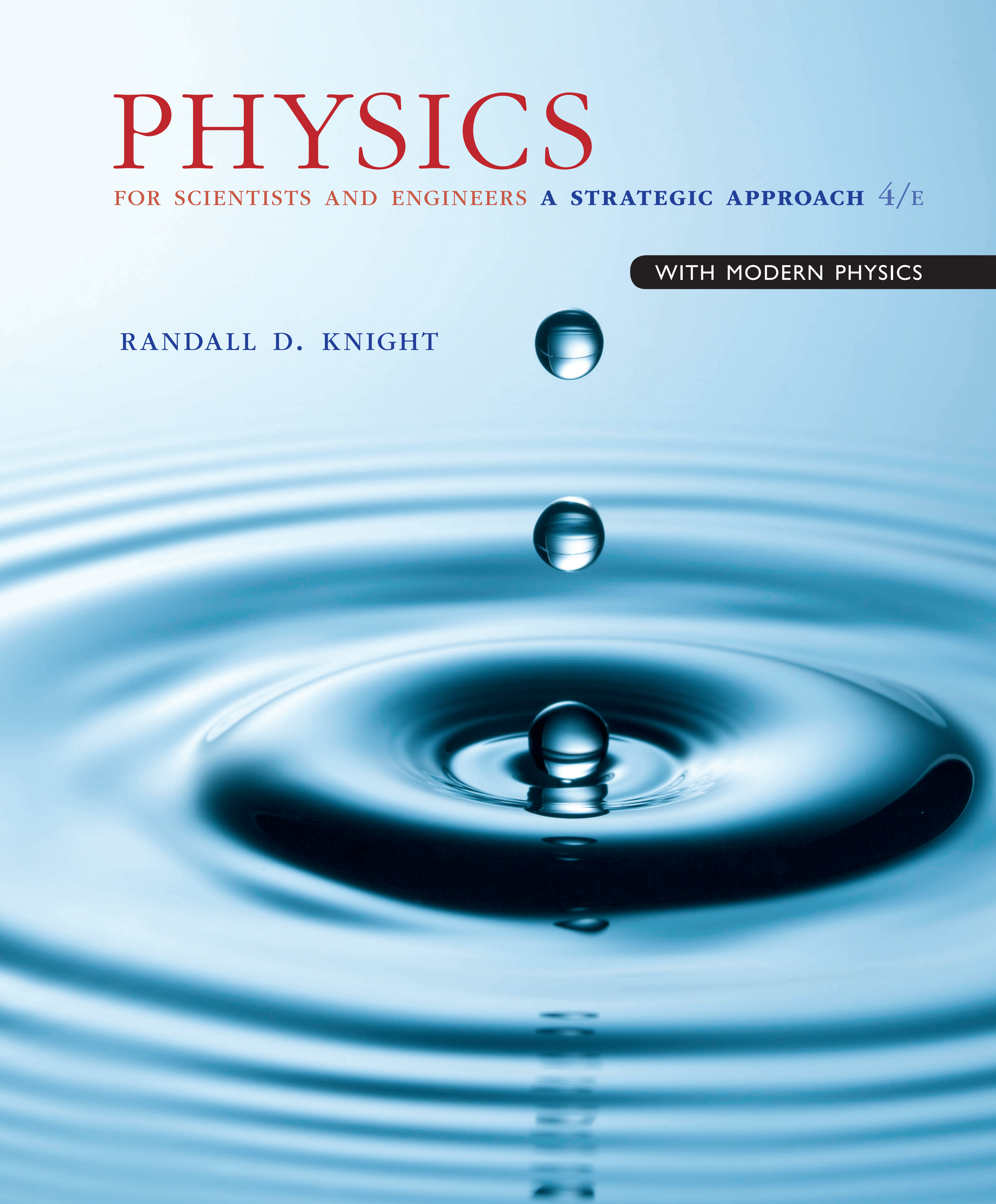
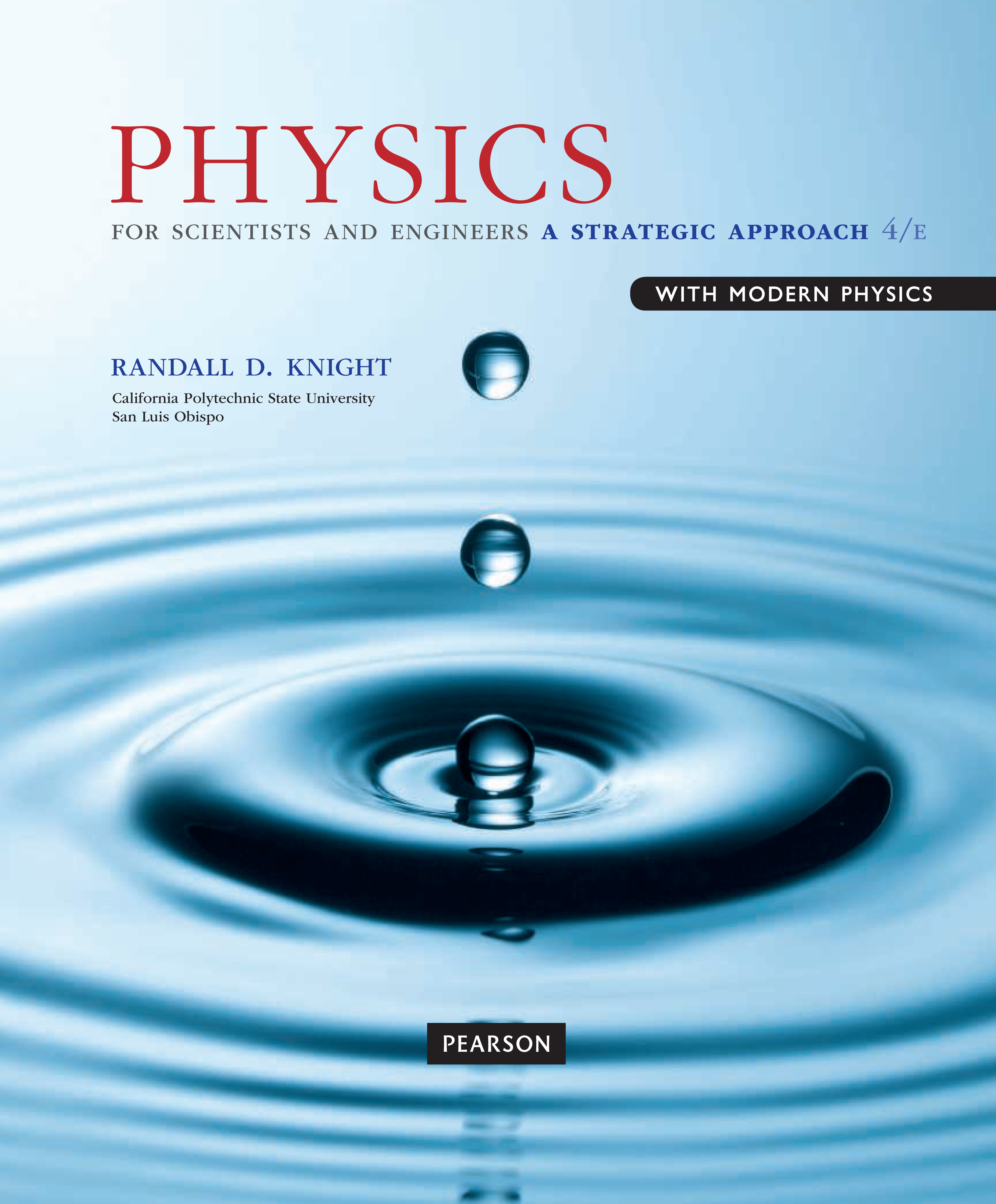
PHYSICS

FOR SCIENTISTS AND ENGINEERS A STRATEGIC APPROACH 4/E

WITH MODERN PHYSICS

RANDALL D. KNIGHT





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San Luis Obispo

PEARSON

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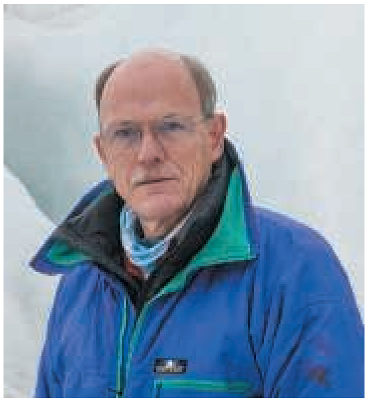
About the Author

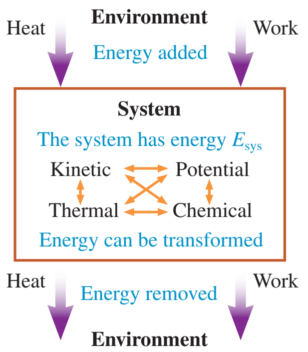


Randy Knight taught introductory physics for 32 years at Ohio State University and California Polytechnic State University, where he is Professor Emeritus of Physics. Professor Knight received a Ph.D. in physics from the University of California, Berkeley and was a post-doctoral fellow at the Harvard-Smithsonian Center for Astrophysics before joining the faculty at Ohio State University. It was at Ohio State that he began to learn about the research in physics education that, many years later, led to *Five Easy Lessons: Strategies for Successful Physics Teaching* and this book, as well as *College Physics: A Strategic Approach,* co-authored with Brian Jones and Stuart Field. Professor Knight's research interests are in the fields of laser spectroscopy and environmental science. When he's not in front of a computer, you can find Randy hiking, sea kayaking, playing the piano, or spending time with his wife Sally and their five cats.

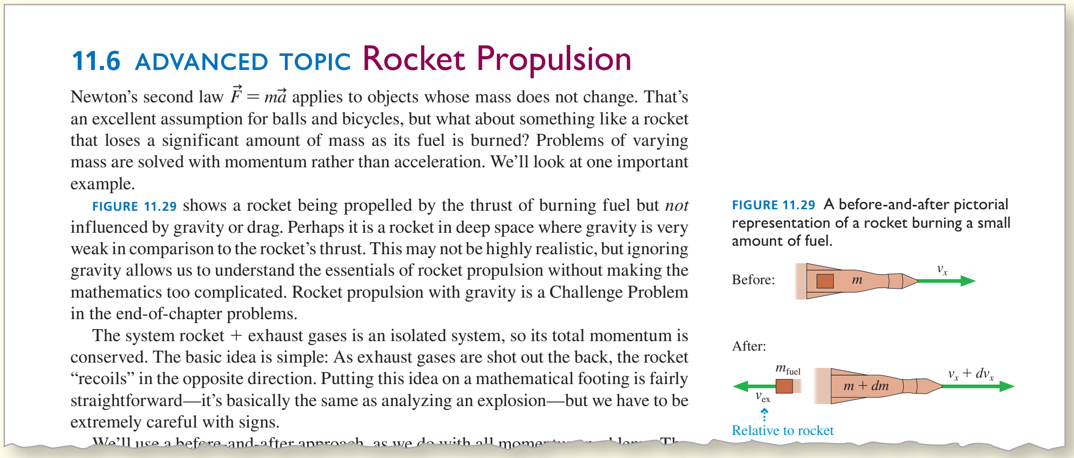
A research-driven approach, fine-tuned for even greater ease-of-use and student success

REVISED COVERAGE AND ORGANIZATION GIVE INSTRUCTORS GREATER CHOICE AND FLEXIBILITY

FIGURE 9.1 A system-environment perspective on energy.



NEW! CHAPTER ORGANIZATION allows instructors to more easily present material as needed to complement labs, course schedules, and different teaching styles. Work and energy are now covered before momentum, oscillations are grouped with mechanical waves, and optics appears after electricity and magnetism. Unchanged is Knight's unique approach of working from concrete to abstract, using multiple representations, balancing qualitative with quantitative, and addressing misconceptions.



11.6 ADVANCED TOPIC Rocket Propulsion

Newton's second law $\vec{F} = m\vec{a}$ applies to objects whose mass does not change. That's an excellent assumption for balls and bicycles, but what about something like a rocket that loses a significant amount of mass as its fuel is burned? Problems of varying mass are solved with momentum rather than acceleration. We'll look at one important example.

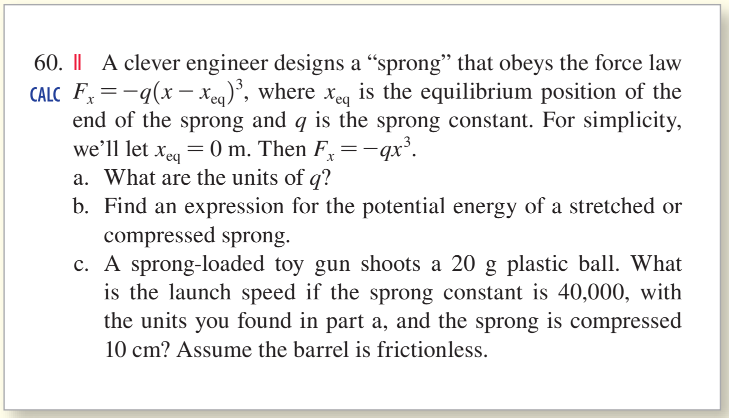
FIGURE 11.29 shows a rocket being propelled by the thrust of burning fuel but *not* influenced by gravity or drag. Perhaps it is a rocket in deep space where gravity is very weak in comparison to the rocket's thrust. This may not be highly realistic, but ignoring gravity allows us to understand the essentials of rocket propulsion without making the mathematics too complicated. Rocket propulsion with gravity is a Challenge Problem in the end-of-chapter problems.

The system rocket + exhaust gases is an isolated system, so its total momentum is conserved. The basic idea is simple: As exhaust gases are shot out the back, the rocket "recoils" in the opposite direction. Putting this idea on a mathematical footing is fairly straightforward—it's basically the same as analyzing an explosion—but we have to be extremely careful with signs.

We'll use a before-and-after approach, as we do with all

FIGURE 11.29 A before-and-after pictorial representation of a rocket burning a small amount of fuel.

NEW! ADVANCED TOPICS as optional sections add even more flexibility for instructors' individual courses. Topics include rocket propulsion, gyroscopes and precession, the wave equation (including for electromagnetic waves), the speed of sound in gases, and more details on the interference of light.



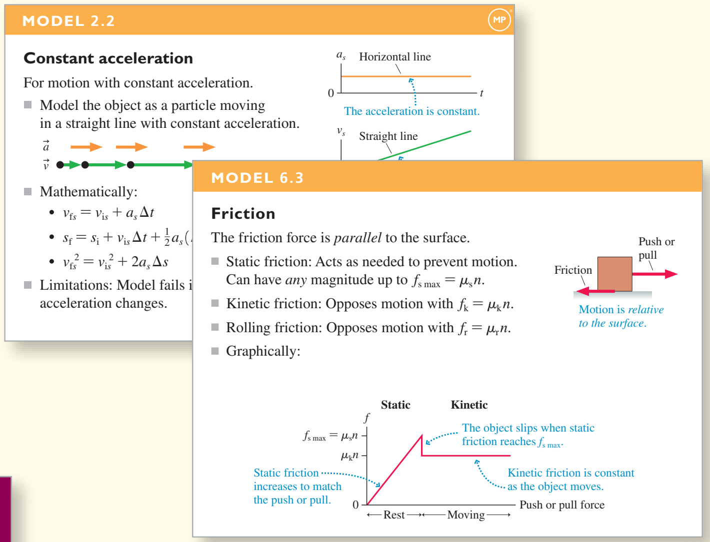
60. ‖ A clever engineer designs a "sprong" that obeys the force law
CALC $F_x = -q(x - x_{eq})^3$, where x_{eq} is the equilibrium position of the end of the sprong and q is the sprong constant. For simplicity, we'll let $x_{eq} = 0$ m. Then $F_x = -qx^3$.
   a. What are the units of q?
   b. Find an expression for the potential energy of a stretched or compressed sprong.
   c. A sprong-loaded toy gun shoots a 20 g plastic ball. What is the launch speed if the sprong constant is 40,000, with the units you found in part a, and the sprong is compressed 10 cm? Assume the barrel is frictionless.

NEW! MORE CALCULUS-BASED PROBLEMS have been added, along with an icon to make these easy to identify. The significantly revised end-of-chapter problem sets, extensively class-tested and both calibrated and improved using MasteringPhysics® data, expand the range of physics and math skills students will use to solve problems.

Built from the ground up on physics education research and crafted using key ideas from learning theory, Knight has set the standard for effective and accessible pedagogical materials in physics. In this fourth edition, Knight continues to refine and expand the instructional techniques to take students further.

NEW AND UPDATED LEARNING TOOLS PROMOTE DEEPER AND BETTER-CONNECTED UNDERSTANDING

NEW! MODEL BOXES enhance the text's emphasis on modeling—analyzing a complex, real-world situation in terms of simple but reasonable idealizations that can be applied over and over in solving problems. These fundamental simplifications are developed in the text and then deployed more explicitly in the worked examples, helping students to recognize when and how to use recurring models, a key critical-thinking skill.



MODEL 2.2

Constant acceleration

For motion with constant acceleration.

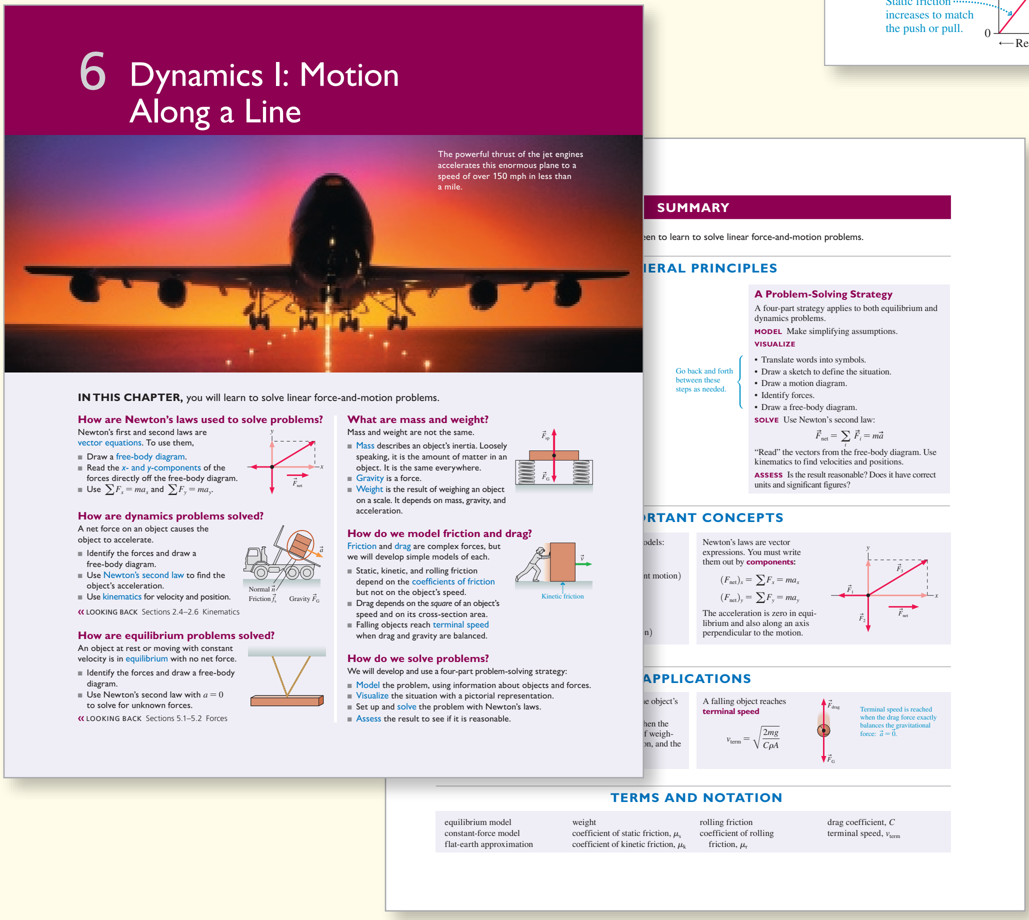
- Model the object as a particle moving in a straight line with constant acceleration.
- Mathematically:
  - $v_{fs} = v_{is} + a_s \Delta t$
  - $s_f = s_i + v_{is}\Delta t + \frac{1}{2}a_s($
  - $v_{fs}^2 = v_{is}^2 + 2a_s \Delta s$
- Limitations: Model fails i acceleration changes.

MODEL 6.3

Friction

The friction force is *parallel* to the surface.

- Static friction: Acts as needed to prevent motion. Can have *any* magnitude up to $f_{s\,max} = \mu_s n$.
- Kinetic friction: Opposes motion with $f_k = \mu_k n$.
- Rolling friction: Opposes motion with $f_r = \mu_r n$.
- Graphically:



6 Dynamics I: Motion Along a Line

The powerful thrust of the jet engines accelerates this enormous plane to a speed of over 150 mph in less than a mile.

IN THIS CHAPTER, you will learn to solve linear force-and-motion problems.

How are Newton's laws used to solve problems?

Newton's first and second laws are vector equations. To use them,

- Draw a free-body diagram.
- Read the x- and y-components of the forces directly off the free-body diagram.
- Use $\sum F_x = ma_x$ and $\sum F_y = ma_y$.

How are dynamics problems solved?

A net force on an object causes the object to accelerate.

- Identify the forces and draw a free-body diagram.
- Use Newton's second law to find the object's acceleration.
- Use kinematics for velocity and position.

« LOOKING BACK Sections 2.4–2.6 Kinematics

How are equilibrium problems solved?

An object at rest or moving with constant velocity is in equilibrium with no net force.

- Identify the forces and draw a free-body diagram.
- Use Newton's second law with $a = 0$ to solve for unknown forces.

« LOOKING BACK Sections 5.1–5.2 Forces

What are mass and weight?

Mass and weight are not the same.

- Mass describes an object's inertia. Loosely speaking, it is the amount of matter in an object. It is the same everywhere.
- Gravity is a force.
- Weight is the result of weighing an object on a scale. It depends on mass, gravity, and acceleration.

How do we model friction and drag?

Friction and drag are complex forces, but we will develop simple models of each.

- Static, kinetic, and rolling friction depend on the coefficients of friction but not on the object's speed.
- Drag depends on the *square* of an object's speed and on its cross-section area.
- Falling objects reach terminal speed when drag and gravity are balanced.

How do we solve problems?

We will develop and use a four-part problem-solving strategy:

- Model the problem, using information about objects and forces.
- Visualize the situation with a pictorial representation.
- Set up and solve the problem with Newton's laws.
- Assess the result to see if it is reasonable.

SUMMARY

een to learn to solve linear force-and-motion problems.

IERAL PRINCIPLES

A Problem-Solving Strategy

A four-part strategy applies to both equilibrium and dynamics problems.

MODEL Make simplifying assumptions.

VISUALIZE

- Translate words into symbols.
- Draw a sketch to define the situation.
- Draw a motion diagram.
- Identify forces.
- Draw a free-body diagram.

Go back and forth between these steps as needed.

SOLVE Use Newton's second law:

$$\vec{F}_{net} = \sum_i \vec{F}_i = m\vec{a}$$

"Read" the vectors from the free-body diagram. Use kinematics to find velocities and positions.

ASSESS Is the result reasonable? Does it have correct units and significant figures?

RTANT CONCEPTS

odels:

nt motion)

n)

Newton's laws are vector expressions. You must write them out by **components:**

$$(F_{net})_x = \sum F_x = ma_x$$

$$(F_{net})_y = \sum F_y = ma_y$$

The acceleration is zero in equilibrium and also along an axis perpendicular to the motion.

APPLICATIONS

e object's

hen the
f weigh-
on, and the

A falling object reaches **terminal speed**

$$v_{term} = \sqrt{\frac{2mg}{C\rho A}}$$

Terminal speed is reached when the drag force exactly balances the gravitational force: $\vec{a} = \vec{0}$.

TERMS AND NOTATION

equilibrium model constant-force model flat-earth approximation	weight coefficient of static friction, μ_s coefficient of kinetic friction, μ_k	rolling friction coefficient of rolling friction, μ_r	drag coefficient, C terminal speed, v_{term}

REVISED! ENHANCED CHAPTER PREVIEWS, based on the educational psychology concept of an "advance organizer," have been reconceived to address the questions students are most likely to ask themselves while studying the material for the first time. Questions cover the important ideas, and provide a big-picture overview of the chapter's key principles. Each chapter concludes with the visual Chapter Summary, consolidating and structuring understanding.

A STRUCTURED AND CONSISTENT APPROACH BUILDS PROBLEM-SOLVING SKILLS AND CONFIDENCE

With a research-based 4-step problem-solving framework used throughout the text, students learn the importance of making assumptions (in the MODEL step) and gathering information and making sketches (in the VISUALIZE step) before treating the problem mathematically (SOLVE) and then analyzing their results (ASSESS).

Detailed PROBLEM-SOLVING STRATEGIES for different topics and categories of problems (circular-motion problems, calorimetry problems, etc.) are developed throughout, each one built on the 4-step framework and carefully illustrated in worked examples.

PROBLEM-SOLVING STRATEGY 10.1

Energy-conservation problems

MODEL Define the system so that there are no external forces or so that any external forces do no work on the system. If there's friction, bring both surfaces into the system. Model objects as particles and springs as ideal.

VISUALIZE Draw a before-and-after pictorial representation and an energy bar chart. A free-body diagram may be needed to visualize forces.

SOLVE If the system is both isolated and nondissipative, then the mechanical energy is conserved:

$$K_i + U_i = K_f + U_f$$

where K is the total kinetic energy of all moving objects and U is the total potential energy of all interactions within the system. If there's friction, then

$$K_i + U_i = K_f + U_f + \Delta E_{th}$$

where the thermal energy increase due to friction is $\Delta E_{th} = f_k \Delta s$.

ASSESS Check that your result has correct units and significant figures, is reasonable, and answers the question.

Exercise 14

TACTICS BOX 26.1

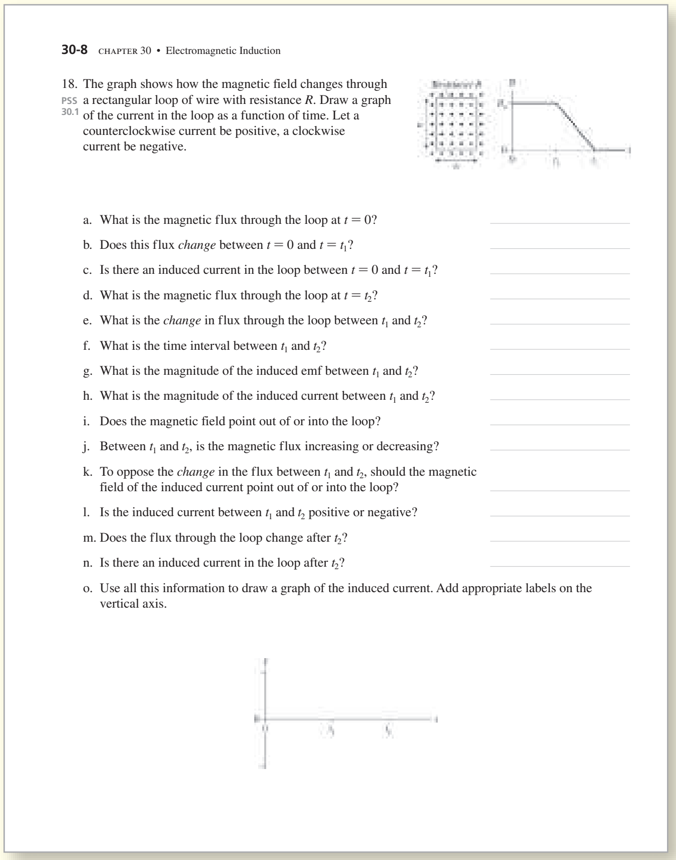
Finding the potential from the electric field

❶ Draw a picture and identify the point at which you wish to find the potential. Call this position f.
❷ Choose the zero point of the potential, often at infinity. Call this position i.
❸ Establish a coordinate axis from i to f along which you already know or can easily determine the electric field component E_s.
❹ Carry out the integration of Equation 26.3 to find the potential.

Exercise 1

TACTICS BOXES give step-by-step procedures for developing specific skills (drawing free-body diagrams, using ray tracing, etc.).

The REVISED STUDENT WORKBOOK is tightly integrated with the main text–allowing students to practice skills from the text's Tactics Boxes, work through the steps of Problem-Solving Strategies, and assess the applicability of the Models. The workbook is referenced throughout the text with the icon ✎.



30-8 CHAPTER 30 • Electromagnetic Induction

18. The graph shows how the magnetic field changes through a rectangular loop of wire with resistance R. Draw a graph of the current in the loop as a function of time. Let a counterclockwise current be positive, a clockwise current be negative.
PSS 30.1

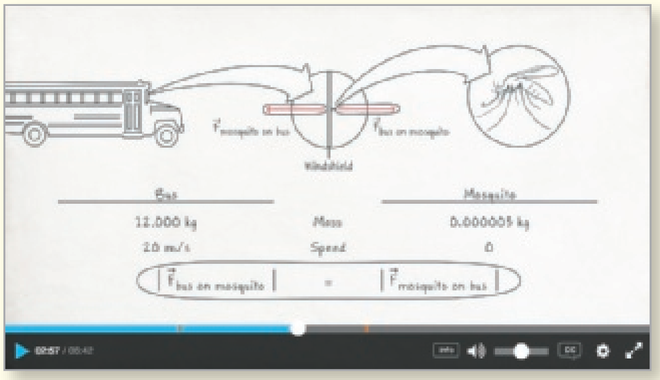
a. What is the magnetic flux through the loop at $t = 0$? __________
b. Does this flux *change* between $t = 0$ and $t = t_1$? __________
c. Is there an induced current in the loop between $t = 0$ and $t = t_1$? __________
d. What is the magnetic flux through the loop at $t = t_2$? __________
e. What is the *change* in flux through the loop between t_1 and t_2? __________
f. What is the time interval between t_1 and t_2? __________
g. What is the magnitude of the induced emf between t_1 and t_2? __________
h. What is the magnitude of the induced current between t_1 and t_2? __________
i. Does the magnetic field point out of or into the loop? __________
j. Between t_1 and t_2, is the magnetic flux increasing or decreasing? __________
k. To oppose the *change* in the flux between t_1 and t_2, should the magnetic field of the induced current point out of or into the loop? __________
l. Is the induced current between t_1 and t_2 positive or negative? __________
m. Does the flux through the loop change after t_2? __________
n. Is there an induced current in the loop after t_2? __________
o. Use all this information to draw a graph of the induced current. Add appropriate labels on the vertical axis.

MasteringPhysics THE ULTIMATE RESOURCE BEFORE, DURING, AND AFTER CLASS

BEFORE CLASS

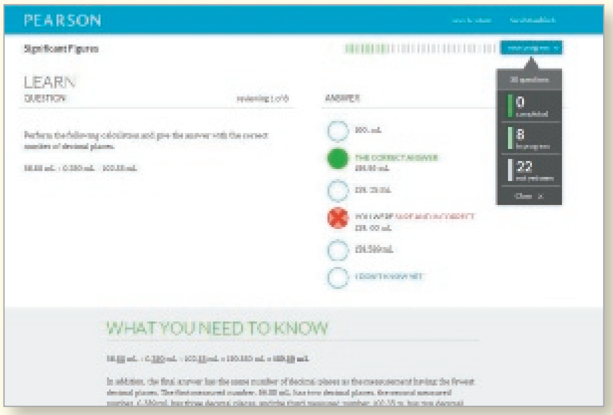
NEW! INTERACTIVE PRELECTURE VIDEOS

address the rapidly growing movement toward pre-lecture teaching and flipped classrooms. These whiteboard-style animations provide an introduction to key topics with embedded assessment to help students prepare and professors identify student misconceptions before lecture.

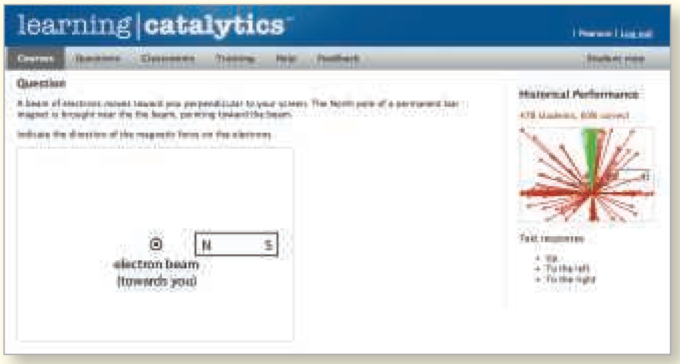


NEW! DYNAMIC STUDY MODULES (DSMs)

continuously assess students' performance in real time to provide personalized question and explanation content until students master the module with confidence. The DSMs cover basic math skills and key definitions and relationships for topics across all of mechanics and electricity and magnetism.



DURING CLASS



NEW! LEARNING CATALYTICS™

is an interactive classroom tool that uses students' devices to engage them in more sophisticated tasks and thinking. Learning Catalytics enables instructors to generate classroom discussion and promote peer-to-peer learning to help students develop critical-thinking skills. Instructors can take advantage of real-time analytics to find out where students are struggling and adjust their instructional strategy.

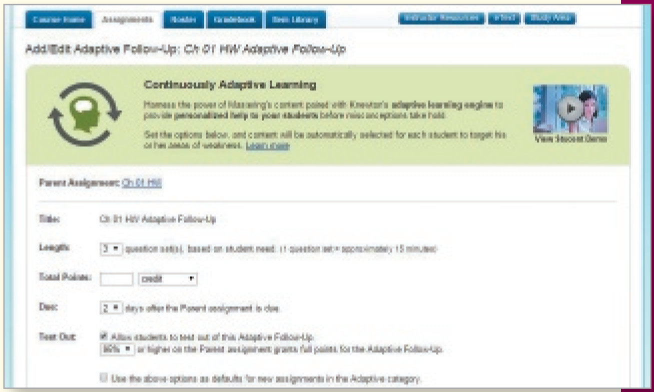
AFTER CLASS

NEW! ENHANCED END-OF-CHAPTER QUESTIONS

offer students instructional support when and where they need it, including links to the eText, math remediation, and wrong-answer feedback for homework assignments.

ADAPTIVE FOLLOW-UPS

are personalized assignments that pair Mastering's powerful content with Knewton's adaptive learning engine to provide individualized help to students before misconceptions take hold. These adaptive follow-ups address topics students struggled with on assigned homework, including core prerequisite topics.



Add/Edit Adaptive Follow-Up: *Ch 01 HW Adaptive Follow-Up*

Continuously Adaptive Learning

Harness the power of Mastering's content paired with Knewton's **adaptive learning engine** to provide **personalized help to your students** before misconceptions take hold.

Set the options below, and content will be automatically selected for each student to target his or her areas of weakness. Learn more

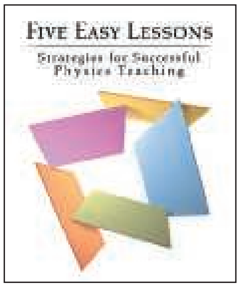
Parent Assignment: Ch 01 HW

Title: Ch 01 HW Adaptive Follow-Up
Length: 3 question set(s), based on student need. (1 question set = approximately 15 minutes)
Total Points: credit
Due: 2 days after the Parent assignment is due.
Test Out: ☑ Allow students to test out of this Adaptive Follow-Up.
90% or higher on the Parent assignment grants full points for the Adaptive Follow-Up.
☐ Use the above options as defaults for new assignments in the Adaptive category.

Preface to the Instructor

This fourth edition of *Physics for Scientists and Engineers: A Strategic Approach* continues to build on the research-driven instructional techniques introduced in the first edition and the extensive feedback from thousands of users. From the beginning, the objectives have been:

- To produce a textbook that is more focused and coherent, less encyclopedic.
- To move key results from physics education research into the classroom in a way that allows instructors to use a range of teaching styles.
- To provide a balance of quantitative reasoning and conceptual understanding, with special attention to concepts known to cause student difficulties.
- To develop students' problem-solving skills in a systematic manner.



These goals and the rationale behind them are discussed at length in the *Instructor's Guide* and in my small paperback book, *Five Easy Lessons: Strategies for Successful Physics Teaching*. Please request a copy from your local Pearson sales representative if it is of interest to you (ISBN 978-0-805-38702-5).

What's New to This Edition

For this fourth edition, we continue to apply the best results from educational research and to tailor them for this course and its students. At the same time, the extensive feedback we've received from both instructors and students has led to many changes and improvements to the text, the figures, and the end-of-chapter problems. These include:

- **Chapter ordering changes** allow instructors to more easily organize content as needed to accommodate labs, schedules, and different teaching styles. Work and energy are now covered before momentum, oscillations are grouped with mechanical waves, and optics appears after electricity and magnetism.
- **Addition of advanced topics** as optional sections further expands instructors' options. Topics include rocket propulsion, gyroscopes, the wave equation (for mechanical and electromagnetic waves), the speed of sound in gases, and more details on the interference of light.
- **Model boxes** enhance the text's emphasis on modeling—analyzing a complex, real-world situation in terms of simple but reasonable idealizations that can be applied over and over in solving problems. These fundamental simplifications are developed in the text and then deployed more explicitly in the worked examples, helping students to recognize when and how to use recurring models.
- **Enhanced chapter previews** have been redesigned, with student input, to address the questions students are most likely to ask themselves while studying the material for the first time. The previews provide a big-picture overview of the chapter's key principles.
- **Looking Back pointers** enable students to look back at a previous chapter when it's important to review concepts. Pointers provide the specific section to consult at the exact point in the text where they need to use this material.
- **Focused Part Overviews and Knowledge Structures** consolidate understanding of groups of chapters and give a tighter structure to the book as a whole. Reworked Knowledge Structures provide more targeted detail on overarching themes.
- **Updated visual program** that has been enhanced by revising over 500 pieces of art to increase the focus on key ideas.
- **Significantly revised end-of-chapter problem sets** include more challenging problems to expand the range of physics and math skills students will use to solve problems. A new icon for calculus-based problems has been added.

At the front of this book, you'll find an illustrated walkthrough of the new pedagogical features in this fourth edition.

Textbook Organization

The 42-chapter extended edition (ISBN 978-0-133-94265-1 / 0-133-94265-1) of *Physics for Scientists and Engineers* is intended for a three-semester course. Most of the 36-chapter standard edition (ISBN 978-0-134-08149-6 / 0-134-08149-8), ending with relativity, can be covered in two semesters, although the judicious omission of a few chapters will avoid rushing through the material and give students more time to develop their knowledge and skills.

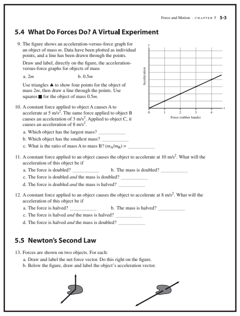
The full textbook is divided into eight parts: Part I: *Newton's Laws,* Part II: *Conservation Laws,* Part III: *Applications of Newtonian Mechanics,* Part IV: *Oscillations and Waves,* Part V: *Thermodynamics,* Part VI: *Electricity and Magnetism,* Part VII: *Optics,* and Part VIII: *Relativity and Quantum Physics*. Note that covering the parts in this order is by no means essential. Each topic is self-contained, and Parts III–VII can be rearranged to suit an instructor's needs. Part VII: *Optics* does need to follow Part IV: *Oscillations and Waves,* but optics can be taught either before or after electricity and magnetism.

There's a growing sentiment that quantum physics is quickly becoming the province of engineers, not just scientists, and that even a two-semester course should include a reasonable introduction to quantum ideas. The *Instructor's Guide* outlines a couple of routes through the book that allow most of the quantum physics chapters to be included in a two-semester course. I've written the book with the hope that an increasing number of instructors will choose one of these routes.

- **Extended edition,** with modern physics (ISBN 978-0-133-94265-1 / 0-133-94265-1): Chapters 1–42.
- **Standard edition** (ISBN 978-0-134-08149-6 / 0-134-08149-8): Chapters 1-36.
- **Volume 1** (ISBN 978-0-134-11068-4 / 0-134-11068-4) covers mechanics, waves, and thermodynamics: Chapters 1–21.
- **Volume 2** (ISBN 978-0-134-11066-0 / 0-134-11066-8) covers electricity and magnetism and optics, plus relativity: Chapters 22–36.
- **Volume 3** (ISBN 978-0-134-11065-3 / 0-134-11065-X) covers relativity and quantum physics: Chapters 36–42.

The Student Workbook

A key component of *Physics for Scientists and Engineers: A Strategic Approach* is the accompanying *Student Workbook*. The workbook bridges the gap between textbook and homework problems by providing students the opportunity to learn and practice skills prior to using those skills in quantitative end-of-chapter problems, much as a musician practices technique separately from performance pieces. The workbook exercises, which are keyed to each section of the textbook, focus on developing specific skills, ranging from identifying forces and drawing free-body diagrams to interpreting wave functions.


Force and Motion · CHAPTER 5 5-3

5.4 What Do Forces Do? A Virtual Experiment

9. The figure shows an acceleration-versus-force graph for an object of mass *m*. Data have been plotted as individual points, and a line has been drawn through the points.

Draw and label, directly on the figure, the acceleration-versus-force graphs for objects of mass

a. 2*m* b. 0.5*m*

Use triangles ▲ to show four points for the object of mass 2*m*, then draw a line through the points. Use squares ■ for the object of mass 0.5*m*.

10. A constant force applied to object A causes A to accelerate at 5 m/s^2. The same force applied to object B causes an acceleration of 3 m/s^2. Applied to object C, it causes an acceleration of 8 m/s^2.

a. Which object has the largest mass? ________

b. Which object has the smallest mass? ________

c. What is the ratio of mass A to mass B? (m_A/m_B) = ________

11. A constant force applied to an object causes the object to accelerate at 10 m/s^2. What will the acceleration of this object be if

a. The force is doubled? ________ b. The mass is doubled? ________

c. The force is doubled *and* the mass is doubled? ________

d. The force is doubled *and* the mass is halved? ________

12. A constant force applied to an object causes the object to accelerate at 8 m/s^2. What will the acceleration of this object be if

a. The force is halved? ________ b. The mass is halved? ________

c. The force is halved *and* the mass is halved? ________

d. The force is halved *and* the mass is doubled? ________

5.5 Newton's Second Law

13. Forces are shown on two objects. For each:

a. Draw and label the net force vector. Do this right on the figure.

b. Below the figure, draw and label the object's acceleration vector.

The workbook exercises, which are generally qualitative and/or graphical, draw heavily upon the physics education research literature. The exercises deal with issues known to cause student difficulties and employ techniques that have proven to be effective at overcoming those difficulties. **New to the fourth edition workbook** are exercises that provide guided practice for the textbook's Model boxes. The workbook exercises can be used in class as part of an active-learning teaching strategy, in recitation sections, or as assigned homework. More information about effective use of the *Student Workbook* can be found in the *Instructor's Guide*.

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Preface to the Student

From Me to You

The most incomprehensible thing about the universe is that it is comprehensible.
—Albert Einstein

The day I went into physics class it was death.
—Sylvia Plath, *The Bell Jar*

Let's have a little chat before we start. A rather one-sided chat, admittedly, because you can't respond, but that's OK. I've talked with many of your fellow students over the years, so I have a pretty good idea of what's on your mind.

What's your reaction to taking physics? Fear and loathing? Uncertainty? Excitement? All the above? Let's face it, physics has a bit of an image problem on campus. You've probably heard that it's difficult, maybe impossible unless you're an Einstein. Things that you've heard, your experiences in other science courses, and many other factors all color your *expectations* about what this course is going to be like.

It's true that there are many new ideas to be learned in physics and that the course, like college courses in general, is going to be much faster paced than science courses you had in high school. I think it's fair to say that it will be an *intense* course. But we can avoid many potential problems and difficulties if we can establish, here at the beginning, what this course is about and what is expected of you—and of me!

Just what is physics, anyway? Physics is a way of thinking about the physical aspects of nature. Physics is not better than art or biology or poetry or religion, which are also ways to think about nature; it's simply different. One of the things this course will emphasize is that physics is a human endeavor. The ideas presented in this book were not found in a cave or conveyed to us by aliens; they were discovered and developed by real people engaged in a struggle with real issues.

You might be surprised to hear that physics is not about "facts." Oh, not that facts are unimportant, but physics is far more focused on discovering *relationships* and *patterns* than on learning facts for their own sake.

For example, the colors of the rainbow appear both when white light passes through a prism and—as in this photo—when white light reflects from a thin film of oil on water. What does this pattern tell us about the nature of light?

Our emphasis on relationships and patterns means that there's not a lot of memorization when you study physics. Some—there are still definitions and equations to learn—but less than in many other courses. Our emphasis, instead, will be on thinking and reasoning. This is important to factor into your expectations for the course.

Perhaps most important of all, *physics is not math!* Physics is much broader. We're going to look for patterns and relationships in nature, develop the logic that relates different ideas, and search for the reasons *why* things happen as they do. In doing so, we're going to stress qualitative reasoning, pictorial and graphical reasoning, and reasoning by analogy. And yes, we will use math, but it's just one tool among many.

It will save you much frustration if you're aware of this physics–math distinction up front. Many of you, I know, want to find a formula and plug numbers into it—that is, to do a math problem. Maybe that worked in high school science courses, but it is *not* what this course expects of you. We'll certainly do many calculations, but the specific numbers are usually the last and least important step in the analysis.

As you study, you'll sometimes be baffled, puzzled, and confused. That's perfectly normal and to be expected. Making mistakes is OK too *if* you're willing to learn from the experience. No one is born knowing how to do physics any more than he or she is born knowing how to play the piano or shoot basketballs. The ability to do physics comes from practice, repetition, and struggling with the ideas until you "own" them and can apply them yourself in new situations. There's no way to make learning effortless, at least for anything worth learning, so expect to have some difficult moments ahead. But also expect to have some moments of excitement at the joy of discovery. There will be instants at which the pieces suddenly click into place and you *know* that you understand a powerful idea. There will be times when you'll surprise yourself by successfully working a difficult problem that you didn't think you could solve. My hope, as an author, is that the excitement and sense of adventure will far outweigh the difficulties and frustrations.

Getting the Most Out of Your Course

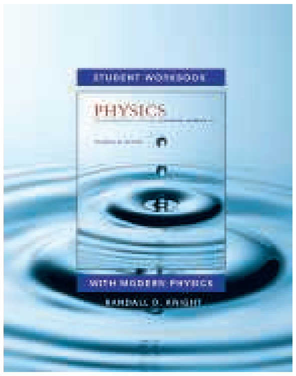
Many of you, I suspect, would like to know the "best" way to study for this course. There is no best way. People are different, and what works for one student is less effective for another. But I do want to stress that *reading the text* is vitally important. The basic knowledge for this course is written down on these pages, and your instructor's *number-one expectation* is that you will read carefully to find and learn that knowledge.

Despite there being no best way to study, I will suggest *one* way that is successful for many students.

1. **Read each chapter *before* it is discussed in class.** I cannot stress too strongly how important this step is. Class attendance is much more effective if you are prepared. When you first read a chapter, focus on learning new vocabulary, definitions, and notation. There's a list of terms and notations at the end of each chapter. Learn them! You won't understand

what's being discussed or how the ideas are being used if you don't know what the terms and symbols mean.

2. **Participate actively in class.** Take notes, ask and answer questions, and participate in discussion groups. There is ample scientific evidence that *active participation* is much more effective for learning science than passive listening.
3. **After class, go back for a careful re-reading of the chapter.** In your second reading, pay closer attention to the details and the worked examples. Look for the *logic* behind each example (I've highlighted this to make it clear), not just at what formula is being used. And use the textbook tools that are designed to help your learning, such as the problem-solving strategies, the chapter summaries, and the exercises in the *Student Workbook*.
4. **Finally, apply what you have learned to the homework problems at the end of each chapter.** I strongly encourage you to form a study group with two or three classmates. There's good evidence that students who study regularly with a group do better than the rugged individualists who try to go it alone.



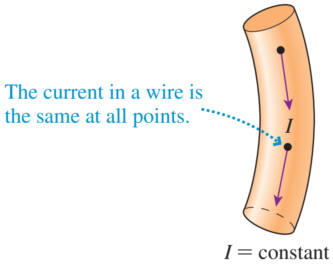
Did someone mention a workbook? The companion *Student Workbook* is a vital part of the course. Its questions and exercises ask you to reason *qualitatively,* to use graphical information, and to give explanations. It is through these exercises that you will learn what the concepts mean and will practice the reasoning skills appropriate to the chapter. You will then have acquired the baseline knowledge and confidence you need *before* turning to the end-of-chapter homework problems. In sports or in music, you would never think of performing before you practice, so why would you want to do so in physics? The workbook is where you practice and work on basic skills.

Many of you, I know, will be tempted to go straight to the homework problems and then thumb through the text looking for a formula that seems like it will work. That approach will not succeed in this course, and it's guaranteed to make you frustrated and discouraged. Very few homework problems are of the "plug and chug" variety where you simply put numbers into a formula. To work the homework problems successfully, you need a better study strategy—either the one outlined above or your own—that helps you learn the concepts and the relationships between the ideas.

Getting the Most Out of Your Textbook

Your textbook provides many features designed to help you learn the concepts of physics and solve problems more effectively.

- **TACTICS BOXES** give step-by-step procedures for particular skills, such as interpreting graphs or drawing special diagrams. Tactics Box steps are explicitly illustrated in subsequent worked examples, and these are often the starting point of a full *Problem-Solving Strategy*.
- **PROBLEM-SOLVING STRATEGIES** are provided for each broad class of problems—problems characteristic of a chapter or group of chapters. The strategies follow a consistent four-step approach to help you develop confidence and proficient problem-solving skills: **MODEL, VISUALIZE, SOLVE, ASSESS**.
- Worked **EXAMPLES** illustrate good problem-solving practices through the consistent use of the four-step problem-solving approach The worked examples are often very detailed and carefully lead you through the *reasoning* behind the solution as well as the numerical calculations.
- **STOP TO THINK** questions embedded in the chapter allow you to quickly assess whether you've understood the main idea of a section. A correct answer will give you confidence to move on to the next section. An incorrect answer will alert you to re-read the previous section.
- Blue annotations on figures help you better understand what the figure is showing. They will help you to interpret graphs; translate between graphs, math, and pictures; grasp difficult concepts through a visual analogy; and develop many other important skills.



- Schematic *Chapter Summaries* help you organize what you have learned into a hierarchy, from general principles (top) to applications (bottom). Side-by-side pictorial, graphical, textual, and mathematical representations are used to help you translate between these key representations.
- Each part of the book ends with a **KNOWLEDGE STRUCTURE** designed to help you see the forest rather than just the trees.

Now that you know more about what is expected of you, what can you expect of me? That's a little trickier because the book is already written! Nonetheless, the book was prepared on the basis of what I think my students throughout the years have expected—and wanted—from their physics textbook. Further, I've listened to the extensive feedback I have received from thousands of students like you, and their instructors, who used the first three editions of this book.

You should know that these course materials—the text and the workbook—are based on extensive research about how students learn physics and the challenges they face. The effectiveness of many of the exercises has been demonstrated through extensive class testing. I've written the book in an informal style that I hope you will find appealing and that will encourage you to do the reading. And, finally, I have endeavored to make clear not only that physics, as a technical body of knowledge, is relevant to your profession but also that physics is an exciting adventure of the human mind.

I hope you'll enjoy the time we're going to spend together.

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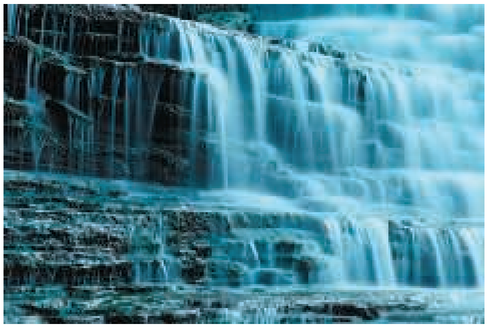
Part I Newton's Laws

Chapter 1 Concepts of Motion 2

Part II Conservation Laws

Part III Applications of Newtonian Mechanics



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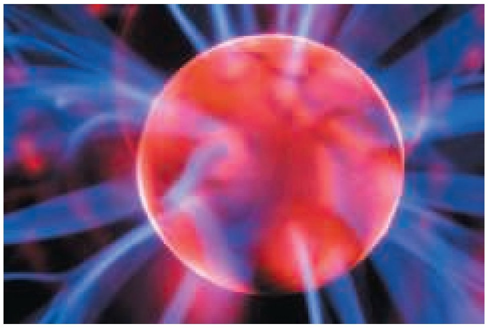

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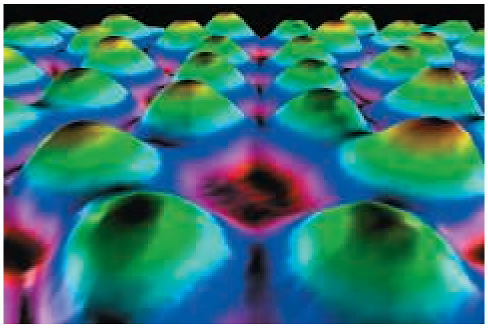


PART

I Newton's Laws

Motion can be slow and steady, or fast and sudden. This rocket, with its rapid acceleration, is responding to forces exerted on it by thrust, gravity, and the air.

OVERVIEW

Why Things Move

Each of the seven parts of this book opens with an overview to give you a look ahead, a glimpse at where your journey will take you in the next few chapters. It's easy to lose sight of the big picture while you're busy negotiating the terrain of each chapter. In Part I, the big picture, in a word, is *motion*.

There are two big questions we must tackle:

- **How do we describe motion?** It is easy to say that an object moves, but it's not obvious how we should measure or characterize the motion if we want to analyze it mathematically. The mathematical description of motion is called *kinematics,* and it is the subject matter of Chapters 1 through 4.
- **How do we explain motion?** Why do objects have the particular motion they do? Why, when you toss a ball upward, does it go up and then come back down rather than keep going up? Are there "laws of nature" that allow us to predict an object's motion? The explanation of motion in terms of its causes is called *dynamics,* and it is the topic of Chapters 5 through 8.

Two key ideas for answering these questions are *force* (the "cause") and *acceleration* (the "effect"). A variety of pictorial and graphical tools will be developed in Chapters 1 through 5 to help you develop an *intuition* for the connection between force and acceleration. You'll then put this knowledge to use in Chapters 5 through 8 as you analyze motion of increasing complexity.

Another important tool will be the use of *models.* Reality is extremely complicated. We would never be able to develop a science if we had to keep track of every little detail of every situation. A model is a simplified description of reality—much as a model airplane is a simplified version of a real airplane—used to reduce the complexity of a problem to the point where it can be analyzed and understood. We will introduce several important models of motion, paying close attention, especially in these earlier chapters, to where simplifying assumptions are being made, and why.

The "laws of motion" were discovered by Isaac Newton roughly 350 years ago, so the study of motion is hardly cutting-edge science. Nonetheless, it is still extremely important. Mechanics—the science of motion—is the basis for much of engineering and applied science, and many of the ideas introduced here will be needed later to understand things like the motion of waves and the motion of electrons through circuits. Newton's mechanics is the foundation of much of contemporary science, thus we will start at the beginning.

1 Concepts of Motion

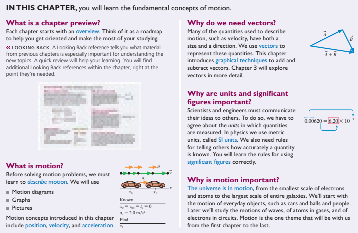
Motion takes many forms. The ski jumper seen here is an example of translational motion.

IN THIS CHAPTER, you will learn the fundamental concepts of motion.

What is a chapter preview?

Each chapter starts with an overview. Think of it as a roadmap to help you get oriented and make the most of your studying.

« LOOKING BACK A Looking Back reference tells you what material from previous chapters is especially important for understanding the new topics. A quick review will help your learning. You will find additional Looking Back references within the chapter, right at the point they're needed.

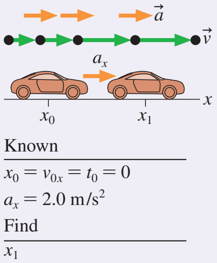


What is motion?

Before solving motion problems, we must learn to *describe* motion. We will use

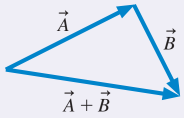
- Motion diagrams
- Graphs
- Pictures

Motion concepts introduced in this chapter include position, velocity, and acceleration.



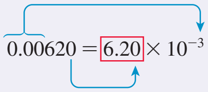
Why do we need vectors?

Many of the quantities used to describe motion, such as velocity, have both a size and a direction. We use vectors to represent these quantities. This chapter introduces graphical techniques to add and subtract vectors. Chapter 3 will explore vectors in more detail.



Why are units and significant figures important?

Scientists and engineers must communicate their ideas to others. To do so, we have to agree about the *units* in which quantities are measured. In physics we use metric units, called SI units. We also need rules for telling others how accurately a quantity is known. You will learn the rules for using significant figures correctly.



Why is motion important?

The universe is in motion, from the smallest scale of electrons and atoms to the largest scale of entire galaxies. We'll start with the motion of everyday objects, such as cars and balls and people. Later we'll study the motions of waves, of atoms in gases, and of electrons in circuits. Motion is the one theme that will be with us from the first chapter to the last.

1.1 Motion Diagrams

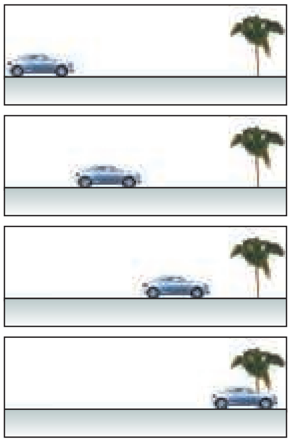
Motion is a theme that will appear in one form or another throughout this entire book. Although we all have intuition about motion, based on our experiences, some of the important aspects of motion turn out to be rather subtle. So rather than jumping immediately into a lot of mathematics and calculations, this first chapter focuses on *visualizing* motion and becoming familiar with the *concepts* needed to describe a moving object. Our goal is to lay the foundations for understanding motion.

FIGURE 1.1 Four basic types of motion.

Linear motion **Circular motion** **Projectile motion** **Rotational motion**

To begin, let's define **motion** as the change of an object's position with time. **FIGURE 1.1** shows four basic types of motion that we will study in this book. The first three—linear, circular, and projectile motion—in which the object moves through space are called **translational motion.** The path along which the object moves, whether straight or curved, is called the object's **trajectory.** Rotational motion is somewhat different because there's movement but the object as a whole doesn't change position. We'll defer rotational motion until later and, for now, focus on translational motion.

FIGURE 1.2 Four frames from a video.

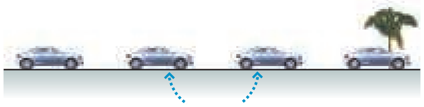


Making a Motion Diagram

An easy way to study motion is to make a video of a moving object. A video camera, as you probably know, takes images at a fixed rate, typically 30 every second. Each separate image is called a *frame*. As an example, **FIGURE 1.2** shows four frames from a video of a car going past. Not surprisingly, the car is in a somewhat different position in each frame.

Suppose we edit the video by layering the frames on top of each other, creating the composite image shown in **FIGURE 1.3**. This edited image, showing an object's position at several *equally spaced instants of time,* is called a **motion diagram.** As the examples below show, we can define concepts such as constant speed, speeding up, and slowing down in terms of how an object appears in a motion diagram.

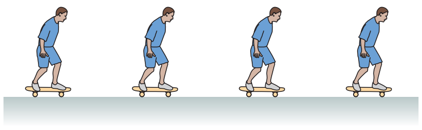
FIGURE 1.3 A motion diagram of the car shows all the frames simultaneously.



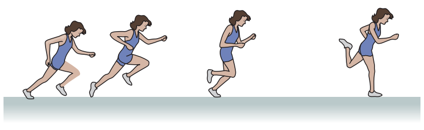
The same amount of time elapses between each image and the next.

NOTE It's important to keep the camera in a *fixed position* as the object moves by. Don't "pan" it to track the moving object.

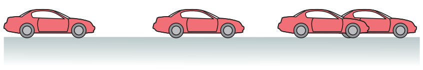
Examples of motion diagrams



Images that are *equally spaced* indicate an object moving with *constant speed.*

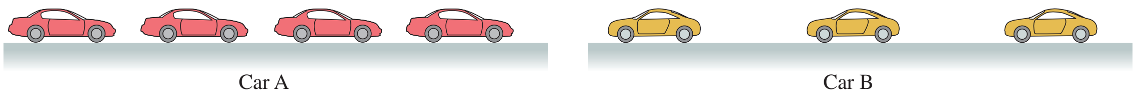


An *increasing distance* between the images shows that the object is *speeding up.*



A *decreasing distance* between the images shows that the object is *slowing down.*

STOP TO THINK 1.1 Which car is going faster, A or B? Assume there are equal intervals of time between the frames of both videos.



NOTE Each chapter will have several *Stop to Think* questions. These questions are designed to see if you've understood the basic ideas that have been presented. The answers are given at the end of the book, but you should make a serious effort to think about these questions before turning to the answers.

1.2 Models and Modeling

We can model an airplane's takeoff as a particle (a descriptive model) undergoing constant acceleration (a descriptive model) in response to constant forces (an explanatory model).

The real world is messy and complicated. Our goal in physics is to brush aside many of the real-world details in order to discern patterns that occur over and over. For example, a swinging pendulum, a vibrating guitar string, a sound wave, and jiggling atoms in a crystal are all very different—yet perhaps not so different. Each is an example of a system moving back and forth around an equilibrium position. If we focus on understanding a very simple oscillating system, such as a mass on a spring, we'll automatically understand quite a bit about the many real-world manifestations of oscillations.

Stripping away the details to focus on essential features is a process called *modeling.* A **model** is a highly simplified picture of reality, but one that still captures the essence of what we want to study. Thus "mass on a spring" is a simple but realistic model of almost all oscillating systems.

Models allow us to make sense of complex situations by providing a framework for thinking about them. One could go so far as to say that developing and testing models is at the heart of the scientific process. Albert Einstein once said, "Physics should be as simple as possible—but not simpler." We want to find the simplest model that allows us to understand the phenomenon we're studying, but we can't make the model so simple that key aspects of the phenomenon get lost.

We'll develop and use many models throughout this textbook; they'll be one of our most important thinking tools. These models will be of two types:

- *Descriptive models:* What are the essential characteristics and properties of a phenomenon? How do we describe it in the simplest possible terms? For example, the mass-on-a-spring model of an oscillating system is a descriptive model.
- *Explanatory models:* Why do things happen as they do? Explanatory models, based on the laws of physics, have predictive power, allowing us to test—against experimental data—whether a model provides an adequate explanation of our observations.

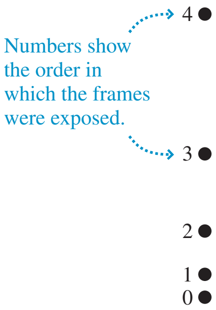
The Particle Model

For many types of motion, such as that of balls, cars, and rockets, the motion of the object *as a whole* is not influenced by the details of the object's size and shape. All we really need to keep track of is the motion of a single point on the object, so we can treat the object *as if* all its mass were concentrated into this single point. An object that can be represented as a mass at a single point in space is called a **particle.** A particle has no size, no shape, and no distinction between top and bottom or between front and back.

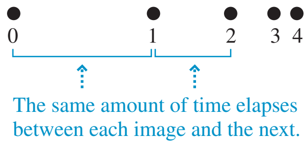
If we model an object as a particle, we can represent the object in each frame of a motion diagram as a simple dot rather than having to draw a full picture. **FIGURE 1.4** shows how much simpler motion diagrams appear when the object is represented as a particle. Note that the dots have been numbered 0, 1, 2, . . . to tell the sequence in which the frames were exposed.

FIGURE 1.4 Motion diagrams in which the object is modeled as a particle.

(a) Motion diagram of a rocket launch



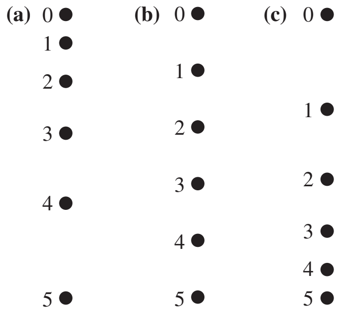
(b) Motion diagram of a car stopping



Treating an object as a particle is, of course, a simplification of reality—but that's what modeling is all about. The **particle model** of motion is a simplification in which we treat a moving object as if all of its mass were concentrated at a single point. The particle model is an excellent approximation of reality for the translational motion of cars, planes, rockets, and similar objects.

Of course, not everything can be modeled as a particle; models have their limits. Consider, for example, a rotating gear. The center doesn't move at all while each tooth is moving in a different direction. We'll need to develop new models when we get to new types of motion, but the particle model will serve us well throughout Part I of this book.

STOP TO THINK 1.2 Three motion diagrams are shown. Which is a dust particle settling to the floor at constant speed, which is a ball dropped from the roof of a building, and which is a descending rocket slowing to make a soft landing on Mars?



1.3 Position, Time, and Displacement

To use a motion diagram, you would like to know *where* the object is (i.e., its *position*) and *when* the object was at that position (i.e., the *time*). Position measurements can be made by laying a coordinate-system grid over a motion diagram. You can then measure the (x, y) coordinates of each point in the motion diagram. Of course, the world does not come with a coordinate system attached. A coordinate system is an artificial grid that *you* place over a problem in order to analyze the motion. You place the origin of your coordinate system wherever you wish, and different observers of a moving object might all choose to use different origins.

Time, in a sense, is also a coordinate system, although you may never have thought of time this way. You can pick an arbitrary point in the motion and label it "$t = 0$ seconds." This is simply the instant you decide to start your clock or stopwatch, so it is the origin of your time coordinate. Different observers might choose to start their clocks at different moments. A video frame labeled "$t = 4$ seconds" was taken 4 seconds after you started your clock.

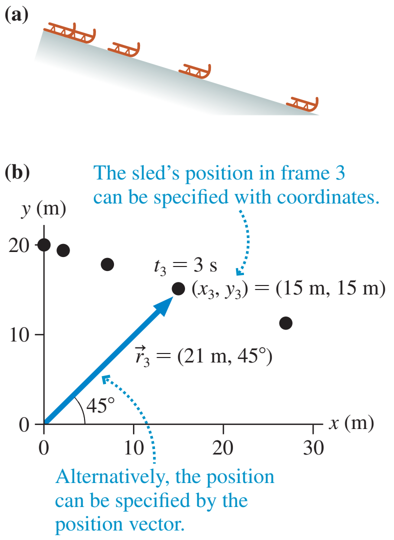
We typically choose $t = 0$ to represent the "beginning" of a problem, but the object may have been moving before then. Those earlier instants would be measured as negative times, just as objects on the x-axis to the left of the origin have negative values of position. Negative numbers are not to be avoided; they simply locate an event in space or time *relative to an origin*.

To illustrate, **FIGURE 1.5a** shows a sled sliding down a snow-covered hill. **FIGURE 1.5b** is a motion diagram for the sled, over which we've drawn an xy-coordinate system. You can see that the sled's position is $(x_3, y_3) = (15\text{ m}, 15\text{ m})$ at time $t_3 = 3$ s. Notice how we've used subscripts to indicate the time and the object's position in a specific frame of the motion diagram.

NOTE The frame at $t = 0$ is frame 0. That is why the fourth frame is labeled 3.

Another way to locate the sled is to draw its **position vector:** an arrow from the origin to the point representing the sled. The position vector is given the symbol $\vec{r}$. Figure 1.5b shows the position vector $\vec{r}_3 = (21\text{ m}, 45°)$. The position vector $\vec{r}$ does not tell us anything different than the coordinates (x, y). It simply provides the information in an alternative form.

FIGURE 1.5 Motion diagram of a sled with frames made every 1 s.



Scalars and Vectors

Some physical quantities, such as time, mass, and temperature, can be described completely by a single number with a unit. For example, the mass of an object is 6 kg and its temperature is 30°C. A single number (with a unit) that describes a physical quantity is called a **scalar.** A scalar can be positive, negative, or zero.

Many other quantities, however, have a directional aspect and cannot be described by a single number. To describe the motion of a car, for example, you must specify not only how fast it is moving, but also the *direction* in which it is moving. A quantity having both a *size* (the "How far?" or "How fast?") and a *direction* (the "Which way?") is called a **vector.** The size or length of a vector is called its *magnitude*. Vectors will be studied thoroughly in Chapter 3, so all we need for now is a little basic information.

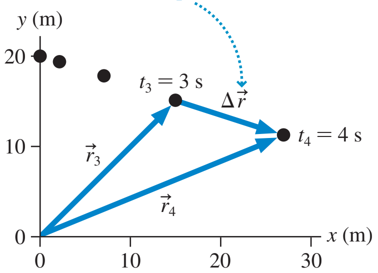
We indicate a vector by drawing an arrow over the letter that represents the quantity. Thus $\vec{r}$ and $\vec{A}$ are symbols for vectors, whereas r and A, without the arrows, are symbols for scalars. In handwritten work you must draw arrows over all symbols that represent vectors. This may seem strange until you get used to it, but it is very important because we will often use both r and $\vec{r}$, or both A and $\vec{A}$, in the same problem, and they mean different things! Note that the arrow over the symbol always points to the right, regardless of which direction the actual vector points. Thus we write $\vec{r}$ or $\vec{A}$, never $\overleftarrow{r}$ or $\overleftarrow{A}$.

Displacement

We said that motion is the change in an object's position with time, but how do we show a change of position? A motion diagram is the perfect tool. **FIGURE 1.6** is the motion diagram of a sled sliding down a snow-covered hill. To show how the sled's position changes between, say, $t_3 = 3$ s and $t_4 = 4$ s, we draw a vector arrow between the two dots of the motion diagram. This vector is the sled's **displacement,** which is given the symbol $\Delta\vec{r}$. The Greek letter delta (Δ) is used in math and science to indicate the *change* in a quantity. In this case, as we'll show, the displacement $\Delta\vec{r}$ is the change in an object's position.

FIGURE 1.6 The sled undergoes a displacement $\Delta\vec{r}$ from position $\vec{r}_3$ to position $\vec{r}_4$.

The sled's displacement between $t_3 = 3$ s and $t_4 = 4$ s is the vector drawn from one postion to the next.



NOTE $\Delta\vec{r}$ is a *single* symbol. You cannot cancel out or remove the Δ.

Notice how the sled's position vector $\vec{r}_4$ is a combination of its early position $\vec{r}_3$ with the displacement vector $\Delta\vec{r}$. In fact, $\vec{r}_4$ is the *vector sum* of the vectors $\vec{r}_3$ and $\Delta\vec{r}$. This is written

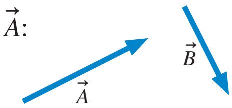
$$\vec{r}_4 = \vec{r}_3 + \Delta\vec{r} \tag{1.1}$$

Here we're adding vector quantities, not numbers, and vector addition differs from "regular" addition. We'll explore vector addition more thoroughly in Chapter 3, but for now you can add two vectors $\vec{A}$ and $\vec{B}$ with the three-step procedure shown in Tactics Box 1.1.

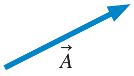
TACTICS BOX 1.1

Vector addition

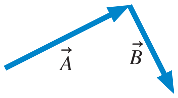
To add $\vec{B}$ to $\vec{A}$:



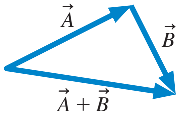
❶ Draw $\vec{A}$.



❷ Place the tail of $\vec{B}$ at the tip of $\vec{A}$.



❸ Draw an arrow from the tail of $\vec{A}$ to the tip of $\vec{B}$. This is vector $\vec{A} + \vec{B}$.



If you examine Figure 1.6, you'll see that the steps of Tactics Box 1.1 are exactly how $\vec{r}_3$ and $\Delta\vec{r}$ are added to give $\vec{r}_4$.

NOTE A vector is not tied to a particular location on the page. You can move a vector around as long as you don't change its length or the direction it points. Vector $\vec{B}$ is not changed by sliding it to where its tail is at the tip of $\vec{A}$.

Equation 1.1 told us that $\vec{r}_4 = \vec{r}_3 + \Delta\vec{r}$. This is easily rearranged to give a more precise definition of displacement: **The displacement $\Delta\vec{r}$ of an object as it moves from an initial position $\vec{r}_i$ to a final position $\vec{r}_f$ is**

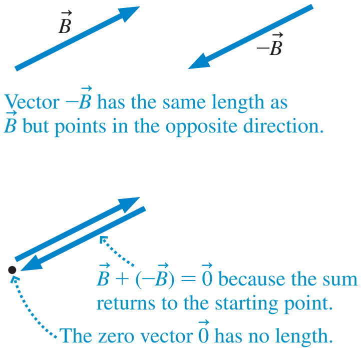
$$\Delta\vec{r} = \vec{r}_f - \vec{r}_i \tag{1.2}$$

Graphically, $\Delta\vec{r}$ is a vector arrow drawn from position $\vec{r}_i$ to position $\vec{r}_f$.

NOTE To be more general, we've written Equation 1.2 in terms of an *initial position* and a *final position,* indicated by subscripts i and f. We'll frequently use i and f when writing general equations, then use specific numbers or values, such as 3 and 4, when working a problem.

This definition of $\Delta\vec{r}$ involves *vector subtraction*. With numbers, subtraction is the same as the addition of a negative number. That is, $5 - 3$ is the same as $5 + (-3)$. Similarly, we can use the rules for vector addition to find $\vec{A} - \vec{B} = \vec{A} + (-\vec{B})$ if we first define what we mean by $-\vec{B}$. As **FIGURE 1.7** shows, the negative of vector $\vec{B}$ is a vector with the same length but pointing in the opposite direction. This makes sense because $\vec{B} - \vec{B} = \vec{B} + (-\vec{B}) = \vec{0}$, where $\vec{0}$, a vector with zero length, is called the **zero vector.**

FIGURE 1.7 The negative of a vector.



Vector $-\vec{B}$ has the same length as $\vec{B}$ but points in the opposite direction.

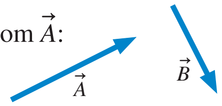
$\vec{B} + (-\vec{B}) = \vec{0}$ because the sum returns to the starting point.

The zero vector $\vec{0}$ has no length.

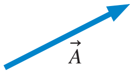
TACTICS BOX 1.2

Vector subtraction

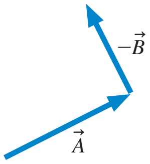
To subtract $\vec{B}$ from $\vec{A}$:



❶ Draw $\vec{A}$.



❷ Place the tail of $-\vec{B}$ at the tip of $\vec{A}$.



❸ Draw an arrow from the tail of $\vec{A}$ to the tip of $-\vec{B}$. This is vector $\vec{A} - \vec{B}$.

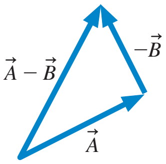
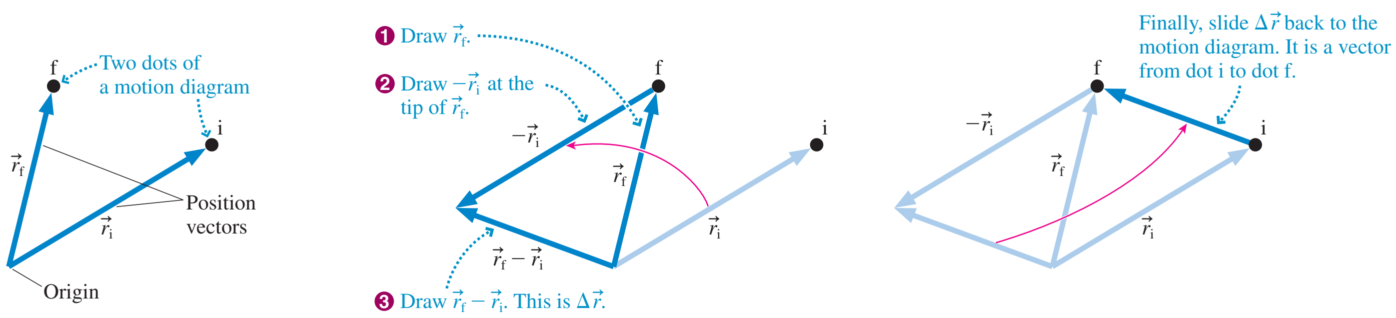


FIGURE 1.8 uses the vector subtraction rules of Tactics Box 1.2 to prove that the displacement $\Delta\vec{r}$ is simply the vector connecting the dots of a motion diagram.

▼ **FIGURE 1.8** Using vector subtraction to find $\Delta\vec{r} = \vec{r}_f - \vec{r}_i$.



(a) Initial and final position vectors

Two dots of a motion diagram

(b) Procedure for finding the particle's displacement vector $\Delta\vec{r}$

❶ Draw $\vec{r}_f$.

❷ Draw $-\vec{r}_i$ at the tip of $\vec{r}_f$.

❸ Draw $\vec{r}_f - \vec{r}_i$. This is $\Delta\vec{r}$.

Finally, slide $\Delta\vec{r}$ back to the motion diagram. It is a vector from dot i to dot f.