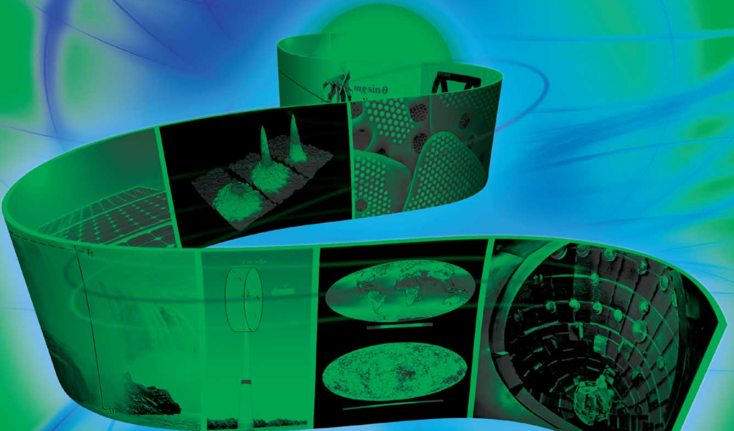
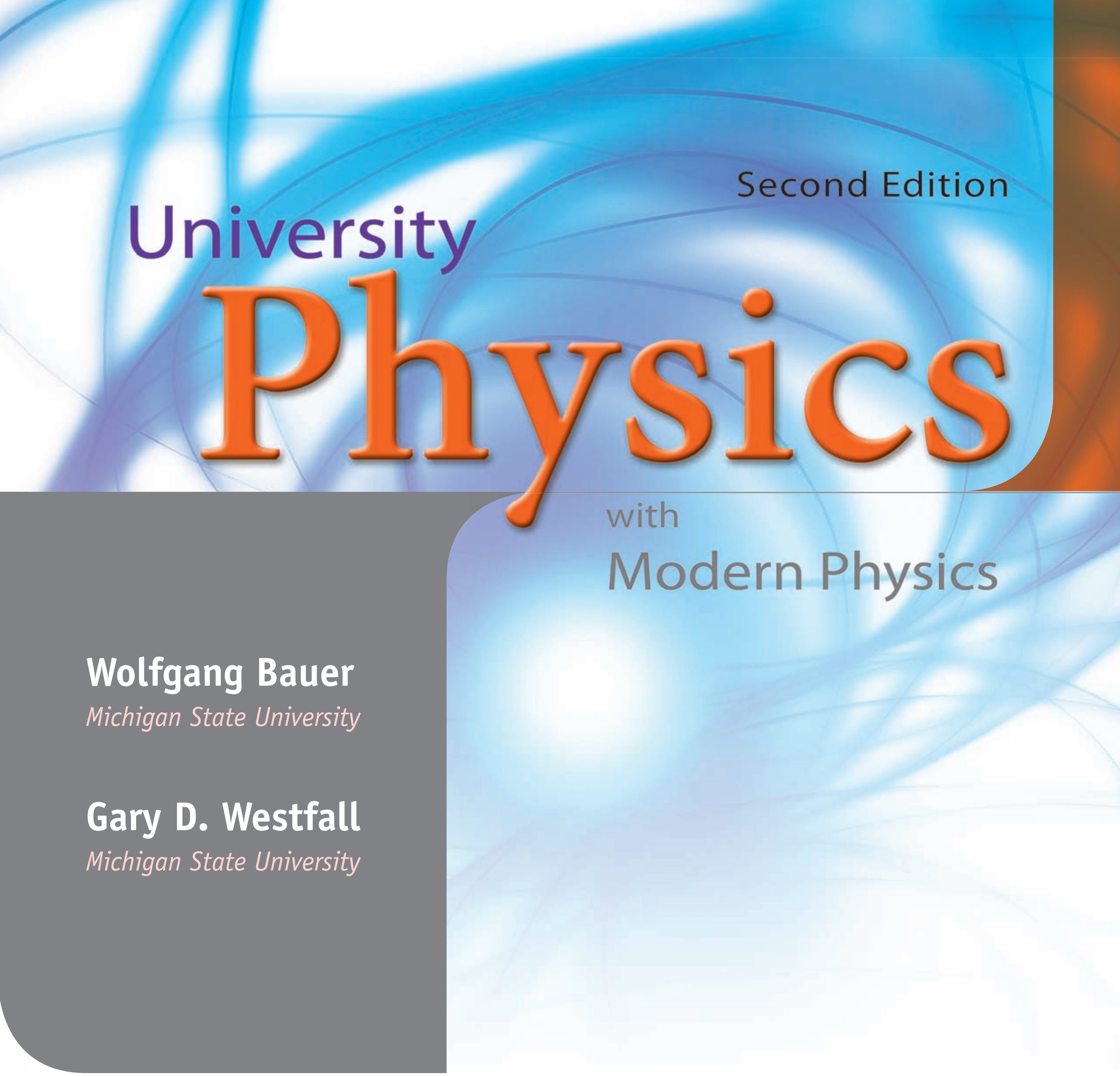
Second Edition

University Physics

with Modern Physics



Wolfgang Bauer | Gary D. Westfall



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University Physics

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Wolfgang Bauer
Michigan State University

Gary D. Westfall
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Brief Contents

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About the Authors

Wolfgang Bauer was born in Germany and obtained his Ph.D. in theoretical nuclear physics from the University of Giessen in 1987. After a post-doctoral fellowship at the California Institute of Technology, he joined the faculty at Michigan State University in 1988, with a dual appointment at the National Superconducting Cyclotron Laboratory (NSCL). He has worked on a large variety of topics in theoretical and computational physics, from high-temperature superconductivity to supernova explosions, but has been especially interested in relativistic nuclear collisions. He is probably best known for his work on phase transitions of nuclear matter in heavy ion collisions. In recent years, Dr. Bauer has focused much of his research and teaching on issues concerning energy, including fossil fuel resources, ways to use energy more efficiently, and, in particular, alternative and carbon-neutral energy resources. In 2009, he founded the Institute for Cyber-Enabled Research and served as its first director until 2013. He presently serves as chairperson of the Department of Physics and Astronomy and is a University Distinguished Professor at Michigan State University.

Gary D. Westfall started his career at the Center for Nuclear Studies at the University of Texas at Austin, where he completed his Ph.D. in experimental nuclear physics in 1975. From there he went to Lawrence Berkeley National Laboratory (LBNL) in Berkeley, California, to conduct his post-doctoral work in high-energy nuclear physics and then stayed on as a staff scientist. While he was at LBNL, Dr. Westfall became internationally known for his work on the nuclear fireball model and the use of fragmentation to produce nuclei far from stability. In 1981, Dr. Westfall joined the National Superconducting Cyclotron Laboratory (NSCL) at Michigan State University (MSU) as a research professor; there he conceived, constructed, and ran the MSU 4π Detector. His research using the 4π Detector produced information concerning the response of nuclear matter as it is compressed in a supernova collapse. In 1987, Dr. Westfall joined the Department of Physics and Astronomy at MSU while continuing to carry out his research at NSCL. In 1994, Dr. Westfall joined the STAR Collaboration, which is carrying out experiments at the Relativistic Heavy Ion Collider (RHIC) at Brookhaven National Laboratory on Long Island, New York. In 2003, he was named University Distinguished Professor at Michigan State University.

The Westfall/Bauer Partnership Drs. Bauer and Westfall have collaborated on nuclear physics research and on physics education research for more than two decades. The partnership started in 1988, when both authors were speaking at the same conference and decided to go downhill skiing together after the session. On this occasion, Westfall recruited Bauer to join the faculty at Michigan State University (in part by threatening to push him off the ski lift if he declined). They obtained NSF funding to develop novel teaching and laboratory techniques, authored multimedia physics CDs for their students at the Lyman Briggs School, and co-authored a textbook on CD-ROM, called *cliXX Physik*. In 1992, they became early adopters of the Internet for teaching and learning by developing the first version of their online homework system. In subsequent years, they were instrumental in creating the Learning*Online* Network with CAPA, which is now used at more than 70 universities and colleges in the United States and around the world. Since 2008, Bauer and Westfall have been part of a team of instructors, engineers, and physicists, who investigate the use of peer-assisted learning in the introductory physics curriculum. This project has received funding from the NSF STEM Talent Expansion Program, and its best practices have been incorporated into this textbook.

Dedication This book is dedicated to our families. Without their patience, encouragement, and support, we could never have completed it.

A Note from the Authors

We are excited to introduce the second edition of our textbook, *University Physics*. Physics is a thriving science, alive with intellectual challenge and presenting innumerable research problems on topics ranging from the largest galaxies to the smallest subatomic particles. Physicists have managed to bring understanding, order, consistency, and predictability to our universe and will continue that endeavor into the exciting future.

However, when we open most current introductory physics textbooks, we find that a different story is being told. Physics is painted as a completed science in which the major advances happened at the time of Newton, or perhaps early in the 20th century. Only toward the end of the standard textbooks is "modern" physics covered, and even that coverage often includes only discoveries made through the 1960s.

Our main motivation in writing this book is to change this perception by weaving exciting, contemporary physics throughout the text. Physics is an amazingly dynamic discipline—continuously on the verge of new discoveries and life-changing applications. In order to help students see this, we need to tell the full, absorbing story of our science by integrating contemporary physics into the first-year calculus-based course. Even the very first semester offers many opportunities to do this by weaving recent results from nonlinear dynamics, chaos, complexity, and high-energy physics research into the introductory curriculum. Because we are actively carrying out research in these fields, we know that many of the cutting-edge results are accessible in their essence to the first-year student.

Recent results involving renewable energy, the environment, engineering, medicine, and technology show physics as an exciting, thriving, and intellectually alive subject motivating students, invigorating classrooms, and making the instructor's job easier and more enjoyable. In particular, we believe that talking about the broad topic of energy provides a great opening gambit to capture students' interest. Concepts of energy sources (fossil, renewable, nuclear, and so forth), energy efficiency, energy storage, alternative energy sources, and environmental effects of energy supply choices (global warming and ocean acidification, for example) are very much accessible on the introductory physics level. We find that discussions of energy spark our students' interest like no other current topic, and we have addressed different aspects of energy throughout our book.

In addition to being exposed to the exciting world of physics, students benefit greatly from gaining the ability to **problem solve and think logically about a situation.** Physics is based on a core set of ideas that is fundamental to all of science. We acknowledge this and provide a useful problem-solving method (outlined in Chapter 1) which is used throughout the entire book. This problem-solving method involves a multistep format that we have developed with students in our classes. But mastery of concepts also involves actively applying them. To this end, we have asked more than a dozen contributors from some of the leading universities across the country to share their best work in the end-of-chapter exercises. New to this edition are approximately 400 multi-version exercises, which allow students to address the same problem from different perspectives.

In 2012, the National Research Council published a framework for K-12 science education, which covers the essential science and engineering practices, the concepts that have application across fields, and the core ideas in four disciplinary areas (in physics, these are matter and its interactions, motion and stability, energy, and waves and their applications in information transfer). We have structured the second edition of this textbook to tie the undergraduate physics experience to this framework and have provided concept checks and self-test opportunities in each chapter.

With all of this in mind, along with the desire to write a captivating textbook, we have created what we hope will be a tool to engage students' imaginations and to better prepare them for future courses in their chosen fields (admittedly, hoping we can convert at least a few students to physics majors along the way). Having feedback from more than 400 people, including a board of advisors, several contributors, manuscript reviewers, and focus group participants, assisted greatly in this enormous undertaking, as did field testing our ideas with approximately 6000 students in our introductory physics classes at Michigan State University. We thank you all!

—Wolfgang Bauer and Gary D. Westfall

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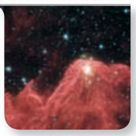

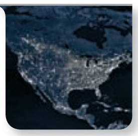

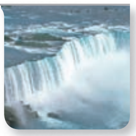

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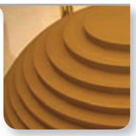

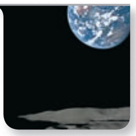

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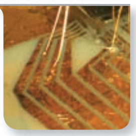

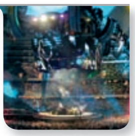

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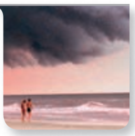

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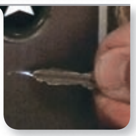

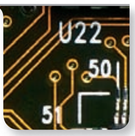

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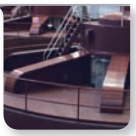

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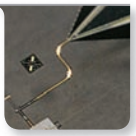
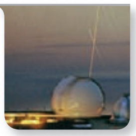




How to Use This Book

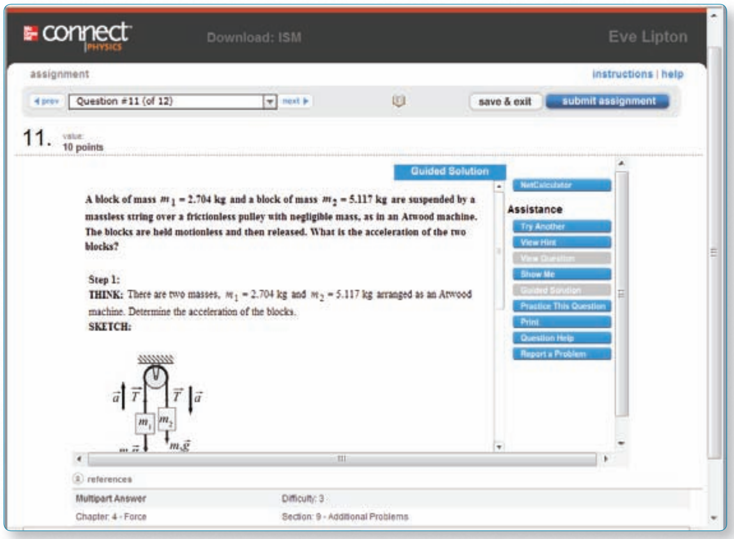
Problem-Solving Skills: Learning to Think Like a Scientist

Perhaps one of the greatest skills students can take from their physics course is the ability to **problem solve and think critically about a situation.** Physics is based on a core set of fundamental ideas that can be applied to various situations and problems. *University Physics* by Bauer and Westfall acknowledges this and provides a problem-solving method that has been class-tested by the authors, which is used throughout the text. The text's problem-solving method has a multistep format.

Problem-Solving Method

Solved Problems

The book's numbered **Solved Problems** are fully worked problems, each consistently following the seven-step method described in Section 1.5. Each Solved Problem begins with the problem statement and then provides a complete solution. The seven-step method is also used in Connect Physics. The familiar seven steps are outlined in the guided solutions, with additional help where you need it.



A block of mass $m_1 = 2.704$ kg and a block of mass $m_2 = 5.117$ kg are suspended by a massless string over a frictionless pulley with negligible mass, as in an Atwood machine. The blocks are held motionless and then released. What is the acceleration of the two blocks?

Step 1:
THINK: There are two masses, $m_1 = 2.704$ kg and $m_2 = 5.117$ kg arranged as an Atwood machine. Determine the acceleration of the blocks.
SKETCH:

SOLVED PROBLEM 13.2 Weighing Earth's Atmosphere

The Earth's atmosphere is composed (by volume) of 78.08% nitrogen (N_2), 20.95% oxygen (O_2), 0.93% argon (Ar), 0.25% water vapor (H_2O), and traces of other gases, most importantly, carbon dioxide (CO_2). The CO_2 content of the atmosphere is currently around 0.039% = 390 ppm (parts per million), but it varies with the seasons by about 6–7 ppm and has been rising since the start of the Industrial Revolution, mainly as a result of the burning of fossil fuels. Approximately 2 ppm of CO_2 are being added to the atmosphere each year.

PROBLEM
What is the mass of the Earth's atmosphere, and what is the mass of 1 ppm of atmospheric CO_2?

SOLUTION
THINK At first glance, this problem seems rather daunting, because very little information is given. However, we know that the atmospheric pressure is $1.01 \cdot 10^5$ Pa and that pressure is force per area.

SKETCH The sketch in Figure 13.13 shows a column of air with weight mg above an area A of Earth's surface. This air exerts a pressure, p, on the surface.

RESEARCH We start with the relationship between pressure and force, $p = F/A$, where the area is the surface area of Earth, $A = 4\pi R^2$, and $R = 6370$ km is the radius of Earth. For the force, we can use the atmospheric weight, $F = mg$, where m is the mass of the atmosphere.

SIMPLIFY We combine the equations just mentioned

$$p = \frac{F}{A} = \frac{mg}{4\pi R^2}$$

and solve for the mass of the atmosphere

$$m = \frac{4\pi R^2 p}{g}.$$

CALCULATE We substitute the numerical values:

$$m = 4\pi(6.37 \cdot 10^6 \text{ m})^2(1.01 \cdot 10^5 \text{ Pa})/(9.81 \text{ m/s}^2) = 5.24978 \cdot 10^{18} \text{ kg}.$$

ROUND We round to three significant figures and obtain

$$m = 5.25 \cdot 10^{18} \text{ kg}.$$

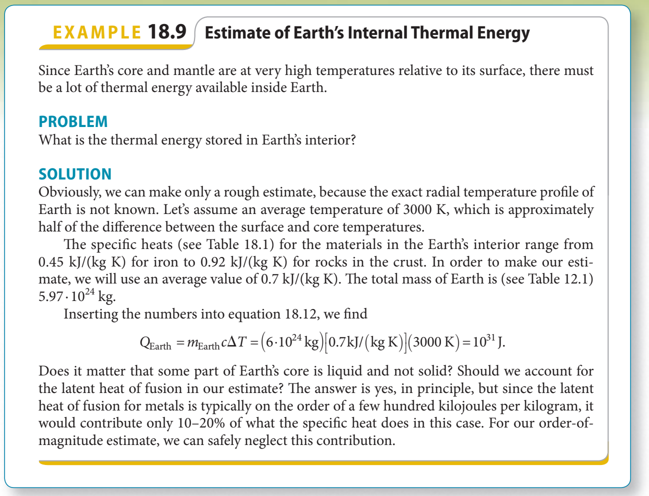
DOUBLE-CHECK In order to obtain the mass of 1 ppm of CO_2 in the atmosphere, we have to realize that the molar mass of CO_2 is $12 + (2 \cdot 16) = 44$ g. The average mass of a mole of the atmosphere is approximately $0.78(2 \cdot 14) + 0.21(2 \cdot 16) + 0.01(40) = 28.96$ g. The mass of 1 ppm of CO_2 in the atmosphere is therefore

$$m_{1 \text{ ppm } CO_2} = 10^{-6} \cdot m \frac{44}{28.96} = 7.97 \cdot 10^{12} \text{ kg} = 8.0 \text{ billion tons}.$$

Humans add approximately 2 ppm of CO_2 to the atmosphere each year by burning fossil fuels, which amounts to approximately 16 billion tons of CO_2, a scary number. It is not easy to double-check the orders of magnitude for this calculation. However, data published by the U.S. Energy Information Administration show that total carbon dioxide emissions from burning fossil fuels are currently approximately 30 billion tons per year, higher than our result by a factor of 2. Where does the other half of the CO_2 go? Mainly, it dissolves in the Earth's oceans.

Examples

Briefer **Examples** (problem statement and solution only) focus on a specific point or concept. The Examples also serve as a bridge between fully worked-out Solved Problems (with all seven steps) and the homework problems.



EXAMPLE 18.9 **Estimate of Earth's Internal Thermal Energy**

Since Earth's core and mantle are at very high temperatures relative to its surface, there must be a lot of thermal energy available inside Earth.

PROBLEM

What is the thermal energy stored in Earth's interior?

SOLUTION

Obviously, we can make only a rough estimate, because the exact radial temperature profile of Earth is not known. Let's assume an average temperature of 3000 K, which is approximately half of the difference between the surface and core temperatures.

The specific heats (see Table 18.1) for the materials in the Earth's interior range from 0.45 kJ/(kg K) for iron to 0.92 kJ/(kg K) for rocks in the crust. In order to make our estimate, we will use an average value of 0.7 kJ/(kg K). The total mass of Earth is (see Table 12.1) $5.97 \cdot 10^{24}$ kg.

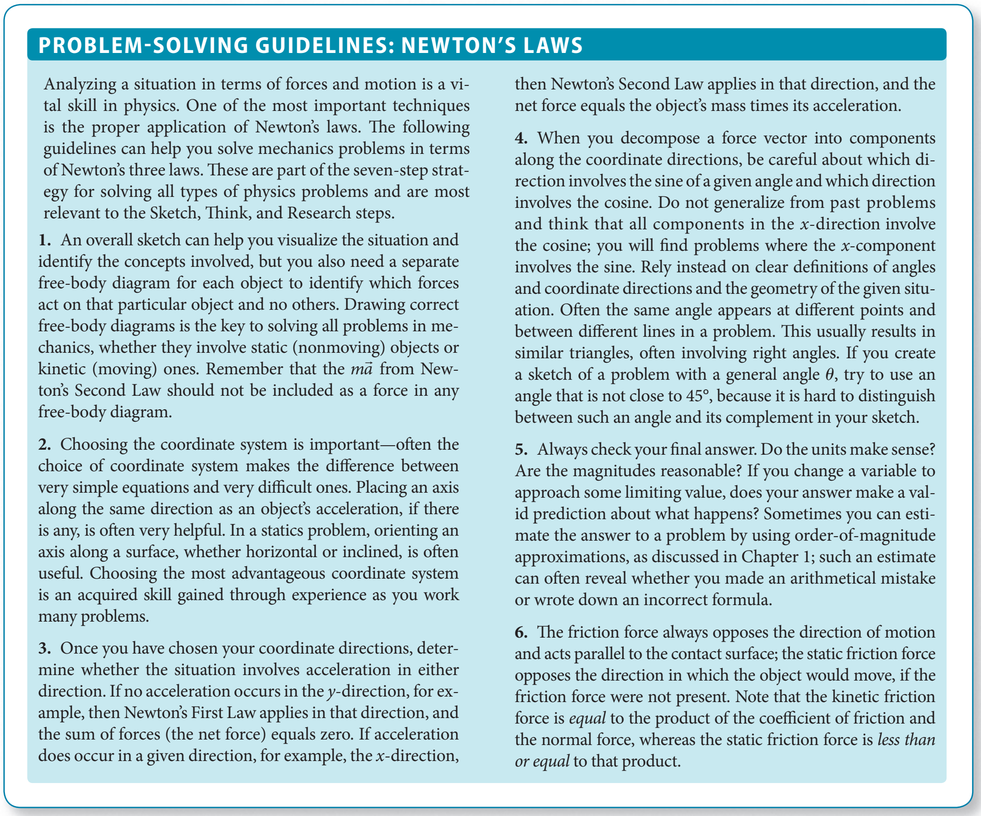
Inserting the numbers into equation 18.12, we find

$$Q_{\text{Earth}} = m_{\text{Earth}} c \Delta T = \left(6 \cdot 10^{24}\ \text{kg}\right)\left[0.7\ \text{kJ}/\left(\text{kg K}\right)\right]\left(3000\ \text{K}\right) = 10^{31}\ \text{J}.$$

Does it matter that some part of Earth's core is liquid and not solid? Should we account for the latent heat of fusion in our estimate? The answer is yes, in principle, but since the latent heat of fusion for metals is typically on the order of a few hundred kilojoules per kilogram, it would contribute only 10–20% of what the specific heat does in this case. For our order-of-magnitude estimate, we can safely neglect this contribution.

Problem-Solving Guidelines

Located before the end-of-chapter exercise sets, **Problem-Solving Guidelines** summarize important skills or techniques that can help you solve problems related to the material in the chapter. Acknowledging that physics is based on a core set of fundamental ideas that can be applied to various situations and problems, *University Physics* emphasizes that there is no single way to solve every problem and helps you think critically about the most effective problem-solving method before beginning to work on a solution.



PROBLEM-SOLVING GUIDELINES: NEWTON'S LAWS

Analyzing a situation in terms of forces and motion is a vital skill in physics. One of the most important techniques is the proper application of Newton's laws. The following guidelines can help you solve mechanics problems in terms of Newton's three laws. These are part of the seven-step strategy for solving all types of physics problems and are most relevant to the Sketch, Think, and Research steps.

1. An overall sketch can help you visualize the situation and identify the concepts involved, but you also need a separate free-body diagram for each object to identify which forces act on that particular object and no others. Drawing correct free-body diagrams is the key to solving all problems in mechanics, whether they involve static (nonmoving) objects or kinetic (moving) ones. Remember that the $m\vec{a}$ from Newton's Second Law should not be included as a force in any free-body diagram.

2. Choosing the coordinate system is important—often the choice of coordinate system makes the difference between very simple equations and very difficult ones. Placing an axis along the same direction as an object's acceleration, if there is any, is often very helpful. In a statics problem, orienting an axis along a surface, whether horizontal or inclined, is often useful. Choosing the most advantageous coordinate system is an acquired skill gained through experience as you work many problems.

3. Once you have chosen your coordinate directions, determine whether the situation involves acceleration in either direction. If no acceleration occurs in the y-direction, for example, then Newton's First Law applies in that direction, and the sum of forces (the net force) equals zero. If acceleration does occur in a given direction, for example, the x-direction, then Newton's Second Law applies in that direction, and the net force equals the object's mass times its acceleration.

4. When you decompose a force vector into components along the coordinate directions, be careful about which direction involves the sine of a given angle and which direction involves the cosine. Do not generalize from past problems and think that all components in the x-direction involve the cosine; you will find problems where the x-component involves the sine. Rely instead on clear definitions of angles and coordinate directions and the geometry of the given situation. Often the same angle appears at different points and between different lines in a problem. This usually results in similar triangles, often involving right angles. If you create a sketch of a problem with a general angle θ, try to use an angle that is not close to 45°, because it is hard to distinguish between such an angle and its complement in your sketch.

5. Always check your final answer. Do the units make sense? Are the magnitudes reasonable? If you change a variable to approach some limiting value, does your answer make a valid prediction about what happens? Sometimes you can estimate the answer to a problem by using order-of-magnitude approximations, as discussed in Chapter 1; such an estimate can often reveal whether you made an arithmetical mistake or wrote down an incorrect formula.

6. The friction force always opposes the direction of motion and acts parallel to the contact surface; the static friction force opposes the direction in which the object would move, if the friction force were not present. Note that the kinetic friction force is *equal* to the product of the coefficient of friction and the normal force, whereas the static friction force is *less than or equal* to that product.

End-of-Chapter Questions and Exercise Sets

Along with providing problem-solving guidelines, examples, and strategies, *University Physics* also offers a **wide variety of end-of-chapter Questions and Exercises.** Included in each chapter are Multiple-Choice Questions, Conceptual Questions, Exercises (by section), Additional Exercises (no section "clue"), and Multi-Version Exercises. One bullet identifies slightly more challenging Exercises, and two bullets identify the most challenging Exercises.

Calculus Primer

Since this course is typically taken in the first year of study at universities, this book assumes knowledge of high school physics and mathematics. It is preferable that students have had a course in calculus before they start this course, but calculus can also be taken in parallel. To facilitate this, the text contains a short calculus primer in an appendix, giving the main results of calculus without the rigorous derivations.

Building Conceptual Understanding

Chapter Opening Outline

At the beginning of each chapter is an outline presenting the section heads within the chapter. The outline also includes the titles of the Examples and Solved Problems found in the chapter. At a quick glance, you will know if a desired topic, example, or problem is in the chapter.

What We Will Learn / What We Have Learned

Each chapter of *University Physics* is organized like a good research seminar. It was once said, "Tell them what you will tell them, then tell them, and then tell them what you told them!" Each chapter starts with **What We Will Learn**—a quick summary of the main points, without any equations. And at the end of each chapter, **What We Have Learned/Exam Study Guide** contains key concepts, including major equations.

WHAT WE WILL LEARN

- An electric field represents the electric force at different points in space.
- Electric field lines represent the net force vectors exerted on a unit positive electric charge. They originate on positive charges and terminate on negative charges.
- The electric field of a point charge is radial, proportional to the charge, and inversely proportional to the square of the distance from the charge.
- An electric dipole consists of a positive charge and a negative charge of equal magnitude.
- The electric flux is the electric field component normal to an area times the area.
- Gauss's Law states that the electric flux through a closed surface is proportional to the net electric charge enclosed within the surface. This law provides simple ways to solve seemingly complicated electric field problems.
- The electric field inside a conductor is zero.
- The magnitude of the electric field due to a uniformly charged, infinitely long wire varies as the inverse of the perpendicular distance from the wire.
- The electric field due to an infinite sheet of charge does not depend on the distance from the sheet.
- The electric field outside a spherical distribution of charge is the same as the field of a point charge with the same total charge located at the sphere's center.

Conceptual Introductions

Conceptual explanations are provided in the text prior to any mathematical explanations, formulas, or derivations in order to establish why the concept or quantity is needed, why it is useful, and why it must be defined accurately. The authors then move from the conceptual explanation and definition to a formula and exact terms.

Self-Test Opportunity 5.3

A block is hanging vertically from a spring at the equilibrium displacement. The block is then pulled down a bit and released from rest. Draw the free-body diagram for the block in each of the following cases:

a) The block is at the equilibrium displacement.

b) The block is at its highest vertical point.

c) The block is at its lowest vertical point.

Self-Test Opportunities

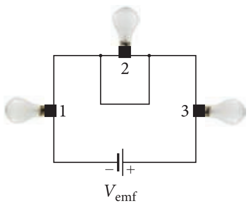
In each chapter, a series of questions focus on major concepts within the text to encourage students to develop an internal dialogue. These questions will help students think critically about what they have just read, decide whether they have a grasp of the concept, and develop a list of follow-up questions to ask in class. The answers to the Self-Tests are found at the end of each chapter.

Concept Checks

Concept Checks are designed to be used with personal response system technology. They will appear in the text so that you may begin contemplating the concepts. Answers will only be available to instructors.

Concept Check 25.8

Three light bulbs are connected in series with a battery that delivers a constant potential difference, V_{emf}. When a wire is connected across light bulb 2 as shown in the figure, light bulbs 1 and 3



a) burn just as brightly as they did before the wire was connected.

b) burn more brightly than they did before the wire was connected.

c) burn less brightly than they did before the wire was connected.

d) go out.

Student Solutions Manual

The *Student Solutions Manual* contains answers and worked-out solutions to selected end-of-chapter Questions and Exercises (those indicated by a blue number). Worked-out solutions for all items in Chapters 1 through 13 follow the complete seven-step problem-solving method introduced in Section 1.5. Chapters 14 through 40 continue to use the seven-step method for challenging (one bullet) and most challenging (two bullet) exercises, but present more abbreviated solutions for the less challenging (no bullet) exercises.

Seeing the Big Picture

Contemporary Examples

The authors have included recent physics research results throughout the text. Results involving renewable energy, the environment, aerospace, engineering, medicine, and technology demonstrate that physics is an exciting, thriving, and intellectually stimulating field. Available online at www.mhhe.com/bauerwestfall2e, the student resource center provides a number of items to enhance your understanding and help you prepare for lectures, labs, and tests.

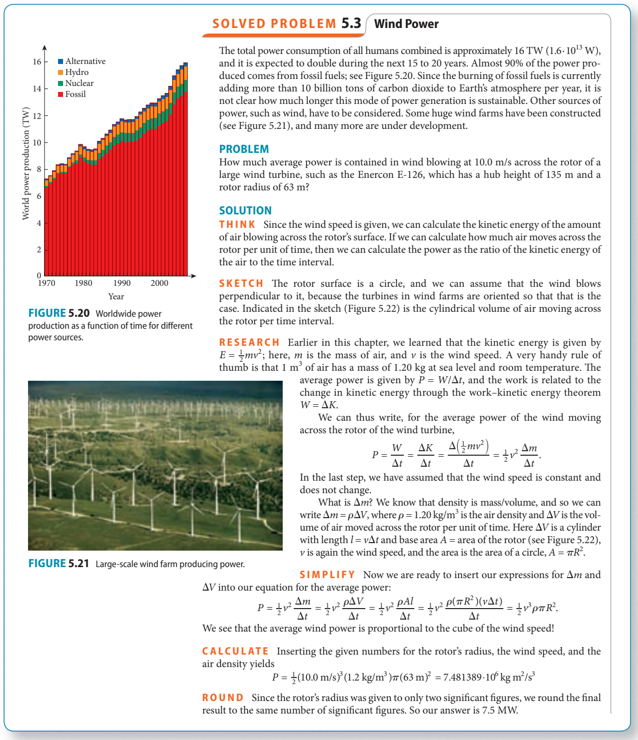
ConnectPlus eBook

Linked to multimedia assets—including author videos, applets that allow you to explore fundamental physics principles, and images—the eBook allows you to take notes, highlight, and even search for specific words or phrases. All of the textbook figures, videos, and interactive content are also listed in line and by chapter, so you can navigate directly to the resource you need. Links to the ConnectPlus eBook are included in the online homework and LearnSmart assignments, so if you are having trouble with an exercise or concept, you can navigate directly to the relevant portion of the text.

Visual Program

Familiarity with graphics and animation on the Internet and in video games has raised the bar for the graphical presentations in textbooks, which must now be more sophisticated to excite both students and faculty. Here are some of the techniques and ideas implemented in *University Physics:*

- Line drawings are superimposed on photographs to connect sometimes very abstract physics concepts to students' realities and everyday experiences.
- A three-dimensional look for line drawings adds plasticity to the presentations. Mathematically accurate graphs and plots were created by the authors in software programs such as Mathematica and then used by the graphic artists to ensure complete accuracy as well as a visually appealing style.



SOLVED PROBLEM 5.3 **Wind Power**

The total power consumption of all humans combined is approximately 16 TW ($1.6 \cdot 10^{13}$ W), and it is expected to double during the next 15 to 20 years. Almost 90% of the power produced comes from fossil fuels; see Figure 5.20. Since the burning of fossil fuels is currently adding more than 10 billion tons of carbon dioxide to Earth's atmosphere per year, it is not clear how much longer this mode of power generation is sustainable. Other sources of power, such as wind, have to be considered. Some huge wind farms have been constructed (see Figure 5.21), and many more are under development.

PROBLEM

How much average power is contained in wind blowing at 10.0 m/s across the rotor of a large wind turbine, such as the Enercon E-126, which has a hub height of 135 m and a rotor radius of 63 m?

SOLUTION

THINK Since the wind speed is given, we can calculate the kinetic energy of the amount of air blowing across the rotor's surface. If we can calculate how much air moves across the rotor per unit of time, then we can calculate the power as the ratio of the kinetic energy of the air to the time interval.

SKETCH The rotor surface is a circle, and we can assume that the wind blows perpendicular to it, because the turbines in wind farms are oriented so that that is the case. Indicated in the sketch (Figure 5.22) is the cylindrical volume of air moving across the rotor per time interval.

RESEARCH Earlier in this chapter, we learned that the kinetic energy is given by $E = \frac{1}{2}mv^2$; here, m is the mass of air, and v is the wind speed. A very handy rule of thumb is that 1 m^3 of air has a mass of 1.20 kg at sea level and room temperature. The average power is given by $P = W/\Delta t$, and the work is related to the change in kinetic energy through the work–kinetic energy theorem $W = \Delta K$.

We can thus write, for the average power of the wind moving across the rotor of the wind turbine,

$$P = \frac{W}{\Delta t} = \frac{\Delta K}{\Delta t} = \frac{\Delta\left(\frac{1}{2}mv^2\right)}{\Delta t} = \frac{1}{2}v^2\frac{\Delta m}{\Delta t}.$$

In the last step, we have assumed that the wind speed is constant and does not change.

What is Δm? We know that density is mass/volume, and so we can write $\Delta m = \rho\Delta V$, where $\rho = 1.20\ \text{kg/m}^3$ is the air density and ΔV is the volume of air moved across the rotor per unit of time. Here ΔV is a cylinder with length $l = v\Delta t$ and base area A = area of the rotor (see Figure 5.22), v is again the wind speed, and the area is the area of a circle, $A = \pi R^2$.

SIMPLIFY Now we are ready to insert our expressions for Δm and ΔV into our equation for the average power:

$$P = \frac{1}{2}v^2\frac{\Delta m}{\Delta t} = \frac{1}{2}v^2\frac{\rho\Delta V}{\Delta t} = \frac{1}{2}v^2\frac{\rho A l}{\Delta t} = \frac{1}{2}v^2\frac{\rho(\pi R^2)(v\Delta t)}{\Delta t} = \frac{1}{2}v^3\rho\pi R^2.$$

We see that the average wind power is proportional to the cube of the wind speed!

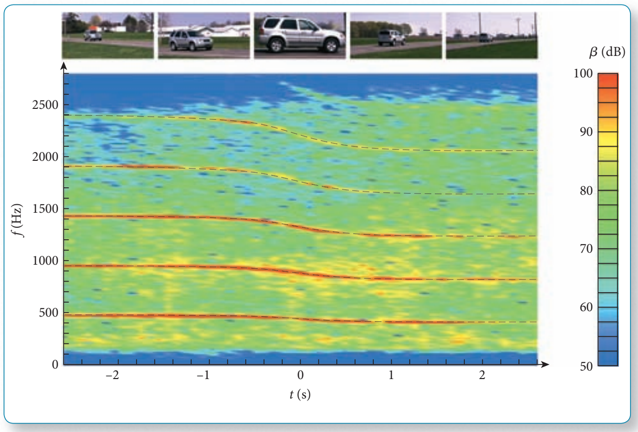
CALCULATE Inserting the given numbers for the rotor's radius, the wind speed, and the air density yields

$$P = \tfrac{1}{2}(10.0\ \text{m/s})^3(1.2\ \text{kg/m}^3)\pi(63\ \text{m})^2 = 7.481389 \cdot 10^6\ \text{kg m}^2/\text{s}^3$$

ROUND Since the rotor's radius was given to only two significant figures, we round the final result to the same number of significant figures. So our answer is 7.5 MW.

FIGURE 5.20 Worldwide power production as a function of time for different power sources.

FIGURE 5.21 Large-scale wind farm producing power.



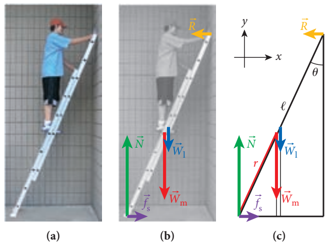
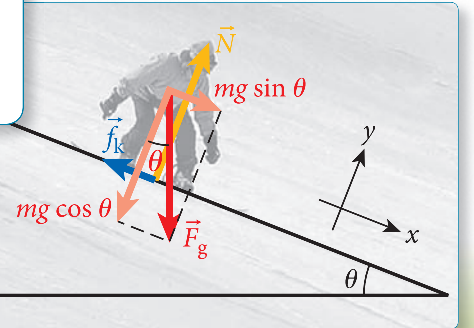
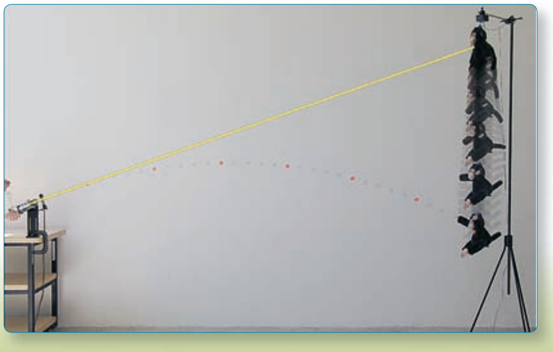


FIGURE 11.12 (a) Student standing on a ladder. (b) Force vectors superimposed. (c) Free-body diagram of the ladder.





Student Resources

Online Resources

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Two boxes, A & B are suspended from a ceiling, as shown. Which of the following forces should be included in the free-body diagram of Box A? Select all that apply.

Do you know the answer? (Be honest.)

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Resources for Instructors

Online Tools

A collection of online tools—including photos, artwork, an *Instructor's Solutions Manual,* and other media—can be accessed from the *University Physics* website at www.mhhe.com/bauerwestfall2e. These tools provide content for novice and experienced instructors who teach in a variety of styles. Included in the collection are PowerPoint® slides containing full-color digital files of all illustrations in the text, a collection of digital files of photographs from the text, libraries of all the solved problems, examples, tables, and numbered equations from the text, and ready-made PowerPoint lecture outlines that include art, lecture notes, and additional examples for each section of the text. An *Instructor's Solutions Manual* with complete worked-out solutions to all of the end-of-chapter Questions and Exercises is available in document and PDF formats. The latest research in physics education shows that in-class use of personal response systems (or "clickers") improves student learning, so a full set of clicker questions based on the Concept Checks from the text is available on the companion website.

Computerized Test Bank Online

Over 2300 text questions in multiple-choice format, written by exceptional instructors and fully updated to reflect the content of the second edition, are included on the Connect website. These questions are organized by test section and represent a variety of difficulty levels. By working within the ConnectPhysics online platform, you can select questions from multiple McGraw-Hill test banks or create your own to better reflect the interests and needs of your students. This test bank allows you to easily create paper and online tests or quizzes from anywhere at any time, without installing any software.

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—Wolfgang Bauer
—Gary D. Westfall

Reviewers, Advisors, and Contributors for the Second Edition

Nina Abramzon, *California State Polytechnic University–Pomona*
Royal Albridge, *Vanderbilt University*
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Advisors, Contributors, Testers, and Reviewers for the First Edition

El Hassan El Aaoud, *University of Hail, Hail KSA*
Mohamed S. Abdelmonem, *King Fahd University of Petroleum and Minerals, Dhahran, Saudi Arabia*
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Kieran Mullen, *University of Oklahoma*
Nazir Mustapha, *Al-Imam University*
Charley Myles, *Texas Tech University*
Tibor Nagy, *Michigan State University*
Reza Nejat, *McMaster University*
Curt Nelson, *Gonzaga University*
Mark Neubauer, *University of Illinois at Urbana–Champaign*
Cindy Neyer, *Tri-State University*
Craig Ogilvie, *Iowa State University*
Bradford G. Orr, *The University of Michigan*
Karur Padmanabhan, *Wayne State University*
Kiumars Parvin, *San Jose State University*
Jacqueline Pau, *University of California–Los Angeles*
Todd Pedlar, *Luther College*
Leo Piilonen, *Virginia Tech*
Amy Pope, *Clemson University*
Bernard Pope, *Michigan State University*
K. Porsezian, *Pondicherry University–Puducherry*
Scott Pratt, *Michigan State University*
Earl Prohofsky, *Purdue University*
Claude Pruneau, *Wayne State University*
Wang Qing-hai, *National University of Singapore*
Corneliu Rablau, *Kettering University*
Johann Rafelski, *University of Arizona*
Kenneth J. Ragan, *McGill University*
Roberto Ramos, *Drexel University*
Ian Redmount, *Saint Louis University*
Lawrence B. Rees, *Brigham Young University*
Andrew J. Rivers, *Northwestern University*
James W. Rohlf, *Boston University*
Philip Roos, *University of Maryland*
Chong-Yu Ruan, *Michigan State University*
Dubravka Rupnik, *Louisiana State University*
Homeyra Sadaghiani, *California State Polytechnic University–Pomona*
Ertan Salik, *California State Polytechnic University–Pomona*
Otto Sankey, *Arizona State University*
Sergey Savrasov, *University of California–Davis*

Hendrik Schatz, *Michigan State University*
Carl Schmidt, *Michigan State University*
Stan Schriber, *Michigan State University*
John Schroeder, *Rensselaer Polytechnic Institute*
Reinhard Schwienhorst, *Michigan State University*
Kunnat Sebastian, *University of Massachusetts–Lowell*
Bjoern Seipel, *Portland State University*
Jerry Shakov, *Tulane University*
Ralph Shiell, *Trent University*
Irfan Siddiqi, *University of California–Berkeley*
Ravindra Kumar Sinha, *Delhi College of Engineering*
Marllin L. Simon, *Auburn University*
Alex Small, *California State Polytechnic University–Pomona*
Leigh Smith, *University of Cincinnati*
Todd Smith, *University of Dayton*
Xian-Ning Song, *Richland College*
Jeff Sonier, *Simon Fraser University–Surrey Central*
Chad E. Sosolik, *Clemson University*
Kris Starosta, *Michigan State University*
Donna W. Stokes, *University of Houston*
James Stone, *Boston University*
Michael G. Strauss, *University of Oklahoma*
Dan Stump, *Michigan State University*
Yang Sun, *University of Notre Dame*
Stephen Swingle, *City College of San Francisco*
Maarij Syed, *Rose-Hulman Institute of Technology*
Gregory Tarlé, *University of Michigan*
Marshall Thomsen, *Eastern Michigan University*
Douglas C. Tussey, *The Pennsylvania State University*
Somdev Tyagi, *Drexel University*
Prem Vaishnava, *Kettering University*
Erich W. Varnes, *University of Arizona*
John Vasut, *Baylor University*
Gautam Vemuri, *Indiana University-Purdue University–Indianapolis*
Thad Walker, *University of Wisconsin–Madison*
Fuqiang Wang, *Purdue University*
David J. Webb, *University of California–Davis*
Kurt Wiesenfeld, *Georgia Tech*
Fred Wietfeldt, *Tulane University*
Gary Williams, *University of California–Los Angeles*
Sun Yang, *University of Notre Dame*
L. You, *Georgia Tech*
Billy Younger, *College of the Albemarle*
C. P. Yuan, *Michigan State University*
Andrew Zangwill, *Georgia Institute of Technology*
Jens Zorn, *University of Michigan–Ann Arbor*
Michael Zudov, *University of Minnesota*

New to the Second Edition

General Changes

The content of the second edition of *University Physics* has been completely updated to reflect new research in physics and physics education. The changes range from the inclusion of newly discovered elements in the periodic table to the addition of new in-text Concept Checks and end-of-chapter exercises. New Multi-Version Exercises have been added to the end of every chapter. These consist of groups of related exercises that use a common problem setup but ask you to solve for a different quantity. The Multi-Version Exercises will help you to build conceptual understanding, learn how different physical quantities are related to one another, and recognize related problems when you see them again.

Chapter-Specific Changes

Chapter 1

Two new Concept Checks and one new Self-Test Opportunity have been added, as well as Example 1.4, "Greenhouse Gas Production." There are six new Multiple-Choice Questions and thirteen new end-of-chapter exercises comprising section-specific, general, and Multi-Version Exercises.

Chapter 2

Five new Concept Checks have been added. There are four new Multiple-Choice Questions and eleven new end-of-chapter exercises comprising section-specific, general, and Multi-Version Exercises.

Chapter 3

Five new Concept Checks have been added. There are three new Multiple-Choice Questions and seven new Multi-Version Exercises.

Chapter 4

One new Concept Check and two new Self-Test Opportunities have been added. Solved Problem 4.2, "Two Blocks Connected by a Rope," has replaced the related example from the first edition. There are four new Multiple-Choice Questions and ten new Multi-Version Exercises.

Chapter 5

Two new Concept Checks have been added. Solved Problems 5.3, "Wind Power," and 5.4, "Riding a Bicycle," are new. There are four new Multiple-Choice Questions and fourteen new end-of-chapter exercises comprising general and Multi-Version Exercises.

Chapter 6

Three new Concept Checks have been added and Example 6.1, "Weightlifting," is new. There are four new Multiple-Choice Questions and nine new Multi-Version Exercises.

Chapter 7

One new Concept Check has been added. There are four new Multiple-Choice Questions and thirteen new end-of-chapter exercises comprising general and Multi-Version Exercises.

Chapter 8

Three new Concept Checks have been added. There are five new Multiple-Choice Questions and eleven new Multi-Version Exercises.

Chapter 9

Four new Concept Checks have been added. There are four new Multiple-Choice Questions and seven new Multi-Version Exercises.

Chapter 10

Three new Concept Checks have been added. Solved Problem 10.5, "Bullet Hitting a Pole," is new. There are three new Multiple-Choice Questions and ten new end-of-chapter exercises comprising Conceptual Questions and Multi-Version Exercises.

Chapter 11

Three new Concept Checks have been added. Example 11.3, "Standing on a Board," is new. There are four new Multiple-Choice Questions and eight new Multi-Version Exercises.

Chapter 12

Three new Concept Checks have been added. There are four new Multiple-Choice Questions and eight new Multi-Version Exercises.

Chapter 13

Four new Concept Checks and one new Self-Test Opportunity have been added. Example 13.7, "Betz Limit," and Solved Problem 13.2, "Weighing Earth's Atmosphere," are new. There are four new Multiple-Choice Questions and nine new Multi-Version Exercises.

Chapter 14

Five new Concept Checks and one new Self-Test Opportunity have been added. Solved Problem 14.4, "Grandfather Clock," is new. There are four new Multiple-Choice Questions and eight new Multi-Version Exercises.

Chapter 15

Two new Concept Checks have been added. There are three new Multiple-Choice Questions and nine new Multi-Version Exercises.

Chapter 16

Three new Concept Checks have been added. Solved Problem 16.2, "Tuning a Violin," is new. There are four new Multiple-Choice Questions and eight new Multi-Version Exercises. New subsections discuss sound attenuation, sound diffraction, and sound localization.

Chapter 17

Solved Problem 17.1, "Temperature Conversion," and a new Concept Check have been added. There are four new Multiple-Choice Questions and nine new Multi-Version Exercises.

Chapter 18

Five new Concept Checks have been added. Example 18.9, "Estimate of Earth's Internal Thermal Energy," and Solved Problem 18.5, "Enhanced Geothermal System," are new. A subsection on geothermal power resources has been added. There are six new Multiple-Choice Questions and six new Multi-Version Exercises.

Chapter 19

Two new Self-Test Opportunities have been added. Solved Problem 19.2, "Home Energy Storage," is new. A new section on real gases and a new subsection on compressed air have been added. There are four new Multiple-Choice Questions and six new Multi-Version Exercises.

Chapter 20

There are four new Multiple-Choice Questions and nine new Multi-Version Exercises.

Chapter 21

One new Concept Check, four new Multiple-Choice Questions, and six new Multi-Version Exercises have been added. A new subsection discusses triboelectric charging.

Chapter 22

Six new Concept Checks have been added. There are two new Multiple-Choice Questions and six new Multi-Version Exercises.

Chapter 23

Two new Concept Checks have been added. Solved Problem 23.4, "Charged Disk," is new. A new subsection covers the case of a dipole in a constant electric field. There are four new Multiple-Choice Questions and six new Multi-Version Exercises.

Chapter 24

In addition to a new subsection on electrolytic capacitors, there are four new Multiple-Choice Questions and six new Multi-Version Exercises.

Chapter 25

Two new Concept Checks and a new Self-Test Opportunity have been added. There are two new Multiple-Choice Questions and eight new Multi-Version Exercises.

Chapter 26

Three new Concept Checks have been added. There are four new Multiple-Choice Questions and nine new Multi-Version Exercises.

Chapter 27

Three new Concept Checks have been added. There are four new Multiple-Choice Questions and six new Multi-Version Exercises.

Chapter 28

There are four new Multiple-Choice Questions and six new Multi-Version Exercises.

Chapter 29

Three new Concept Checks have been added. There are six new Multiple-Choice Questions and six new Multi-Version Exercises.

Chapter 30

There are two new Multiple-Choice Questions and five new end-of-chapter exercises comprising section-specific and Multi-Version Exercises.

Chapter 31

There are two new Multiple-Choice Questions and six new Multi-Version Exercises.

Chapter 32

Six new Concept Checks and a new Self-Test Opportunity have been added. There are six new Multiple-Choice Questions and eight new Multi-Version Exercises. A new subsection discusses concentrating solar power.

Chapter 33

Seven new Concept Checks and a new Self-Test Opportunity have been added. There are six new Multiple-Choice Questions and six new Multi-Version Exercises. The section on converging and diverging lenses has been extensively revised, and a new subsection on lens equations has been added.

Chapter 34

Four new Concept Checks have been added. There are four new Multiple-Choice Questions and eight new Multi-Version Exercises.

Chapter 35

One new Concept Check has been added. There are six new Multiple-Choice Questions and six new Multi-Version Exercises.

Chapter 36

An example on Compton scattering has been replaced by Solved Problem 36.1, "Compton Scattering," with a complete seven-step solution. There are eight new Multi-Version Exercises.

Chapter 37

Improved notation for quantum operators and new material on wave functions have been added. An example concerning a finite potential well has been replaced by Solved Problem 37.1, "Finite Potential Well." There are seven new Multi-Version Exercises.

Chapter 38

New Problem-Solving Guidelines and five new Multi-Version Exercises have been added.

Chapter 39

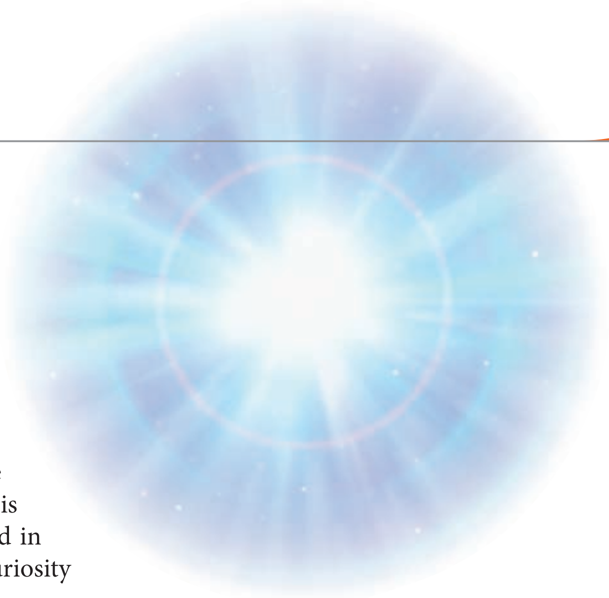
New Problem-Solving Guidelines, one new end-of-chapter exercise, and six new Multi-Version Exercises have been added. The text discussion of fundamental particles has been revised to include the 2012 discovery of a Higgs boson at CERN.

Chapter 40

There is a new subsection on the thorium fission cycle. Three new Multi-Version Exercises have been added.

The Big Picture

Frontiers of Modern Physics



This book will give you insight into some of the astounding recent progress made in physics and show you how this progress aids practically all other areas of science and engineering. Examples from advanced areas of research are accessible with the knowledge available at the introductory level. At many universities, freshmen and sophomores are already involved in cutting-edge physics research. Often, this participation requires nothing more than the tools developed in this book, a few days or weeks of additional reading, and the curiosity and willingness necessary to learn new facts and skills.

The following pages present some of the amazing frontiers of current physics research and describe some of the results that have been obtained during the last few years. This introduction stays at a qualitative level, skipping all mathematical and other technical details. Chapter references indicate where more in-depth explorations of the topics can be found.

Energy and Power

Probably the greatest problem facing humanity in this century is how to satisfy the ever-increasing demand for energy and power. Energy is a very basic physics topic, and power is the rate at which energy is converted; we will devote two entire chapters to these key concepts (Chapters 5 and 6). In 2010 and 2011, the twin disasters of the explosion of the Deepwater Horizon oil rig in the Gulf of Mexico and the destruction of the Fukushima Daiichi nuclear reactors by a tsunami following a very strong earthquake off the Pacific Coast of Japan (Figure 1) made it abundantly clear that satisfying our energy needs can carry huge risks.

(a) (b)

FIGURE 1 Two environmental disasters: (a) The burning Deepwater Horizon oil rig in the Gulf of Mexico, source of the biggest accidental ocean oil spill of all time. (b) The heavily damaged reactor buildings at the Fukushima Daiichi nuclear power plant, source of the largest nuclear radiation contamination to occur in the last quarter century.

FIGURE 2 An offshore wind farm between Malmö, Sweden, and Copenhagen, Denmark, that delivers a power output comparable to that of a large coal-fired power plant.

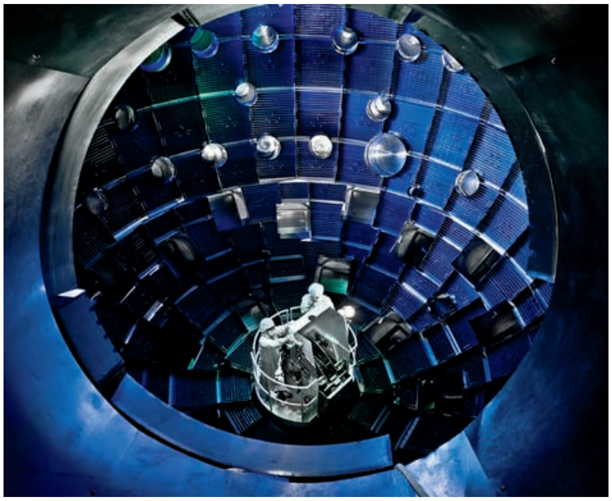


FIGURE 3 Target chamber of the National Ignition Facility, which is used to study nuclear fusion.

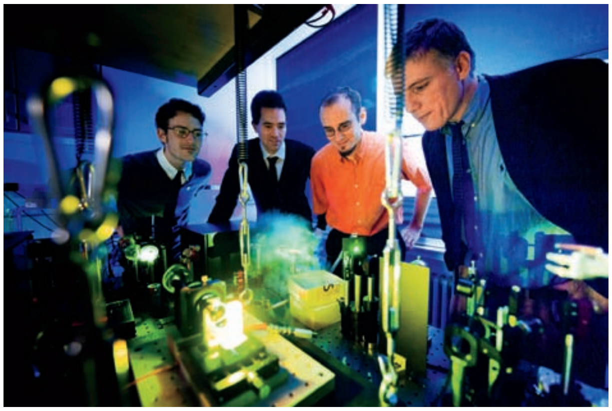


FIGURE 4 Physicists from the University of Bonn, Germany, observing their newly created "super-photons," or Bose-Einstein condensate consisting of light, which they discovered in 2010.

Physics is at the center of a large number of interdisciplinary collaborations seeking ways to secure our future energy supply in the face of strongly rising demand. Wind (Figure 2), water, biomass, and sunlight are all possible alternative sources of energy. The coming decades will see increased emphasis on exploiting these resources, and physicists will work on optimizing these processes. Some of these technologies and their physical foundations are highlighted in many chapters in this book.

Seventy years ago, nuclear physicist Hans Bethe and his colleagues figured out how nuclear fusion in the Sun produces the light that makes life on Earth possible. Today, nuclear physicists are working on how to utilize nuclear fusion on Earth to produce nearly limitless energy. Both the International Thermonuclear Experimental Reactor (ITER) (Chapter 40), presently under construction in southern France through a collaborative effort involving many industrialized countries, and the National Ignition Facility (Chapters 38 and 40, Figure 3) at Lawrence Livermore National Laboratory, completed in 2009, will help researchers investigate many of the important questions that need to be resolved before the use of fusion is technically feasible and commercially viable.

Quantum Physics

The year 2005 marked the 100th anniversary of Albert Einstein's landmark papers on Brownian motion (proving that atoms are real; see Chapters 13 and 38), on the theory of relativity (Chapter 35), and on the photoelectric effect (Chapter 36). This last paper introduced one of the basic ideas underlying quantum mechanics, the physics of matter on the scale of atoms and molecules. Quantum mechanics is a product of the 20th century that led, for example, to the invention of lasers, which are now routinely used in CD, DVD, and Blu-ray players, in price scanners, and even in eye surgery, among many other applications. Quantum mechanics has also provided a more fundamental understanding of chemistry: Physicists are using ultrashort laser pulses less than 10^{-15} s in duration to gain an understanding of how chemical bonds develop. The quantum revolution has included exotic discoveries such as antimatter, and there is no end in sight. During the last decade, groups of atoms called *Bose-Einstein condensates* have been formed in electromagnetic traps; this work has opened an entirely new realm of research in atomic and quantum physics (see Chapters 36 through 38, Figure 4).

Condensed Matter Physics and Electronics

Physics innovations created and continue to drive high-tech industry. Only slightly more than 50 years ago, the first transistor was invented at Bell Labs, ushering in the electronic age. The central processing unit (CPU) of a typical desktop or laptop computer contains more than 100 million transistor elements. The incredible growth in the capabilities and the scope of applications of computers over the last few decades has been made possible by research in condensed matter physics. Gordon Moore, cofounder of Intel, famously observed that computer processing power doubles every 2 years, a trend that is predicted to continue for at least another decade or more.

Computer storage capacity grows even faster than processing power, with a doubling time of 12 months. The 2007 Nobel Prize in Physics was awarded to Albert Fert and Peter Grünberg for their

1988 discovery of *giant magnetoresistance*. It took only a decade for this discovery to be applied in computer hard disks, enabling storage capacities of hundreds of gigabytes (1 gigabyte = 1 billion pieces of information) and even terabytes (1 terabyte = 1 trillion pieces of information).

Network capacity and bandwidth doubles every 9 months. You can now go to almost any country on Earth and find wireless access points, from which you can connect your laptop or WiFi-enabled smartphone to the Internet. Yet it is only a couple of decades since the conception of the World Wide Web by Tim Berners-Lee, who was then working at the particle physics laboratory CERN in Switzerland and who developed this new medium to facilitate collaboration among particle physicists in different parts of the world.

Cell phones and other powerful communication devices have found their way into just about everybody's hands. Modern physics research enables a progressive miniaturization of consumer electronics devices. This process drives a digital convergence, making it possible to equip cell phones with digital cameras, video recorders, e-mail capability, Web browsers, and global positioning system receivers. More functionality is added continuously, while prices continue to fall. Less than 50 years after the first Moon landing smart phones now pack more computing power than the Apollo spaceship used for that trip to the Moon.

Quantum Computing

Physics researchers are still pushing the limits of computing. At present, many groups are investigating ways to build a quantum computer. Theoretically, a quantum computer consisting of N processors would be able to execute 2^N instructions simultaneously, whereas a conventional computer consisting of N processors can execute only N instructions at the same time. Thus, a quantum computer consisting of 100 processors would exceed the combined computing power of all currently existing supercomputers. Although many complex problems have to be solved before this vision can become reality, remember that 50 years ago it seemed utterly impossible to pack 100 million transistors onto a computer chip the size of a thumbnail.

Computational Physics

The interaction between physics and computers works both ways. Traditionally, physics investigations were either experimental or theoretical in nature. Textbooks appear to favor the theoretical side, because they analyze the conceptual ideas that are encapsulated in the main formulas of physics. On the other hand, much research originates on the experimental side, when newly observed phenomena seem to defy theoretical description. However, the rise of computers has made possible a third branch of physics: computational physics. Most physicists now rely on computers to process data, visualize data, solve large sets of coupled equations, or study systems for which simple analytical formulations are not known.

The emerging field of chaos and nonlinear dynamics is the prime example of such study. Arguably, MIT atmospheric physicist Edward Lorenz first simulated chaotic behavior with the aid of a computer in 1963, when he solved three coupled equations for a simple model of weather and detected a sensitive dependence on the initial conditions—even the smallest differences in the beginning of the simulation resulted in very large deviations later in time. This phenomenon is now sometimes called the *butterfly effect,* from the idea that a butterfly flapping its wings in China could change the weather in the United States a few weeks later. This sensitivity to initial conditions implies that long-term deterministic weather prediction is impossible.

Complexity and Chaos

Systems of many constituents often exhibit very complex behavior, even if the individual constituents follow simple rules of nonlinear dynamics. Physicists have started to address complexity in many systems, including simple sand piles, traffic jams, the stock market, biological evolution, fractals, and self-assembly of molecules and nanostructures. The science of complexity is another field that emerged only during the last decade and is experiencing rapid growth. Chaos and nonlinear dynamics are discussed in Chapter 7 on momentum and

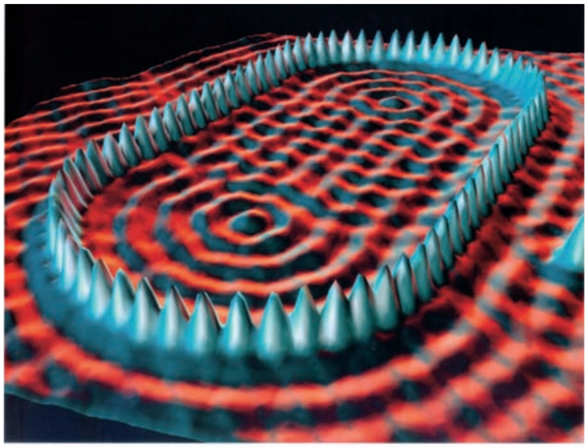


FIGURE 5 Individual iron atoms, arranged in the shape of a stadium on a copper surface. The ripples inside the "stadium" are the result of standing waves formed by electron density distributions. This arrangement was created and then imaged by using a scanning tunneling microscope (Chapter 37).

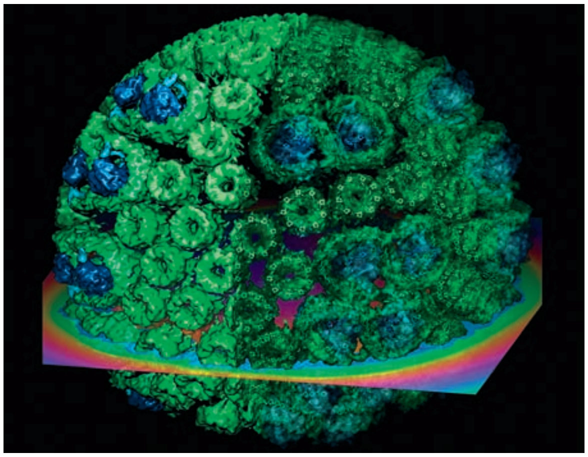


FIGURE 6 Computer simulation of the approximately 200 proteins in a chromatophore vesicle, which channels the energy of sunlight into the synthesis of adenosine triphosphate.

FIGURE 7 Aerial view of Geneva, Switzerland, with the location of the underground tunnel of the Large Hadron Collider superimposed in red.

in Chapter 14 on oscillations. The models are often quite straightforward, and first-year physics students can make valuable contributions. However, contributing generally requires some computer programming skills. Programming expertise will enable you to contribute to many advanced physics research projects.

Nanotechnology

Physicists are beginning to acquire the knowledge and skills needed to manipulate matter one atom at a time. During the last two decades, scanning, tunneling, and atomic force microscopes have allowed researchers to see individual atoms (Figure 5) and, in some cases, to move them around in controlled ways. Nanoscience and nanotechnology are devoted to these types of challenges, whose solution holds promise for great technological advances, from even more miniaturized and thus more powerful electronics to the design of new drugs, or even the manipulation of DNA to cure some diseases.

Biophysics

Just as physicists moved into the domain of chemists during the 20th century, a rapid interdisciplinary convergence of physics and molecular biology is taking place in the 21st century. Researchers are already able to use laser tweezers (Chapter 33) to move individual biomolecules. X-ray diffraction (Chapter 34) has become sophisticated enough that researchers can obtain pictures of the three-dimensional structures of very complicated proteins. In addition, theoretical biophysicists are beginning to be successful in predicting the spatial structure and the associated functionality of these molecules from the sequences of amino acids they contain. Researchers are beginning to obtain a microscopic understanding of biological entities, and some groups are making progress toward molecular-level simulation of biological processes (Figure 6).

High-Energy/Particle Physics

Nuclear and particle physicists are probing deeper and deeper into the smallest constituents of matter (Chapters 39 and 40). For example, the Large Hadron Collider (LHC) started its physics program as the highest-energy accelerator in the world in March 2010 at the CERN laboratory in Geneva, Switzerland. The LHC is located in a circular underground tunnel with a circumference of 27 km (17 mi), indicated by the red circle in Figure 7. This new instrument is the most expensive research facility ever built, at a cost of more than \$8 billion. Particle physicists use this facility to collide protons at the highest energies ever produced to try to find out what causes different elementary particles to have different masses, to probe what the true elementary constituents of the universe are, and perhaps to look for hidden extra dimensions or other exotic phenomena. Nuclear physicists at CERN smash lead nuclei into each other at very high energies in order to recreate the state of the universe a small fraction of a second after its beginning, the *Big Bang*. The ALICE (A Large Ion Collider Experiment) detector (Figure 8a) generates computerized images of the tracks (Figure 8b) of the several thousand subatomic particles produced by such a collision. Chapters 27 and 28 on magnetism and the magnetic field will explain how these tracks are analyzed in order to discover the properties of the particles that produced them.

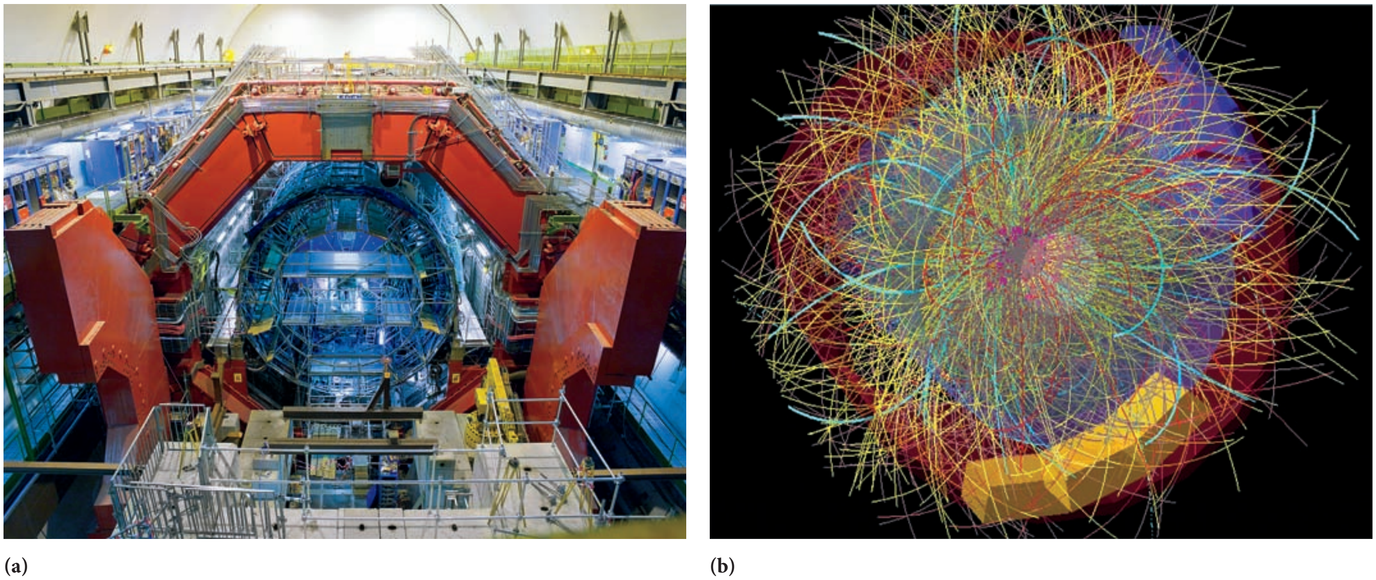

(a) (b)

FIGURE 8 (a) The ALICE detector at the Large Hadron Collider during its construction. (b) Electronically reconstructed tracks of thousands of charged subatomic particles produced inside the ALICE detector by a high-energy collision of two lead nuclei.

String Theory

Particle physics has a standard model of all particles and their interactions (Chapter 39), but why this model works so well is not yet understood. String theory is currently thought to be the most likely candidate for a framework that will eventually provide this explanation. Sometimes string theory is hubristically called the *Theory of Everything*. It predicts extra spatial dimensions, which sounds at first like science fiction, but many physicists are trying to find ways in which to test this theory experimentally.

Astrophysics

Physics and astronomy have extensive interdisciplinary overlap in the areas of investigating the history of the early universe, modeling the evolution of stars, and studying the origin of gravitational waves or cosmic rays of the highest energies. Ever more precise and sophisticated observatories, such as the James Webb Space Telescope (Figure 9), are being built to study these phenomena.

Astrophysicists continue to make astounding discoveries that reshape our understanding of the universe. Only during the last few years has it been discovered that most of the matter in the universe is not contained in stars. The composition of this *dark matter* is still unknown (Chapter 12), but its effects are revealed through *gravitational lensing,* as shown in Figure 10 by the arcs observed in the galaxy cluster Abell 2218, which is 2 billion light-years away from Earth, in the constellation Draco. These arcs are images of even more distant galaxies, distorted by the presence of large quantities of dark matter. This phenomenon is discussed in more detail in Chapter 35 on relativity.

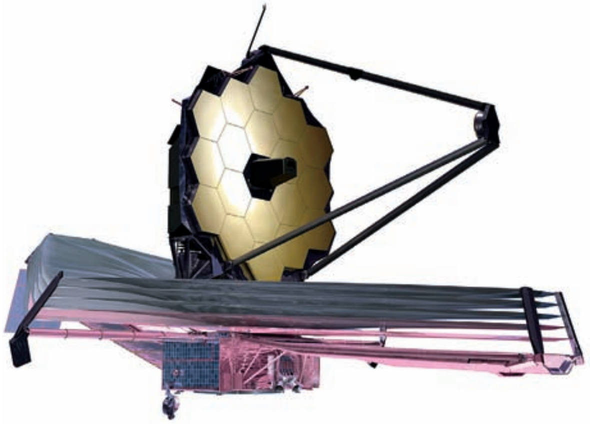


FIGURE 9 The James Webb Space Telescope.

Symmetry, Simplicity, and Elegance

From the smallest subatomic particles to the universe at large, physical laws govern all structures and dynamics from atomic nuclei to black holes. Physicists have discovered a tremendous amount, but each new discovery opens more exciting unknown territory. Thus, we continue to construct theories to explain any and all physical phenomena. The development of these theories is guided by the need to match experimental facts, as well as by the

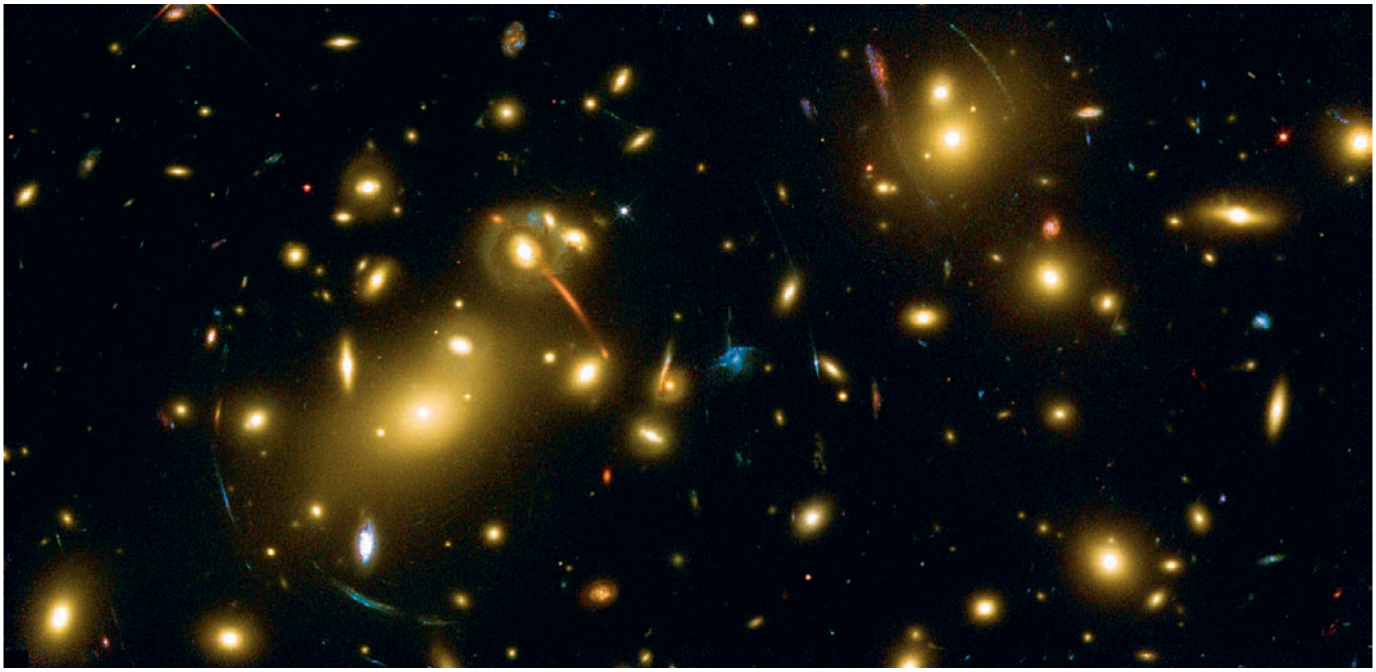


FIGURE 10 Galaxy cluster Abell 2218, with the arcs that are created by gravitational lensing due to dark matter.

conviction that symmetry, simplicity, and elegance are key design principles. The fact that laws of nature can be formulated in simple mathematical equations ($F = ma$, $E = mc^2$, and many other, less famous ones) is stunning.

This introduction has tried to convey a bit about the frontiers of modern physics research and their relevance to progress in other fields, from biology and medicine to engineering. This textbook should help you build a foundation for appreciating, understanding, and perhaps even participating in this vibrant research enterprise, which continues to refine and even to reshape our understanding of the world around us.

PART 1 MECHANICS OF POINT PARTICLES

1

Overview

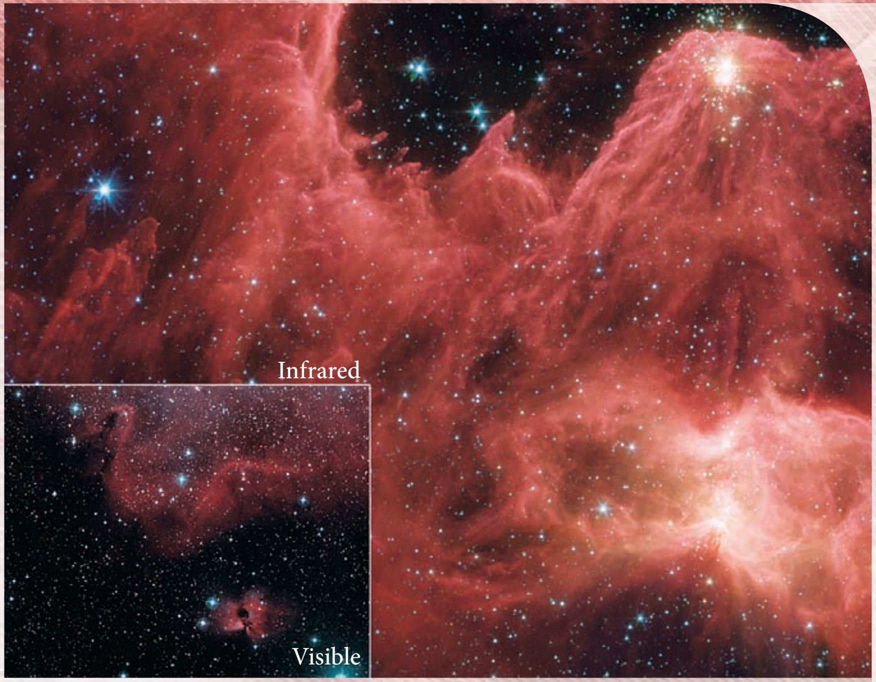


FIGURE 1.1 An image of the W5 star-forming region taken by the Spitzer Space Telescope using infrared light.

The dramatic image in Figure 1.1 could be showing any of several things: a colored liquid spreading out in a glass of water, or perhaps biological activity in some organism, or maybe even an artist's idea of mountains on some unknown planet. If we said the view was 70 wide, would that help you decide what the picture shows? Probably not—you need to know if we mean, for example, 70 meters or 70 millionths of an inch or 70 thousand miles.

In fact, this infrared image taken by the Spitzer Space Telescope shows huge clouds of gas and dust about 70 light-years across. (A light-year is the distance traveled by light in 1 year, about 10 quadrillion meters.) These clouds are about 6500 light-years away from Earth and contain newly formed stars embedded in the glowing regions. The technology that enables us to see images such as this one is at the forefront of contemporary astronomy, but it depends in a real way on the basic ideas of numbers, units, and vectors presented in this chapter.

The ideas described in this chapter are not necessarily principles of physics, but they help us to formulate and communicate physical ideas and observations. We will use the concepts of units, scientific notation, significant figures, and vector quantities throughout the course. Once you have understood these concepts, we can go on to discuss physical descriptions of motion and its causes.

WHAT WE WILL LEARN

- The use of scientific notation and the appropriate number of significant figures is important in physics.
- We will become familiar with the international unit system and the definitions of the base units as well as methods of converting among other unit systems.
- We will use available length, mass, and time scales to establish reference points for grasping the vast diversity of systems in physics.
- We will apply a problem-solving strategy that will be useful in analyzing and understanding problems throughout this course and in science and engineering applications.
- We will work with vectors: vector addition and subtraction, multiplication of vectors, unit vectors, and length and direction of vectors.

1.1 Why Study Physics?

Perhaps your reason for studying physics can be quickly summed up as "Because it is required for my major!" While this motivation is certainly compelling, the study of science, and particularly physics, offers a few additional benefits.

Physics is the science on which all other natural and engineering sciences are built. All modern technological advances—from laser surgery to television, from computers to refrigerators, from cars to airplanes—trace back directly to basic physics. A good grasp of essential physics concepts gives you a solid foundation on which to construct advanced knowledge in all sciences. For example, the conservation laws and symmetry principles of physics also hold true for all scientific phenomena and many aspects of everyday life.

The study of physics will help you grasp the scales of distance, mass, and time, from the smallest constituents inside the nuclei of atoms to the galaxies that make up our universe. All natural systems follow the same basic laws of physics, providing a unifying concept for understanding how we fit into the overall scheme of the universe.

Physics is intimately connected with mathematics because it brings to life the abstract concepts used in trigonometry, algebra, and calculus. The analytical thinking and general techniques for problem solving that you learn here will remain useful for the rest of your life.

Science, especially physics, helps remove irrationality from our explanations of the world around us. Prescientific thinking resorted to mythology to explain natural phenomena. For example, the old Germanic tribes believed the god Thor using his hammer caused thunder. You may smile when you read this account, knowing that thunder and lightning come from electric discharges in the atmosphere. However, if you read the daily news, you will find that some misconceptions from prescientific thinking persist even today. You may not find the answer to the meaning of life in this course, but at the very least you will come away with some of the intellectual tools that enable you to weed out inconsistent, logically flawed theories and misconceptions that contradict experimentally verifiable facts. Scientific progress over the last millennium has provided a rational explanation for most of what occurs in the natural world surrounding us.

Through consistent theories and well-designed experiments, physics has helped us obtain a deeper understanding of our surroundings and has given us greater ability to control them. In a time when the consequences of air and water pollution, limited energy resources, and global warming threaten the continued existence of huge portions of life on Earth, the need to understand the results of our interactions with the environment has never been greater. Much of environmental science is based on fundamental physics, and physics drives much of the technology essential to progress in chemistry and the life sciences. You may well be called upon to help decide public policy in these areas, whether as a scientist, an engineer, or simply as a citizen. Having an objective understanding of basic scientific issues is of vital importance in making such decisions. Thus, you need to acquire scientific literacy, an essential tool for every citizen in our technology-driven society.

You cannot become scientifically literate without command of the necessary elementary tools, just as it is impossible to make music without the ability to play an instrument. This is the main purpose of this text: to properly equip you to make sound contributions to the important discussions and decisions of our time. You will emerge from reading and working with this text with a deeper appreciation for the fundamental laws that govern our universe and for the tools that humanity has developed to uncover them, tools that transcend cultures and historic eras.

1.2 Working with Numbers

Scientists have established logical rules to govern how they communicate quantitative information to one another. If you want to report the result of a measurement—for example, the distance between two cities, your own weight, or the length of a lecture—you have to specify this result in multiples of a standard unit. Thus, a measurement is the combination of a number and a unit.

At first thought, writing down numbers doesn't seem very difficult. However, in physics, we need to deal with two complications: how to deal with very big or very small numbers, and how to specify precision.

Scientific Notation

If you want to report a really big number, it becomes tedious to write it out. For example, the human body contains approximately 7,000,000,000,000,000,000,000,000,000 atoms. If you used this number often, you would surely like to have a more compact notation for it. This is exactly what **scientific notation** is. It represents a number as the product of a number greater than or equal to 1 and less than 10 (called the *mantissa*) and a power (or exponent) of 10:

$$\text{number} = \text{mantissa} \cdot 10^{\text{exponent}}. \tag{1.1}$$

The number of atoms in the human body can thus be written compactly as $7 \cdot 10^{27}$, where 7 is the mantissa and 27 is the exponent.

Another advantage of scientific notation is that it makes it easy to multiply and divide large numbers. To multiply two numbers in scientific notation, we multiply their mantissas and then add their exponents. If we wanted to estimate, for example, how many atoms are contained in the bodies of all the people on Earth, we could do this calculation rather easily. Earth hosts approximately 7 billion ($= 7 \cdot 10^9$) humans. All we have to do to find our answer is to multiply $7 \cdot 10^{27}$ by $7 \cdot 10^9$. We do this by multiplying the two mantissas and adding the exponents:

$$(7 \cdot 10^{27}) \cdot (7 \cdot 10^9) = (7 \cdot 7) \cdot 10^{27+9} = 49 \cdot 10^{36} = 4.9 \cdot 10^{37}. \tag{1.2}$$

In the last step, we follow the common convention of keeping only one digit in front of the decimal point of the mantissa and adjusting the exponent accordingly. (But be advised that we will have to further adjust this answer—read on!)

Division with scientific notation is equally straightforward: If we want to calculate A / B, we divide the mantissa of A by the mantissa of B and subtract the exponent of B from the exponent of A.

Concept Check 1.1

The total surface area of Earth is $A = 4\pi R^2 = 4\pi(6370 \text{ km})^2 = 5.099 \cdot 10^{14} \text{ m}^2$. Assuming there are 7.0 billion humans on the planet, what is the available surface area per person?

a) $7.3 \cdot 10^4 \text{ m}^2$
b) $7.3 \cdot 10^{24} \text{ m}^2$
c) $3.6 \cdot 10^{24} \text{ m}^2$
d) $3.6 \cdot 10^4 \text{ m}^2$

Significant Figures

When we specified the number of atoms in the average human body as $7 \cdot 10^{27}$, we meant to indicate that we know it is at least $6.5 \cdot 10^{27}$ but smaller than $7.5 \cdot 10^{27}$. However, if we had written $7.0 \cdot 10^{27}$, we would have implied that we know the true number is somewhere between $6.95 \cdot 10^{27}$ and $7.05 \cdot 10^{27}$. This statement is more precise than the previous statement.

As a general rule, the number of digits you write in the mantissa specifies how precisely you claim to know it. The more digits specified, the more precision is implied (see Figure 1.2). We call the number of digits in the mantissa the number of **significant figures.** Here are some rules about using significant figures followed in each case by an example:

- The number of significant figures is the number of reliably known digits. For example, 1.62 has three significant figures; 1.6 has two significant figures.