complete learning experience, with a strategy statement, a side-by-side solution and commentary, conceptual training, and an exercise. Every effort has been made to ensure the collection of examples, as a whole, is comprehensive in covering all the physical concepts, physics problem types, and required mathematical techniques. The examples are in a two-column format for a pedagogic purpose: students can study the example, then cover up the right column and attempt to solve the problem using the cues in the left column. Once successful in that exercise, the student can cover up both solution columns and attempt to solve the problem using only the strategy statement, and finally just the problem statement. The Question at the end of the example usually requires a conceptual response or determination, but they also include estimates requiring knowledge of the relationships between concepts. The answers for the Questions can be found at the back of the book. On the next page is an in-text worked example, with an explanation of each of the example's main parts.

Artwork Every piece of artwork in the eleventh edition is in a modern style that helps express the physics principles at work in a clear and precise fashion. Every piece of art is also drawn to make certain that the physical situations presented correspond exactly to the text discussion at hand.

Guidance labels are included with many figures in the text; these point out important features of the figure and guide students through figures without having to go back and forth from the figure legend to the figure itself. This format also helps those students who are visual learners. An example of this kind of figure appears at the bottom of this page.

Conceptual Questions At the end of each topic are approximately fifteen conceptual questions. The Applying Physics examples presented in the text serve as models for students when conceptual questions are assigned and show how the concepts can be applied to understanding the physical world. The conceptual questions provide the student with a means of self-testing the concepts presented in the topic. Some conceptual questions are appropriate for initiating classroom

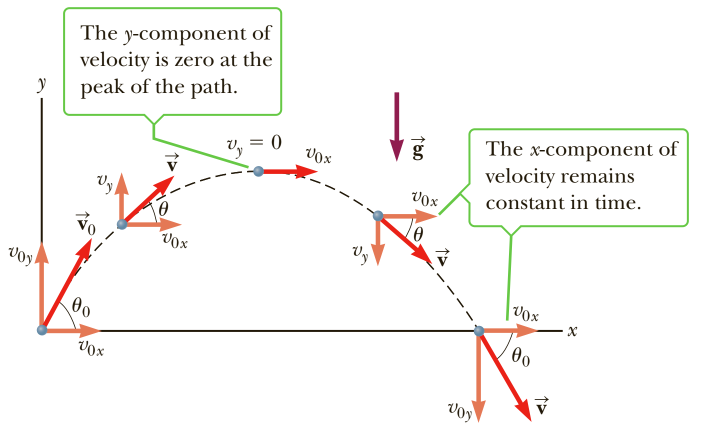

Figure 3.5 The parabolic trajectory of a particle that leaves the origin with a velocity of $\vec{\mathbf{v}}_0$. Note that $\vec{\mathbf{v}}$ changes with time. However, the x-component of the velocity, v_x, remains constant in time, equal to its initial velocity, v0x. Also, $v_y = 0$ at the peak of the trajectory, but the acceleration is always equal to the free-fall acceleration and acts vertically downward.

The **Goal** describes the physical concepts being explored within the worked example.

The **Problem** statement presents the problem itself.

The **Strategy** section helps students analyze the problem and create a framework for working out the solution.

The **Solution** section uses a two-column format that gives the explanation for each step of the solution in the left-hand column, while giving each accompanying mathematical step in the right-hand column. This layout facilitates matching the idea with its execution and helps students learn how to organize their work. Another benefit: students can easily use this format as a training tool, covering up the solution on the right and solving the problem using the comments on the left as a guide.

EXAMPLE 13.7 MEASURING THE VALUE OF *g*

GOAL Determine g from pendulum motion.

PROBLEM Using a small pendulum of length 0.171 m, a geophysicist counts 72.0 complete swings in a time of 60.0 s. What is the value of g in this location?

STRATEGY First calculate the period of the pendulum by dividing the total time by the number of complete swings. Solve Equation 13.15 for g and substitute values.

SOLUTION

Calculate the period by dividing the total elapsed time by the number of complete oscillations:

$$T = \frac{\text{time}}{\#\text{ of oscillations}} = \frac{60.0\text{ s}}{72.0} = 0.833\text{ s}$$

Solve Equation 13.15 for g and substitute values:

$$T = 2\pi\sqrt{\frac{L}{g}} \rightarrow T^2 = 4\pi^2\frac{L}{g}$$

$$g = \frac{4\pi^2 L}{T^2} = \frac{(39.5)(0.171\text{ m})}{(0.833\text{ s})^2} = 9.73\text{ m/s}^2$$

REMARKS Measuring such a vibration is a good way of determining the local value of the acceleration of gravity.

QUESTION 13.7 True or False: A simple pendulum of length 0.50 m has a larger frequency of vibration than a simple pendulum of length 1.0 m.

EXERCISE 13.7 What would be the period of the 0.171-m pendulum on the Moon, where the acceleration of gravity is 1.62 m/s^2?

ANSWER 2.04 s

Remarks follow each Solution and highlight some of the underlying concepts and methodology used in arriving at a correct solution. In addition, the remarks are often used to put the problem into a larger, real-world context.

Question Each worked example features a conceptual question that promotes student understanding of the underlying concepts contained in the example.

Exercise/Answer Every Question is followed immediately by an exercise with an answer. These exercises allow students to reinforce their understanding by working a similar or related problem, with the answers giving them instant feedback. At the option of the instructor, the exercises can also be assigned as homework. Students who work through these exercises on a regular basis will find the end-of-topic problems less intimidating.

discussions. Answers to odd-numbered conceptual questions are included in the Answers section at the end of the book. Answers to even-numbered questions are in the *Instructor's Solutions Manual*.

Problems All questions and problems for this revision were carefully reviewed to improve their variety, interest, and pedagogical value while maintaining their clarity and quality. An extensive set of problems is included at the end of each topic (in all, more than 2 100 problems are provided in the eleventh edition). Answers to odd-numbered problems are given at the end of the book. For the convenience of both the student and instructor, about two-thirds of the problems are keyed to specific sections of the topic. The remaining problems, labeled "Additional Problems," are not keyed to specific sections. The three levels of problems are graded according to their difficulty. Straightforward problems are numbered in **black**, intermediate level problems are numbered in **blue**, and the most challenging problems are numbered in **red**.

There are six other types of problems we think instructors and students will find interesting as they work through the text; these are indicated in the problems set by the following icons:

- T **Tutorials** available in MindTap help students solve problems by having them work through a stepped-out solution.
- V **Show Me a Video** solutions available in MindTap explain fundamental problem-solving strategies to help students step through selected problems.

- BIO **Biomedical problems** deal with applications to the life sciences and medicine.
- S **Symbolic problems** require the student to obtain an answer in terms of symbols. In general, some guidance is built into the problem statement. The goal is to better train the student to deal with mathematics at a level appropriate to this course. Most students at this level are uncomfortable with symbolic equations, which is unfortunate because symbolic equations are the most efficient vehicle for presenting relationships between physics concepts. Once students understand the physical concepts, their ability to solve problems is greatly enhanced. As soon as the numbers are substituted into an equation, however, all the concepts and their relationships to one another are lost, melded together in the student's calculator. Symbolic problems train the student to postpone substitution of values, facilitating their ability to think conceptually using the equations. An example of a symbolic problem is provided here:

> 14. S An object of mass m is dropped from the roof of a building of height h. While the object is falling, a wind blowing parallel to the face of the building exerts a constant horizontal force F on the object. (a) How long does it take the object to strike the ground? Express the time t in terms of g and h. (b) Find an expression in terms of m and F for the acceleration a_x of the object in the horizontal direction (taken as the positive x-direction). (c) How far is the object displaced horizontally before hitting the ground? Answer in terms of m, g, F, and h. (d) Find the magnitude of the object's acceleration while it is falling, using the variables F, m, and g.

- Q|C **Quantitative/conceptual problems** encourage the student to think conceptually about a given physics problem rather than rely solely on computational skills. Research in physics education suggests that standard physics problems requiring calculations may not be entirely adequate in training students to think conceptually. Students learn to substitute numbers for symbols in the equations without fully understanding what they are doing or what the symbols mean. Quantitative/conceptual problems combat this tendency by asking for answers that require something other than a number or a calculation. An example of a quantitative/conceptual problem is provided here:

> 5. Q|C Starting from rest, a 5.00-kg block slides 2.50 m down a rough 30.0° incline. The coefficient of kinetic friction between the block and the incline is $\mu_k = 0.436$. Determine (a) the work done by the force of gravity, (b) the work done by the friction force between block and incline, and (c) the work done by the normal force. (d) Qualitatively, how would the answers change if a shorter ramp at a steeper angle were used to span the same vertical height?

- GP **Guided problems** help students break problems into steps. A physics problem typically asks for one physical quantity in a given context. Often, however, several concepts must be used and a number of calculations are required to get that final answer. Many students are not accustomed to this level of complexity and often don't know where to start. A guided problem breaks a problem into smaller steps, enabling students to grasp all the concepts and strategies required to arrive at a correct solution. Unlike standard physics problems, guidance is often built into the problem statement. For example, the problem might say "Find the speed using conservation of energy" rather than asking only for the speed. In any given topic, there are usually two or three problem types that are particularly suited to this problem form. The problem must have a certain level of complexity, with a similar problem-solving strategy involved each time it appears. Guided problems are reminiscent of how a student might interact with a professor in an office visit.

These problems help train students to break down complex problems into a series of simpler problems, an essential problem-solving skill. An example of a guided problem is provided here:

62. GP Two blocks of masses m_1 and m_2 ($m_1 > m_2$) are placed on a frictionless table in contact with each other. A horizontal force of magnitude F is applied to the block of mass m_1 in Figure P4.62. (a) If P is the magnitude of the contact force between the blocks, draw the free-body diagrams for each block. (b) What is the net force on the system consisting of both blocks? (c) What is the net force acting on m_1? (d) What is the net force acting on m_2? (e) Write the x-component of Newton's second law for each block. (f) Solve the resulting system of two equations and two unknowns, expressing the acceleration a and contact force P in terms of the masses and force. (g) How would the answers change if the force had been applied to m_2 instead? (*Hint:* use symmetry; don't calculate!) Is the contact force larger, smaller, or the same in this case? Why?

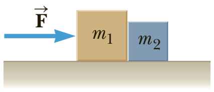

Figure P4.62

Quick Quizzes All the Quick Quizzes (see example below) are cast in an objective format, including multiple-choice, true–false, matching, and ranking questions. Quick Quizzes provide students with opportunities to test their understanding of the physical concepts presented. The questions require students to make decisions on the basis of sound reasoning, and some have been written to help students overcome common misconceptions. Answers to all Quick Quiz questions are found at the end of the textbook, and answers with detailed explanations are provided in the *Instructor's Solutions Manual*. Many instructors choose to use Quick Quiz questions in a "peer instruction" teaching style.

Quick Quiz

4.4 A small sports car collides head-on with a massive truck. The greater impact force (in magnitude) acts on (a) the car, (b) the truck, (c) neither, the force is the same on both. Which vehicle undergoes the greater magnitude acceleration? (d) the car, (e) the truck, (f) the accelerations are the same.

Problem-Solving Strategies A general problem-solving strategy to be followed by the student is outlined at the end of Topic 1. This strategy provides students with a structured process for solving problems. In most topics, more specific strategies and suggestions (see example below) are included for solving the types of problems featured in both the worked examples and the end-of-topic problems.

PROBLEM-SOLVING STRATEGY

Newton's Second Law

Problems involving Newton's second law can be very complex. The following protocol breaks the solution process down into smaller, intermediate goals:

1. **Read** the problem carefully at least once.
2. **Draw** a picture of the system, identify the object of primary interest, and indicate forces with arrows.
3. **Label** each force in the picture in a way that will bring to mind what physical quantity the label stands for (e.g., T for tension).
4. **Draw** a free-body diagram of the object of interest, based on the labeled picture. If additional objects are involved, draw separate free-body diagrams for them. Choose convenient coordinates for each object.
5. **Apply Newton's second law.** The x- and y-components of Newton's second law should be taken from the vector equation and written individually. This usually results in two equations and two unknowns.
6. **Solve** for the desired unknown quantity, and substitute the numbers.

This feature helps students identify the essential steps in solving problems and increases their skills as problem solvers.

Biomedical Applications For biology and pre-med students, BIO icons point the way to various practical and interesting applications of physical principles to biology and medicine. A list of these applications can be found on pages xxi-xxii.

MCAT Test Preparation Guide Located on pages xxiii and xxiv, this guide outlines the six content categories related to physics on the new MCAT exam that began being administered in 2015. Students can use the guide to prepare for the MCAT exam, class tests, or homework assignments.

Applying Physics The Applying Physics features provide students with an additional means of reviewing concepts presented in that section. Some Applying Physics examples demonstrate the connection between the concepts presented in that topic and other scientific disciplines. These examples also serve as models for students when they are assigned the task of responding to the Conceptual Questions presented at the end of each topic. For examples of Applying Physics boxes, see Applying Physics 9.5 (Home Plumbing) on page 292 and Applying Physics 13.1 (Bungee Jumping) on page 433.

Tips Placed in the margins of the text, Tips address common student misconceptions and situations in which students often follow unproductive paths (see example at right). More than 95 Tips are provided in this edition to help students avoid common mistakes and misunderstandings.

Tip 4.3 Newton's Second Law Is a *Vector* Equation

In applying Newton's second law, add all of the forces on the object as vectors and then find the resultant vector acceleration by dividing by m. Don't find the individual magnitudes of the forces and add them like scalars.

Marginal Notes Comments and notes appearing in the margin (see example at the right) can be used to locate important statements, equations, and concepts in the text.

◀ Newton's third law

Applications Although physics is relevant to so much in our modern lives, it may not be obvious to students in an introductory course. Application margin notes (see example to the right) make the relevance of physics to everyday life more obvious by pointing out specific applications in the text. Some of these applications pertain to the life sciences and are marked with a BIO icon. A list of the Applications appears on pages xxi and xxii.

BIO **APPLICATION**

Diet Versus Exercise in Weight-loss Programs

Style To facilitate rapid comprehension, we have attempted to write the book in a style that is clear, logical, relaxed, and engaging. The somewhat informal and relaxed writing style is designed to connect better with students and enhance their reading enjoyment. New terms are carefully defined, and we have tried to avoid the use of jargon.

Introductions All topics begin with a brief preview that includes a discussion of the topic's objectives and content.

Units The international system of units (SI) is used throughout the text. The U.S. customary system of units is used only to a limited extent in the topics on mechanics and thermodynamics.

Pedagogical Use of Color Readers should consult the pedagogical color chart (inside the front cover) for a listing of the color-coded symbols used in the text diagrams. This system is followed consistently throughout the text.

Important Statements and Equations Most important statements and definitions are set in **boldface** type or are highlighted with a background screen for added emphasis and ease of review. Similarly, important equations are highlighted with a tan background to facilitate location.

Illustrations and Tables The readability and effectiveness of the text material, worked examples, and end-of-topic conceptual questions and problems are enhanced by the large number of figures, diagrams, photographs, and tables. Full color adds clarity to the artwork and makes illustrations as realistic as possible. Three-dimensional effects are rendered with the use of shaded and lightened areas where appropriate. Vectors are color coded, and curves in graphs are drawn in color. Color photographs have been carefully selected, and their accompanying captions have been written to serve as an added instructional tool. A complete description of the pedagogical use of color appears on the inside front cover.

Summary The end-of-topic Summary is organized by individual section heading for ease of reference. Most topic summaries also feature key figures from the topic.

Significant Figures Significant figures in both worked examples and end-of-topic problems have been handled with care. Most numerical examples and problems are worked out to either two or three significant figures, depending on the accuracy of the data provided. Intermediate results presented in the examples are rounded to the proper number of significant figures, and only those digits are carried forward.

Appendices and Endpapers Several appendices are provided at the end of the textbook. Most of the appendix material (Appendix A) represents a review of mathematical concepts and techniques used in the text, including scientific notation, algebra, geometry, and trigonometry. Reference to these appendices is made as needed throughout the text. Most of the mathematical review sections include worked examples and exercises with answers. In addition to the mathematical review, some appendices contain useful tables that supplement textual information. For easy reference, the front endpapers contain a chart explaining the use of color throughout the book and a list of frequently used conversion factors.

Teaching Options

This book contains more than enough material for a one-year course in introductory physics, which serves two purposes. First, it gives the instructor more flexibility in choosing topics for a specific course. Second, the book becomes more useful as a resource for students. On average, it should be possible to cover about one topic each week for a class that meets three hours per week. Those sections, examples, and end-of-topic problems dealing with applications of physics to life sciences are identified with the BIO icon. We offer the following suggestions for shorter courses for those instructors who choose to move at a slower pace through the year.

Option A: If you choose to place more emphasis on contemporary topics in physics, you could omit all or parts of Topic 8 (Rotational Equilibrium and Rotational Dynamics), Topic 21 (Alternating-Current Circuits and Electromagnetic Waves), and Topic 25 (Optical Instruments).

Option B: If you choose to place more emphasis on classical physics, you could omit all or parts of Part 6 of the textbook, which deals with special relativity and other topics in twentieth-century physics.

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Lecture Presentation Resources

Cengage Learning Testing Powered by Cognero is a flexible, online system that allows you to author, edit, and manage test bank content from multiple Cengage Learning solutions, create multiple test versions in an instant, and deliver tests from your LMS, your classroom, or wherever you want.

Instructor Resource Website for Serway/Vuille *College Physics, Eleventh Edition*

The Instructor Resource Website contains a variety of resources to aid you in preparing and presenting text material in a manner that meets your personal preferences and course needs. The posted *Instructor's Solutions Manual* presents complete worked solutions for all end-of-chapter problems and even-numbered conceptual questions, answers for all even-numbered problems, and full answers with explanations for the Quick Quizzes. Robust PowerPoint lecture outlines that have been designed for an active classroom are available, with reading check questions and Think-Pair-Share questions as well as the traditional section-by-section outline. Images from the textbook can be used to customize your own presentations. Available online via **www.cengage.com/login**.

Student Resources

To register or access your online learning solution or purchase materials for your course, visit **www.cengagebrain.com**.

CENGAGEbrain.com buy. rent. access.

***Physics Laboratory Manual*, Fourth Edition** by David Loyd (Angelo State University). Ideal for use with any introductory physics text, Loyd's *Physics Laboratory Manual* is suitable for either calculus- or algebra/trigonometry-based physics courses. Designed to help students demonstrate a physical principle and teach techniques of careful measurement, Loyd's *Physics Laboratory Manual* also emphasizes conceptual understanding and includes a thorough discussion of physical theory to help students see the connection between the lab and the lecture. Many labs give students hands-on experience with statistical analysis, and now five computer-assisted data entry labs are included in the printed manual. The fourth edition maintains the minimum equipment requirements to allow for maximum flexibility and to make the most of preexisting lab equipment. For instructors interested in using some of Loyd's experiments, a customized lab manual is another option available through the Cengage Learning Custom Solutions program. Now, you can select specific experiments from Loyd's *Physics Laboratory Manual*, include your own original lab experiments, and create one affordable bound book. Contact your Cengage Learning representative for more information on our Custom Solutions program. Available with InfoTrac® Student Collections http://gocengage.com/infotrac.

***Physics Laboratory Experiments,* Eighth Edition** by Jerry D. Wilson (Lander College) and Cecilia A. Hernández (American River College). This market-leading manual for the first-year physics laboratory course offers a wide range of class-tested experiments designed specifically for use in small to midsize lab programs. A series of integrated experiments emphasizes the use of computerized instrumentation and includes a set of "computer-assisted experiments" to allow students and instructors to gain experience with modern equipment. It also lets instructors determine the appropriate balance of traditional versus computer-based experiments for their courses. By analyzing data through two different methods, students gain a greater understanding of the concepts behind the experiments. The Eighth Edition is updated with four new economical labs to accommodate shrinking department budgets and thirty new Pre-Lab Demonstrations, designed to capture students' interest prior to the lab and requiring only widely available materials and items.

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Raymond A. Serway
St. Petersburg, Florida

Chris Vuille
Daytona Beach, Florida

Engaging Applications

Although physics is relevant to so much in our lives, it may not be obvious to students in an introductory course. In this eleventh edition of *College Physics,* we continue a design feature begun in the seventh edition. This feature makes the relevance of physics to everyday life more obvious by pointing out specific applications in the form of a marginal note. Some of these applications pertain to the life sciences and are marked with the BIO icon. The list below is not intended to be a complete listing of all the applications of the principles of physics found in this textbook. Many other applications are to be found within the text and especially in the worked examples, conceptual questions, and end-of-topic problems.

Topic 3

Long jumping, p. 65

Topic 4

Seat belts, p. 83
Helicopter flight, p. 90
Colliding vehicles, p. 91
Skydiving, p. 110

Topic 5

Accident reconstruction, p. 142
BIO Flagellar movement; bioluminescence, p. 143
Asteroid impact, p. 144
BIO Shamu sprint (power generated by killer whale), p. 146
BIO Energy and power in a vertical jump, pp. 147–149
BIO Diet versus exercise in weight-loss programs, p. 148
BIO Maximum power output from humans over various periods (table), p. 149

Topic 6

BIO Boxing and brain injury, p. 163
BIO Injury to passengers in car collisions, p. 165
BIO Conservation of momentum and squid propulsion, p. 167
BIO Glaucoma testing, p. 170
Professor Goddard was right all along: Rockets work in space! p. 178
Multistage rockets, p. 179

Topic 7

ESA launch sites, p. 196
Phonograph records and compact discs, p. 197
Artificial gravity, p. 202
Banked roadways, p. 204
Why is the Sun hot? p. 210
Geosynchronous orbit and telecommunications satellites, p. 215

Topic 8

BIO Locating your lab partner's center of gravity, pp. 230–231
BIO A weighted forearm, pp. 235–236
Bicycle gears, p. 240
BIO Warming up, pp. 243–244
Figure skating, p. 249
Aerial somersaults, p. 249
Rotating neutron stars, p. 250

Topic 9

Snowshoes, p. 270
Bed-of-nails trick, p. 271
BIO A pain in the ear, p. 273
Hydraulic lifts, p. 274
Building the pyramids, p. 276
BIO Decompression and injury to the lungs, p. 276
BIO Measuring blood pressure, p. 277
Ballpoint pens, p. 277
BIO Buoyancy control in fish, p. 279
BIO Cerebrospinal fluid, p. 279
Testing your car's antifreeze, pp. 279–280
Checking the battery charge, p. 280
Flight of a golf ball, pp. 289–290
"Atomizers" in perfume bottles and paint sprayers, p. 290
BIO Vascular flutter and aneurysms, p. 290
Lift on aircraft wings, p. 290
Sailing upwind, p. 291
Home plumbing, p. 292
Rocket engines, p. 292
BIO Air sac surface tension, p. 294
BIO Walking on water, p. 294
Detergents and waterproofing agents, p. 295
BIO Blood samples with capillary tubes, p. 296
BIO Capillary action in plants, p. 296
BIO Poiseuille's law and blood flow, p. 298
BIO A blood transfusion, p. 299
BIO Turbulent flow of blood, pp. 299–300
BIO Effect of osmosis on living cells, p. 301
BIO Kidney function and dialysis, p. 301
BIO Separating biological molecules with centrifugation, p. 304
BIO Football injuries, pp. 307–308
Arch structures in buildings, p. 309

Topic 10

BIO Skin temperature, p. 325
Thermal expansion joints, p. 326
Pyrex glass, p. 327
Bimetallic strips and thermostats, p. 328
Rising sea levels, p. 330
BIO Global warming and coastal flooding, pp. 330–331
BIO The expansion of water on freezing and life on Earth, p. 332
Bursting pipes in winter, p. 332
Expansion and temperature, p. 342

Topic 11

BIO Working off breakfast, pp. 350–351
BIO Physiology of exercise, p. 351
Sea breezes and thermals, p. 352
BIO Conductive losses from the human body, p. 363
BIO Minke whale temperature, p. 363
Home insulation, pp. 364–365
Construction and thermal insulation, pp. 365–366
Cooling automobile engines, p. 367
BIO Algal blooms in ponds and lakes, p. 367
BIO Body temperature, p. 368
Light-colored summer clothing, p. 369
BIO Thermography, p. 369
BIO Radiation thermometers for measuring body temperature, p. 369
Thermal radiation and night vision, p. 370
BIO Polar bear club, pp. 370–371
Estimating planetary temperatures, pp. 371–372
Thermos bottles, p. 372
BIO Global warming and greenhouse gases, pp. 372–374

Topic 12

Refrigerators and heat pumps, pp. 401–403
"Perpetual motion" machines, p. 407
The direction of time, p. 410
BIO Human metabolism, pp. 412–414
BIO Fighting fat, p. 413
Physical fitness and efficiency of the human body as a machine, p. 414

Topic 13

Archery, p. 428
Pistons and drive wheels, p. 431
Bungee jumping, p. 433
Pendulum clocks, p. 438
Use of pendulum in prospecting, p. 438
Shock absorbers, p. 440
Bass guitar strings, p. 446

Topic 14

BIO Medical uses of ultrasound, p. 458
BIO Cavitron ultrasonic surgical aspirator, p. 459
BIO High-intensity focused ultrasound (HIFU), p. 459
Ultrasonic ranging unit for cameras, p. 459
The sounds heard during a storm, pp. 460–461
BIO OSHA noise-level regulations, p. 464
Out-of-tune speakers, p. 468
Sonic booms, p. 471
Connecting your stereo speakers, p. 472
Tuning a musical instrument, p. 475
Guitar fundamentals, pp. 475–476
Shattering goblets with the voice, p. 477
Structural integrity and resonance, p. 478
Oscillations in a harbor, p. 480
Why are instruments warmed up? p. 480
How do bugles work? p. 480

Using beats to tune a musical instrument, p. 482
Why does the professor sound like Donald Duck? p. 485
BIO The ear, pp. 485–487
BIO Cochlear implants, p. 487

Topic 15
Measuring atmospheric electric fields, p. 509
Lightning rods, p. 511
Driver safety during electrical storms, p. 512

Topic 16
Automobile batteries, p. 532
The electrostatic precipitator, p. 539
The electrostatic air cleaner, p. 540
Xerographic copiers, p. 540
Laser printers, p. 541
Camera flash attachments, p. 542
Computer keyboards, p. 542
Electrostatic confinement, p. 542
BIO Defibrillators, p. 551
Stud finders, p. 554

Topic 17
Dimming of aging lightbulbs, p. 574
Lightbulb failures, p. 578
BIO Electrical activity in the heart, pp. 582–584
BIO Electrocardiograms, p. 582
BIO Cardiac pacemakers, p. 583
BIO Implanted cardioverter defibrillators, p. 583

Topic 18
Christmas lights in series, p. 592
Circuit breakers, p. 596
Three-way lightbulbs, p. 597
Timed windshield wipers, p. 603
BIO Bacterial growth, p. 604
Roadway flashers, p. 604
Fuses and circuit breakers, p. 607
Third wire on consumer appliances, p. 608
BIO Conduction of electrical signals by neurons, pp. 609–611

Topic 19
Dusting for fingerprints, p. 621
BIO Magnetic bacteria, p. 623
Labeling airport runways, p. 623
Compasses down under, p. 623
Mass spectrometers, p. 629
Loudspeaker operation, p. 631
BIO Electromagnetic pumps for artificial hearts and kidneys, p. 631
Lightning strikes, p. 631
Electric motors, p. 634

Topic 20
Ground fault interrupters (GFIs), p. 663
Electric guitar pickups, p. 663
BIO Apnea monitors, p. 664
Space catapult, p. 666
Alternating-current generators, p. 668
Direct-current generators, p. 670
Motors, p. 671

Topic 21
BIO Electric fields and cancer treatment, p. 691
Shifting phase to deliver more power, p. 699
Tuning your radio, p. 700
Metal detectors at the courthouse, p. 700
Long-distance electric power transmission, p. 702
Radio-wave transmission, p. 706
Solar system dust, p. 709
A hot tin roof (solar-powered homes), pp. 709–710
BIO Light and wound treatment, pp. 713–714
BIO The sun and the evolution of the eye, p. 714

Topic 22
Seeing the road on a rainy night, p. 725
BIO Red eyes in flash photographs, p. 726
The colors of water ripples at sunset, p. 726
Double images, p. 726
Refraction of laser light in a digital video disc (DVD), p. 732
Identifying gases with a spectrometer, p. 733
The rainbow, p. 736
Submarine periscopes, p. 739
BIO Fiber optics in medical diagnosis and surgery, p. 741
Fiber optics in telecommunications, p. 741
Design of an optical fiber, p. 741

Topic 23
Day and night settings for rearview mirrors, p. 752
Illusionist's trick, p. 752
Concave vs. convex, p. 757
Reversible waves, p. 757
BIO Underwater vision, p. 761
BIO Vision and diving masks, p. 767

Topic 24
A smoky Young's experiment, p. 786
Analog television signal interference, p. 786
Checking for imperfections in optical lenses, p. 789
Perfect mirrors, p. 792
The physics of CDs and DVDs, p. 792
Diffraction of sound waves, p. 796
Prism vs. grating, p. 798
Rainbows from a CD, p. 799
Tracking information on a CD, p. 799
Polarizing microwaves, p. 802
Polaroid sunglasses, p. 804
Finding the concentrations of solutions by means of their optical activity, p. 805
Liquid crystal displays (LCDs), p. 805

Topic 25
The camera, pp. 814–815
BIO The eye, pp. 815–819
BIO Using optical lenses to correct for defects, p. 817
BIO Prescribing a corrective lens for a farsighted patient, p. 818
BIO A corrective lens for nearsightedness, p. 819
Vision of the invisible man, p. 819
BIO Cat's eyes, p. 827

Topic 26
GPS, p. 857
Faster clocks in a "mile-high city," p. 859

Topic 27
Star colors, p. 865
Photocells, p. 869
Using x-rays to study the work of master painters, p. 871
BIO Electron microscopes, p. 877
X-ray microscopes? p. 878

Topic 28
Thermal or spectral? p. 888
Auroras, p. 888
Laser technology, p. 902
Laser eye surgery, p. 902

Topic 29
Binding nucleons and electrons, p. 912
Energy and half-life, p. 917
Carbon dating, p. 919
Smoke detectors, p. 920
BIO Radon pollution, p. 920
Should we report this skeleton to homicide? p. 921
BIO Medical applications of radiation, pp. 924–927
BIO Occupational radiation exposure limits, p. 925
BIO Irradiation of food and medical equipment, p. 925
BIO Radioactive tracers in medicine, p. 925
BIO Magnetic resonance imaging (MRI), pp. 926–927

Topic 30
Unstable products, p. 933
Nuclear reactor design, p. 935
Fusion reactors, p. 937
BIO Positron-emission tomography (PET scanning), p. 940
Breaking conservation laws, p. 944
Conservation of meson number, p. 946

Welcome to Your MCAT Test Preparation Guide

The MCAT Test Preparation Guide makes your copy of *College Physics,* eleventh edition, the most comprehensive MCAT study tool and classroom resource in introductory physics. The MCAT was revised in 2015 (see **www.aamc.org/students/applying/mcat/mcat2015** for more details); the test section that now includes problems related to physics is *Chemical and Physical Foundations of Biological Systems.* Of the ~65 test questions in this section, approximately 25% relate to introductory physics topics from the six content categories shown below:

Content Category 4A: Translational motion, forces, work, energy, and equilibrium in living systems

Review Plan

Motion

- **Topic 1, Sections 1.1, 1.3, 1.5, and 1.9–1.10**
  Quick Quizzes 1.1–1.2
  Examples 1.1–1.2, and 1.11–1.13
  Topic problems 1–6, 15–27, and 54–71
- **Topic 2, Sections 2.1–2.2**
  Quick Quizzes 2.1–2.5
  Examples 2.1–2.3
  Topic problems 1–25
- **Topic 3, Sections 3.1–3.2**
  Quick Quizzes 3.1–3.5
  Examples 3.1–3.6
  Topic problems 1–19, 47, 50, 53, and 56

Force and Equilibrium

- **Topic 4, Sections 4.1–4.4 and 4.6**
  Quick Quizzes 4.1–4.9
  Examples 4.1–4.12
  Topic problems 1–31, 38, 40, 49, and 53
- **Topic 8, Sections 8.1–8.3**
  Quick Quiz 8.1
  Examples 8.1–8.11
  Topic problems 1–36, 85, 91, and 92

Work

- **Topic 5, Sections 5.1 and 5.2**
  Quick Quiz 5.1–5.2
  Examples 5.1–5.3
  Topic problems 1–18 and 27
- **Topic 12, Section 12.1**
  Quick Quiz 12.1
  Examples 12.1–12.2
  Topic problems 1–10

Energy

- **Topic 5, Sections 5.2–5.7**
  Quick Quizzes 5.2–5.7
  Examples 5.3–5.14
  Topic problems 9–58, 67, 73, 74, and 78

Periodic Motion

- **Topic 13, Sections 13.7–13.9**
  Examples 13.8–13.10
  Topic problems 41–60

Content Category 4B: Importance of fluids for the circulation of blood, gas movement, and gas exchange

Review Plan

Fluids

- **Topic 9, Sections 9.1–9.3 and 9.5–9.9**
  Quick Quizzes 9.1–9.2 and 9.5–9.7
  Examples 9.1–9.16
  Topic problems 1–64, 79, 80, 81, 83, and 84

Gas phase

- **Topic 9, Section 9.5**
  Quick Quizzes 9.3–9.4
  Topic problems 8, 10, 14–15, and 83
- **Topic 10, Sections 10.2, 10.4, and 10.5**
  Quick Quiz 10.6
  Examples 10.1–10.2 and 10.6–10.10
  Topic problems 1–10 and 29–50

Content Category 4C: Electrochemistry and electrical circuits and their elements.

Review Plan

Electrostatics

- **Topic 15, Sections 15.1–15.4**
  Quick Quizzes 15.1 and 15.3–15.5
  Examples 15.1–15.5
  Topic problems 1–39
- **Topic 16, Sections 16.1–16.3**
  Quick Quizzes 16.1–16.7
  Examples 16.1–16.5
  Topic problems 1–24

Circuit elements

- **Topic 16, Sections 16.5–16.8**
  Quick Quizzes 16.8–16.11
  Examples 16.6–16.12
  Topic problems 29–57

- **Topic 17, Sections 17.1 and 17.3–17.5**
  Quick Quizzes 17.1 and 17.3–17.6
  Examples 17.1 and 17.3–17.4
  Topic problems 1–32 and 34
- **Topic 18, Sections 18.1–18.3 and 18.8**
  Quick Quizzes 18.1–18.8
  Examples 18.1–18.3
  Topic problems 1–17

Magnetism

- **Topic 19, Sections 19.1 and 19.3–19.4**
  Quick Quizzes 19.1–19.3
  Examples 19.1–19.4
  Topic problems 1–21

Content Category 4D: How light and sound interact with matter

Review Plan

Sound

- **Topic 13, Sections 13.7 and 13.8**
  Examples 13.8–13.9
  Topic problems 41–48
- **Topic 14, Sections 14.1–14.4, 14.6, 14.9–14.10, and 14.12–14.13**
  Quick Quizzes 14.1–14.3 and 14.5–14.6
  Examples 14.1–14.2, 14.4–14.5, and 14.9–14.10
  Topic problems 1–36 and 54–60

Light, electromagnetic radiation

- **Topic 21, Sections 21.10–21.12**
  Quick Quizzes 21.7 and 21.8
  Examples 21.8 and 21.9
  Topic problems 49–63 and 76
- **Topic 22, Sections 22.1**
  Topic problems 1–6
- **Topic 24, Sections 24.1, 24.4, and 24.6–24.9**
  Quick Quizzes 24.1–24.6
  Examples 24.1–24.4 and 24.6–24.8
  Topic problems 1–61
- **Topic 27, Section 27.3–27.4**
  Example 27.2
  Topic problems 15–23

Geometrical optics

- **Topic 22, Sections 22.2–22.4 and 22.7**
  Quick Quizzes 22.2–22.4
  Examples 22.1–22.6
  Topic problems 7–44 and 52
- **Topic 23, Sections 23.1–23.3 and 23.5–23.6**
  Quick Quizzes 23.1–23.6
  Examples 23.1–23.10
  Topic problems 1–46
- **Topic 25, Sections 25.1–25.6**
  Quick Quizzes 25.1–25.2
  Examples 25.1–25.8
  Topic problems 1–40, 60, and 62–65

Content Category 4E: Atoms, nuclear decay, electronic structure, and atomic chemical behavior

Review Plan

Atomic nucleus

- **Topic 29, Sections 29.1–29.5 and 29.7**
  Quick Quizzes 29.1–29.3
  Examples 29.1–29.5
  Topic problems 1–35, 44–50, and 57

Electronic structure

- **Topic 19, Section 19.10**
- **Topic 27, Sections 27.2 and 27.8**
  Examples 27.1 and 27.5
  Topic problems 9–14 and 35–40
- **Topic 28, Sections 28.2–28.3, 28.5, and 28.7**
  Quick Quizzes 28.1 and 28.3
  Examples 28.1 and 28.2
  Topic problems 1–30 and 37–41

Content Category 5E: Principles of chemical thermodynamics and kinetics

Review Plan

Energy changes in chemical reactions

- **Topic 10, Sections 10.1 and 10.3**
  Quick Quizzes 10.1–10.5
  Examples 10.3–10.5
  Topic problems 11–28
- **Topic 11, Sections 11.1–11.5**
  Quick Quizzes 11.1–11.5
  Examples 11.1–11.11
  Topic problems 1–50
- **Topic 12, Sections 12.1–12.2 and 12.4–12.6**
  Quick Quizzes 12.1 and 12.4–12.5
  Examples 12.1–12.3, 12.10–12.12, and 12.14–12.16
  Topic problems 1–61, 73–74

Units, Trigonometry, and Vectors

TOPIC 1

1.1 Standards of Length, Mass, and Time
1.2 The Building Blocks of Matter
1.3 Dimensional Analysis
1.4 Uncertainty in Measurement and Significant Figures
1.5 Unit Conversions for Physical Quantities
1.6 Estimates and Order-of-Magnitude Calculations
1.7 Coordinate Systems
1.8 Trigonometry Review
1.9 Vectors
1.10 Components of a Vector
1.11 Problem-Solving Strategy

THE GOAL OF PHYSICS IS TO PROVIDE an understanding of the physical world by developing theories based on experiments. A physical theory, usually expressed mathematically, describes how a given physical system works. The theory makes certain predictions about the physical system which can then be checked by observations and experiments. If the predictions turn out to correspond closely to what is actually observed, then the theory stands, although it remains provisional. No theory to date has given a complete description of all physical phenomena, even within a given subdiscipline of physics. Every theory is a work in progress.

The basic laws of physics involve such physical quantities as force, velocity, volume, and acceleration, all of which can be described in terms of more fundamental quantities. In mechanics, it is conventional to use the quantities of **length** (L), **mass** (M), and **time** (T); all other physical quantities can be constructed from these three.

1.1 Standards of Length, Mass, and Time

To communicate the result of a measurement of a certain physical quantity, a *unit* for the quantity must be defined. If our fundamental unit of length is defined to be 1.0 meter, for example, and someone familiar with our system of measurement reports that a wall is 2.0 meters high, we know that the height of the wall is twice the fundamental unit of length. Likewise, if our fundamental unit of mass is defined as 1.0 kilogram and we are told that a person has a mass of 75 kilograms, then that person has a mass 75 times as great as the fundamental unit of mass.

In 1960 an international committee agreed on a standard system of units for the fundamental quantities of science, called **SI** (Système International). Its units of length, mass, and time are the meter, kilogram, and second, respectively.

Tip 1.1 No Commas in Numbers with Many Digits

In science, numbers with more than three digits are written in groups of three digits separated by spaces rather than commas, so that 10 000 is the same as the common American notation 10,000. Similarly, $\pi = 3.14159265$ is written as 3.141 592 65.

1.1.1 Length

In 1799 the legal standard of length in France became the meter, defined as one ten-millionth of the distance from the equator to the North Pole. Until 1960, the official length of the meter was the distance between two lines on a specific bar of platinum–iridium alloy stored under controlled conditions. This standard was abandoned for several reasons, the principal one being that measurements of the separation between the lines were not precise enough. In 1960 the meter was defined as 1 650 763.73 wavelengths of orange-red light emitted from a krypton-86 lamp. In October 1983 this definition was abandoned also, and **the meter was redefined as the distance traveled by light in vacuum during a time interval of 1/299 792 458 second.** This latest definition establishes the speed of light at 299 792 458 meters per second.

◀ Definition of the meter

1.1.2 Mass

The SI unit of mass, the kilogram, is defined as the mass of a specific platinum–iridium alloy cylinder kept at the International Bureau of Weights and Measures at Sèvres, France (similar to that shown in Fig. 1.1a). As we'll see in Topic 4, mass is a

◀ Definition of the kilogram

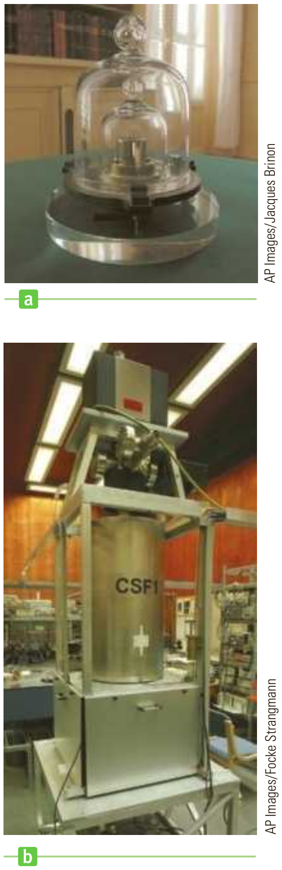

Figure 1.1 (a) International Prototype of the Kilogram, an accurate copy of the International Standard Kilogram kept at Sèvres, France, is housed under a double bell jar in a vault at the National Institute of Standards and Technology. (b) A cesium fountain atomic clock. The clock will neither gain nor lose a second in 20 million years.

quantity used to measure the resistance to a change in the motion of an object. It's more difficult to cause a change in the motion of an object with a large mass than an object with a small mass.

1.1.3 Time

Before 1960, the time standard was defined in terms of the average length of a solar day in the year 1900. (A solar day is the time between successive appearances of the Sun at the highest point it reaches in the sky each day.) The basic unit of time, the second, was defined to be $(1/60)(1/60)(1/24) = 1/86\ 400$ of the average solar day. In 1967 the second was redefined to take advantage of the high precision attainable with an atomic clock, which uses the characteristic frequency of the light emitted from the cesium-133 atom as its "reference clock." **The second is now defined as 9 192 631 700 times the period of oscillation of radiation from the cesium atom.** The newest type of cesium atomic clock is shown in Figure 1.1b.

1.1.4 Approximate Values for Length, Mass, and Time Intervals

Approximate values of some lengths, masses, and time intervals are presented in Tables 1.1, 1.2, and 1.3, respectively. Note the wide ranges of values. Study these tables to get a feel for a kilogram of mass (this book has a mass of about 2 kilograms), a time interval of 10^{10} seconds (one century is about 3×10^9 seconds), or 2 meters of length (the approximate height of a forward on a basketball team). Appendix A reviews the notation for powers of 10, such as the expression of the number 50 000 in the form 5×10^4.

Systems of units commonly used in physics are the Système International, in which the units of length, mass, and time are the meter (m), kilogram (kg), and second (s); the cgs, or Gaussian, system, in which the units of length, mass, and time are the centimeter (cm), gram (g), and second; and the U.S. customary system, in which the units of length, mass, and time are the foot (ft), slug, and second. SI units are almost universally accepted in science and industry and will be used throughout the book. Limited use will be made of Gaussian and U.S. customary units.

Table 1.1 Approximate Values of Some Measured Lengths

	Length (m)
Observable Universe	1×10^{26}
Earth to Andromeda	2×10^{22}
Earth to Proxima Centauri	4×10^{16}
One light-year	9×10^{15}
Earth to Sun	2×10^{11}
Earth to Moon	4×10^{8}
Radius of Earth	6×10^{6}
World's tallest building	8×10^{2}
Football field	9×10^{1}
Housefly	5×10^{-3}
Typical organism cell	1×10^{-5}
Hydrogen atom	1×10^{-10}
Atomic nucleus	1×10^{-14}
Proton diameter	1×10^{-15}

Table 1.2 Approximate Values of Some Masses

	Mass (kg)
Observable Universe	1×10^{52}
Milky Way galaxy	7×10^{41}
Sun	2×10^{30}
Earth	6×10^{24}
Moon	7×10^{22}
Shark	1×10^{2}
Human	7×10^{1}
Frog	1×10^{-1}
Mosquito	1×10^{-5}
Bacterium	1×10^{-15}
Hydrogen atom	2×10^{-27}
Electron	9×10^{-31}

Table 1.3 Approximate Values of Some Time Intervals

	Time Interval (s)
Age of Universe	5×10^{17}
Age of Earth	1×10^{17}
Age of college student	6×10^{8}
One year	3×10^{7}
One day	9×10^{4}
Heartbeat	8×10^{-1}
Audible sound wave period[a]	1×10^{-3}
Typical radio wave period[a]	1×10^{-6}
Visible light wave period[a]	2×10^{-15}
Nuclear collision	1×10^{-22}

[a]A *period* is defined as the time required for one complete vibration.

Some of the most frequently used "metric" (SI and cgs) prefixes representing powers of 10 and their abbreviations are listed in Table 1.4. For example, 10^{-3} m is equivalent to 1 millimeter (mm), and 10^{3} m is 1 kilometer (km). Likewise, 1 kg is equal to 10^{3} g, and 1 megavolt (MV) is 10^{6} volts (V). It's a good idea to memorize the more common prefixes early on: femto- to centi-, and kilo- to giga- are used routinely by most physicists.

Table 1.4 Some Prefixes for Powers of Ten Used with "Metric" (SI and cgs) Units

Power	Prefix	Abbreviation
10^{-18}	atto-	a
10^{-15}	femto-	f
10^{-12}	pico-	p
10^{-9}	nano-	n
10^{-6}	micro-	μ
10^{-3}	milli-	m
10^{-2}	centi-	c
10^{-1}	deci-	d
10^{1}	deka-	da
10^{3}	kilo-	k
10^{6}	mega-	M
10^{9}	giga-	G
10^{12}	tera-	T
10^{15}	peta-	P
10^{18}	exa-	E

1.2 The Building Blocks of Matter

A 1-kg ($\approx$ 2-lb) cube of solid gold has a length of about 3.73 cm ($\approx$ 1.5 in.) on a side. If the cube is cut in half, the two resulting pieces retain their chemical identity. But what happens if the pieces of the cube are cut again and again, indefinitely? The Greek philosophers Leucippus and Democritus couldn't accept the idea that such cutting could go on forever. They speculated that the process ultimately would end when it produced a particle that could no longer be cut. In Greek, *atomos* means "not sliceable." From this term comes our English word *atom*, once believed to be the smallest particle of matter but since found to be a composite of more elementary particles.

The atom can be naively visualized as a miniature solar system, with a dense, positively charged nucleus occupying the position of the Sun and negatively charged electrons orbiting like planets. This model of the atom, first developed by the great Danish physicist Niels Bohr nearly a century ago, led to the understanding of certain properties of the simpler atoms such as hydrogen but failed to explain many fine details of atomic structure.

Notice the size of a hydrogen atom, listed in Table 1.1, and the size of a proton—the nucleus of a hydrogen atom—one hundred thousand times smaller. If the proton were the size of a ping-pong ball, the electron would be a tiny speck about the size of a bacterium, orbiting the proton a kilometer away! Other atoms are similarly constructed. So there is a surprising amount of empty space in ordinary matter.

After the discovery of the nucleus in the early 1900s, questions arose concerning its structure. Although the structure of the nucleus remains an area of active research even today, by the early 1930s scientists determined that two basic entities—protons and neutrons—occupy the nucleus. The *proton* is nature's most common carrier of positive charge, equal in magnitude but opposite in sign to the charge on the electron. The number of protons in a nucleus determines what the element is. For instance, a nucleus containing only one proton is the nucleus of an atom of hydrogen, regardless of how many neutrons may be present. Extra neutrons correspond to different isotopes of hydrogen—deuterium and tritium—which react chemically in exactly the same way as hydrogen, but are more massive. An atom having two protons in its nucleus, similarly, is always helium, although again, differing numbers of neutrons are possible.

The existence of *neutrons* was verified conclusively in 1932. A neutron has no charge and has a mass about equal to that of a proton. Except for hydrogen, all atomic nuclei contain neutrons, which, together with the protons, interact through the strong nuclear force. That force opposes the strongly repulsive electrical force of the protons, which otherwise would cause the nucleus to disintegrate.

The division doesn't stop here; strong evidence collected over many years indicates that protons, neutrons, and a zoo of other exotic particles are composed of six particles called **quarks** (rhymes with "sharks" though some rhyme it with "forks"). These particles have been given the names *up, down, strange, charm, bottom,* and *top.* The up, charm, and top quarks each carry a charge equal to $+\frac{2}{3}$ that of the proton, whereas the down, strange, and bottom quarks each carry a charge equal to $-\frac{1}{3}$ the proton charge. The proton consists of two up quarks and one down quark (see Fig. 1.2), giving the correct charge for the proton, +1. The neutron is composed of two down quarks and one up quark and has a net charge of zero.

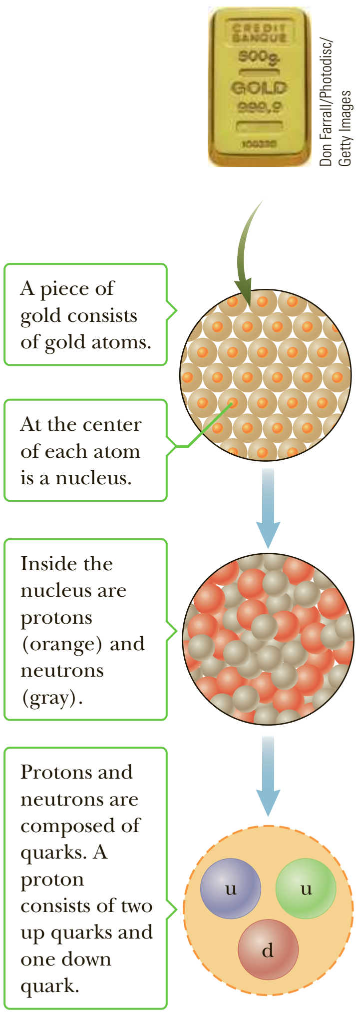

Figure 1.2 Levels of organization in matter.

The up and down quarks are sufficient to describe all normal matter, so the existence of the other four quarks, indirectly observed in high-energy experiments, is something of a mystery. Despite strong indirect evidence, no isolated quark has ever been observed. Consequently, the possible existence of yet more fundamental particles remains purely speculative.

1.3 Dimensional Analysis

In physics the word *dimension* denotes the physical nature of a quantity. The distance between two points, for example, can be measured in feet, meters, or furlongs, which are different ways of expressing the dimension of *length*.

The symbols used in this section to specify the dimensions of length, mass, and time are L, M, and T, respectively. Brackets [ ] will often be used to denote the dimensions of a physical quantity. In this notation, for example, the dimensions of velocity v are written $[v] = \mathrm{L/T}$, and the dimensions of area A are $[A] = \mathrm{L}^2$. The dimensions of area, volume, velocity, and acceleration are listed in Table 1.5, along with their units in the three common systems. The dimensions of other quantities, such as force and energy, will be described later as they are introduced.

In physics it's often necessary to deal with mathematical expressions that relate different physical quantities. One way to analyze such expressions, called **dimensional analysis,** makes use of the fact that **dimensions can be treated as algebraic quantities.** Adding masses to lengths, for example, makes no sense, so it follows that quantities can be added or subtracted only if they have the same dimensions. If the terms on the opposite sides of an equation have the same dimensions, then that equation may be correct, although correctness can't be guaranteed on the basis of dimensions alone. Nonetheless, dimensional analysis has value as a partial check of an equation and can also be used to develop insight into the relationships between physical quantities.

The procedure can be illustrated by developing some relationships between acceleration, velocity, time, and distance. Distance x has the dimension of length: $[x] = \mathrm{L}$. Time t has dimension $[t] = \mathrm{T}$. Velocity v has the dimensions length over time: $[v] = \mathrm{L/T}$, and acceleration the dimensions length divided by time squared: $[a] = \mathrm{L/T}^2$. Notice that velocity and acceleration have similar dimensions, except for an extra dimension of time in the denominator of acceleration. It follows that

$$[v] = \frac{\mathrm{L}}{\mathrm{T}} = \frac{\mathrm{L}}{\mathrm{T}^2}\mathrm{T} = [a][t]$$

From this it might be guessed that velocity equals acceleration multiplied by time, $v = at$, and that is true for the special case of motion with constant acceleration starting at rest. Noticing that velocity has dimensions of length divided by time and distance has dimensions of length, it's reasonable to guess that

$$[x] = \mathrm{L} = \mathrm{L}\frac{\mathrm{T}}{\mathrm{T}} = \frac{\mathrm{L}}{\mathrm{T}}\mathrm{T} = [v][t] = [a][t]^2$$

Here it appears that $x = at^2$ might correctly relate the distance traveled to acceleration and time; however, that equation is not even correct in the case of constant acceleration starting from rest. The correct expression in that case is $x = \frac{1}{2}at^2$.

Table 1.5 Dimensions and Some Units of Area, Volume, Velocity, and Acceleration

System	Area (L^2)	Volume (L^3)	Velocity (L/T)	Acceleration ($\mathrm{L/T}^2$)
SI	m^2	m^3	m/s	$\mathrm{m/s}^2$
cgs	cm^2	cm^3	cm/s	$\mathrm{cm/s}^2$
U.S. customary	ft^2	ft^3	ft/s	$\mathrm{ft/s}^2$

These examples serve to show the inherent limitations in using dimensional analysis to discover relationships between physical quantities. Nonetheless, such simple procedures can still be of value in developing a preliminary mathematical model for a given physical system. Further, because it's easy to make errors when solving problems, dimensional analysis can be used to check the consistency of the results. When the dimensions in an equation are not consistent, it indicates an error has been made in a prior step.

EXAMPLE 1.1 ANALYSIS OF AN EQUATION

GOAL Check an equation using dimensional analysis.

PROBLEM Show that the expression $v = v_0 + at$ is dimensionally correct, where v and v_0 represent velocities, a is acceleration, and t is a time interval.

STRATEGY Analyze each term, finding its dimensions, and then check to see if all the terms agree with each other.

SOLUTION

Find dimensions for v and v_0.

$$[v] = [v_0] = \frac{\mathrm{L}}{\mathrm{T}}$$

Find the dimensions of at.

$$[at] = [a][t] = \frac{\mathrm{L}}{\mathrm{T}^2}(\mathrm{T}) = \frac{\mathrm{L}}{\mathrm{T}}$$

REMARKS All the terms agree, so the equation is dimensionally correct.

QUESTION 1.1 True or False: An equation that is dimensionally correct is always physically correct, up to a constant of proportionality.

EXERCISE 1.1 Determine whether the equation $x = vt^2$ is dimensionally correct. If not, provide a correct expression, up to an overall constant of proportionality.

ANSWER Incorrect. The expression $x = vt$ is dimensionally correct.

EXAMPLE 1.2 FIND AN EQUATION

GOAL Derive an equation by using dimensional analysis.

PROBLEM Find a relationship between an acceleration of constant magnitude a, speed v, and distance r from the origin for a particle traveling in a circle.

STRATEGY Start with the term having the most dimensionality, a. Find its dimensions, and then rewrite those dimensions in terms of the dimensions of v and r. The dimensions of time will have to be eliminated with v, because that's the only quantity (other than a, itself) in which the dimension of time appears.

SOLUTION

Write down the dimensions of a:

$$[a] = \frac{\mathrm{L}}{\mathrm{T}^2}$$

Solve the dimensions of speed for T:

$$[v] = \frac{\mathrm{L}}{\mathrm{T}} \quad \rightarrow \quad \mathrm{T} = \frac{\mathrm{L}}{[v]}$$

Substitute the expression for T into the equation for $[a]$:

$$[a] = \frac{\mathrm{L}}{\mathrm{T}^2} = \frac{\mathrm{L}}{(\mathrm{L}/[v])^2} = \frac{[v]^2}{\mathrm{L}}$$

Substitute $\mathrm{L} = [r]$, and guess at the equation:

$$[a] = \frac{[v]^2}{[r]} \quad \rightarrow \quad a = \frac{v^2}{r}$$

REMARKS This is the correct equation for the magnitude of the centripetal acceleration—acceleration towards the center of motion—to be discussed in Topic 7. In this case it isn't necessary to introduce a numerical factor. Such a factor is often displayed explicitly as a constant k in front of the right-hand side; for example, $a = kv^2/r$. As it turns out, $k = 1$ gives the correct expression. A good technique sometimes introduced in calculus-based textbooks involves using unknown powers of the dimensions. This problem would then be set up as $[a] = [v]^b[r]^c$. Writing out the dimensions and equating powers of each dimension on both sides of the equation would result in $b = 2$ and $c = -1$.

(*Continued*)