5th EDITION

PHYSICS

for SCIENTISTS and ENGINEERS

DOUGLAS

GIANCOLI

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Pearson

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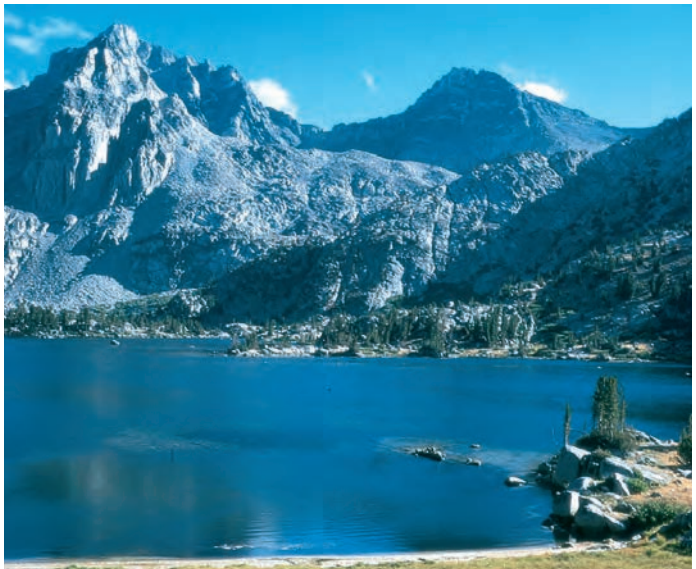

Estimate how much this lake weighs.

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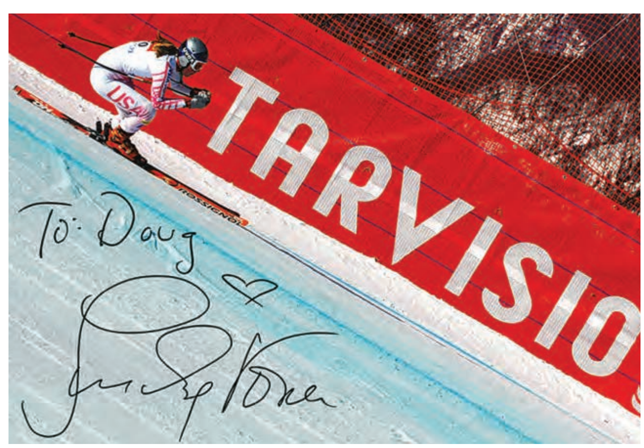

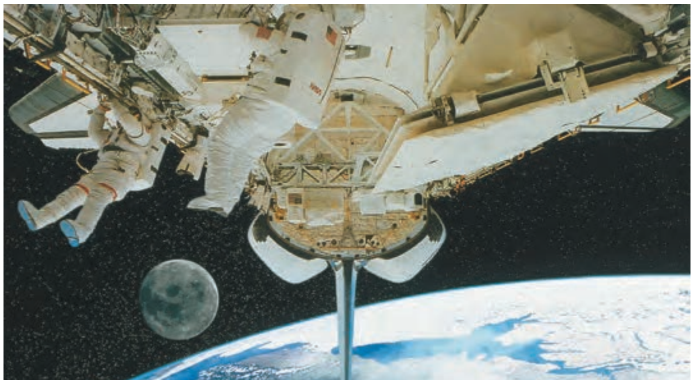

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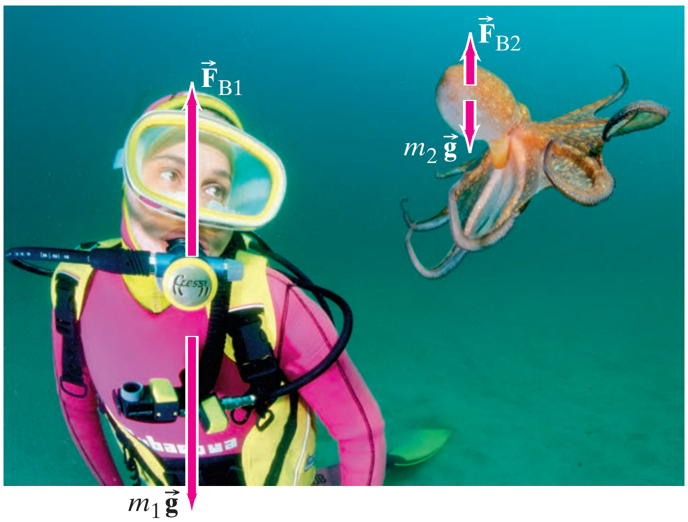

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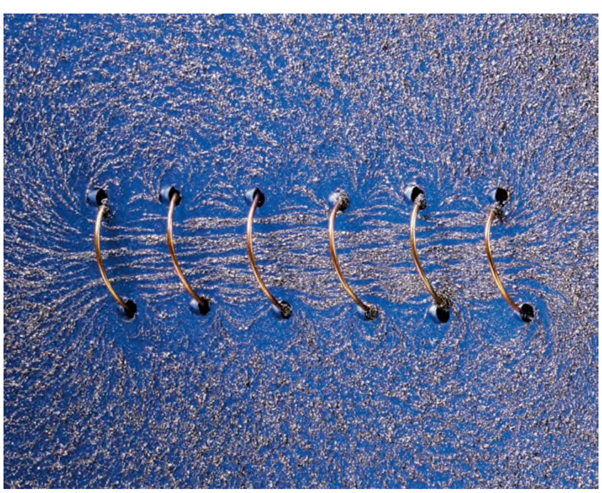

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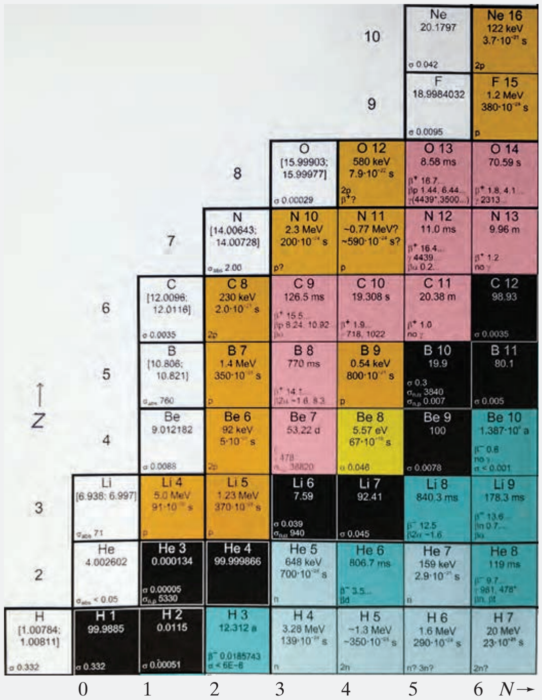

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Preface

New Stuff!

1. **MisConceptual Questions**, 10 or 15 at the end of each chapter. The multiple-choice answers include common misconceptions as well as correct responses. Pedagogically, asking students to think, to consider the options, is more effective than just telling them what is valid and what is wrong. (These are in addition to the one at the start of each chapter.
2. **Digital** is all around us. Yet that word is not always used carefully. In this new edition we have 20 new pages describing the basics from the ground up. **Binary** numbers, *bits* and *bytes*, are introduced in Chapter 23 along with analog-to-digital conversion (ADC), and vice versa, including *digital audio* and how video screens work. Also information **compression**, *sampling rate*, *bit depth*, *pixel addressing*, *digital transmission* and, in later chapters, information **storage** (RAM, DRAM, flash), *digital cameras* and their *sensors* (CCD, CMOS).
3. **Gravitational Assist** (Slingshot) to accelerate spacecraft (Chapter 8).
4. **Magnetic field** of a **single moving charge**, rarely treated (and if it is, maybe not well), and it shows the need for relativity theory.
5. Seeing **yourself** in a **magnifying mirror** (concave), angular magnification and blurriness with a paradox. Also **convex** (rearview) **mirrors** (Chapter 32).
6. Pedagogical clarification on defining **potential energy**, and energy itself (Chapter 8), and on hundreds of other topics.
7. The **Moon** rises an hour later each day (Chapter 6), its *phases*, *periods*, and diagram.
8. Efficiency of **lightbulbs** (Chapter 34).
9. **Idealization** vs. reality emphasized—such as PV diagrams (Chapter 19) as an idealized approximation.
10. Many new Problems (~ 500) plus new Questions as well as the 500 or so MisConceptual Questions (point 1 above).
11. Many new worked-out Examples.
12. More **math** steps included in derivations and Examples.
13. **State** of a system and *state variables* clarified (Chapter 17).
14. Contemporary physics: Gravitational waves, LIGO and Virgo, Higgs, WIMPS, OLEDS and other semiconductor physics, nuclear fusion updates, neutrino-less double beta decay.
15. New SI units (Chapter 1, Chapter 21, Tables).
16. *Boiling* temperature of water vs. *elevation* (Chapter 18).
17. Modern physics in earlier classical Chapters (sometimes in Problems): Light-years, observable universe (Chapter 1); optical tweezers (Chapter 4); uranium enrichment (Chapter 5); black holes and curved space, white dwarfs (Chapter 6); crystal structure (Chapter 7); Yukawa potential, Lennard-Jones potential (Chapter 8); neutrons, nuclear reactors, moderator, nuclear collisions, radioactive decay, neutron star collapse (Chapter 9); galaxy redshift (Chapter 16); gas diffusion of uranium (Chapter 18); quarks (Chapter 21); liquid-drop model of nucleus, Geiger counter, Van de Graaff (Chapter 23); transistors (Chapters 23, 29); isotopes, cyclotron (Chapter 27); MOSFET (Chapter 29); semiconductor (camera sensor), photon (Chapter 33); line spectra, X-ray crystallography (Chapter 35).
18. Second law of thermodynamics and heat energy reorganized (Chapter 20).
19. **Symmetry** emphasized throughout.
20. *Uranium enrichment*, % needed in reactors, bombs (Chapters 5, 42).
21. Mass excess, mass defect (Chapter 41).
22. The *mole*, more careful definition (Chapter 17).
23. Liquid-gas ambiguity above critical temperature (Chapter 18).
24. Measurement affects quantity measured, new emphasis.

25. New **Applications**:
- Ocean Tides (Chapter 6)
- Anticyclonic weather (Chapter 11)
- Jump starting a car safely (Chapter 26)
- Light bulb efficiency (Chapter 34)
- Specialty microscopes and contrast (Chapter 35)
- Forces on Muscles and Joints (Chapter 12)
- Doppler ultrasound imaging (Chapter 16)
- Lake level change when rock thrown from boat (Chapter 13)
- Skier speed on snow vs. flying through the air (Chapter 5)
- Inductive charging (Chapter 29)
- Human body internal heat transfer is convection (blood) (Chapter 19)
- Blood pressure measurement (Chapter 13)
- Sports (lots)
- Voltage divider (Chapter 26, Problems)
- Flat screen TV (Chapters 23, 34, 40)
- Carbon footprint and climate (Chapter 20)
- Electrocardiogram (Chapter 23)
- Wireless from the Moon unimaginable (Chapter 31)
- Why snorkels are short (Chapter 17 Problem)
- Electric cars (Chapter 25)
- Digital (Chapters 23, 29, 33, 40) includes (in addition to details in point 2 above) quantization error, digital error correction, noise, bit error rate, digital TV data stream, refresh rate, active matrix, thin film transistors, digital memory, bit-line, reading and writing of memory cells (MOSFET), floating gate, volatile and nonvolatile memory, Bayer, JPEG, ASCII code, and more.

Seeing the World through Eyes that Know Physics

I was motivated to write a textbook different from others which typically present physics as a sequence of facts, like a catalog. Instead of beginning formally and dogmatically, I aim to begin each topic with everyday observations and experiences the students can relate to: start with specifics, the real world, and then go to the great generalizations and the more formal aspects of the physics, showing why we believe what we believe. This approach reflects how science is actually practiced.

The aim is to give students a thorough understanding of the basic concepts of physics in all its aspects, from mechanics to modern physics. Also important is to show students how useful physics is in their own everyday lives and in their future professions by means of interesting applications to biology, medicine, engineering, architecture, and more.

Much effort has gone into approaches for the practical techniques of solving problems: worked-out Examples, Problem Solving sections, and Problem Solving Strategies.

Chapter 1 is *not* a throwaway. It is fundamental to physics to realize that every measurement has an *uncertainty*, and how significant figures are used. Being able to make rapid *estimates* is a powerful tool useful for every student, and used throughout the book starting in Chapter 1 (you can estimate the Earth's radius!).

Mathematics can be an obstacle to students. I have aimed at including all steps in a derivation. Important mathematical tools, such as addition of vectors and vector product, are incorporated in the text where first needed, so they come with a context rather than in a forbidding introductory Chapter. Appendices contain a basic math review, derivatives and integrals, plus some more advanced topics including numerical integration, gravitational field of spherical mass distribution, Maxwell's equations in differential form, and a Table of selected nuclear isotopes (carefully updated, as are the Periodic Table and the Fundamental Constants found inside the back and front covers).

Some instructors may find this book contains more material than can be covered in their courses. The text offers great flexibility. Sections marked with a star * may be considered optional. These contain slightly more advanced

Versions of this Book

Complete version: 44 Chapters including 9 Chapters of modern physics.

Classic version: 37 Chapters, 35 on classical physics, plus one each on relativity and quantum theory.

3 Volume version: Available separately or packaged together

Volume 1: Chapters 1–20 on mechanics, including fluids, oscillations, waves, plus heat and thermodynamics.

Volume 2: Chapters 21–35 on electricity and magnetism, plus light and optics.

Volume 3: Chapters 36–44 on modern physics: relativity, quantum theory, atomic physics, condensed matter, nuclear physics, elementary particles, cosmology and astrophysics.

physics material, or material not usually covered in typical courses, or interesting applications; they contain no material needed in later Chapters (except perhaps in later optional Sections). For a brief course, all optional material could be dropped as well as significant parts of Chapters 13, 16, 26, 30, and 35, and selected parts of Chapters 9, 12, 19, 20, 33. Topics not covered in class can be a valuable resource for outside study by students. Indeed, this text can serve as a useful reference for years because of its wide range of coverage.

Thanks

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The final responsibility for all errors lies with me. I welcome comments, corrections, and suggestions as soon as possible to benefit students for the next reprint.

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Doug Giancoli obtained his BA in physics (summa cum laude) from UC Berkeley, his MS in physics at MIT, and his PhD in elementary particle physics back at UC Berkeley. He spent 2 years as a post-doctoral fellow at UC Berkeley's Virus Lab developing skills in molecular biology and biophysics.

His mentors include Nobel winners Emilio Segrè, Barry Barish, and Donald Glaser.

He has taught a wide range of undergraduate courses, traditional as well as innovative ones, and works to improve his textbooks meticulously, seeking ways to provide a better understanding of physics for students.

Doug loves the outdoors, especially climbing peaks. He says climbing peaks is like learning physics: it takes effort and the rewards are great.

Students Advice

HOW TO STUDY

1. Read the Chapter. Learn new vocabulary and notation. Respond to questions and exercises as they occur. Follow carefully the steps of worked-out Examples and derivations. Avoid time looking at a screen. Paper is better than pixels when it comes to learning and thinking.
2. Attend all class meetings. Listen. Take notes. Ask questions (everyone wants to, but maybe you will have the courage). You will get more out of class if you read the Chapter first.
3. Read the Chapter again, paying attention to details. Follow derivations and worked-out Examples. Absorb their logic. Answer Exercises and as many of the end-of-Chapter Questions as you can, and all MisConceptual Questions.
4. Solve at least 10 to 20 end-of-Chapter Problems, especially those assigned. In doing Problems you may find out what you learned and what you didn't. Discuss them with other students. Problem solving is one of the great learning tools. Don' t just look for a formula—it might be the wrong one.

NOTES ON THE FORMAT AND PROBLEM SOLVING

1. Sections marked with a star (*) may be considered optional or advanced. They can be omitted without interrupting the main flow of topics. No later material depends on them except possibly later starred Sections. They may be fun to read, though.
2. The customary **conventions** are used: symbols for quantities (such as m for mass) are italicized, whereas units (such as m for meter) are not italicized. Symbols for vectors are shown in boldface with a small arrow above: $\vec{\mathbf{F}}$.
3. Few equations are valid in all situations. Where practical, the **range of validity** of important equations are stated in square brackets next to the equation. The equations that represent the great laws of physics are displayed with a tan background, as are a few other indispensable equations.
4. At the end of each Chapter is a set of **Questions** you should try to answer. Attempt all the multiple-choice **MisConceptual Questions**, which are intendend to get common misconceptions "out on the table" by including them as responses (temptations) along with correct answers. Most important are **Problems** which are ranked as Level I, II, or III, according to estimated difficulty. Level I Problems are easiest, Level II are standard Problems, and Level III are "challenge problems." These ranked Problems are arranged by Section, but Problems for a given Section may depend on earlier material too. There follows a group of **General Problems**, not arranged by Section or ranked. Problems that relate to optional Sections are starred (*). Answers to odd-numbered Problems are given at the end of the book.
5. Being able to solve **Problems** is a crucial part of learning physics, and provides a powerful means for understanding the concepts and principles. This book contains many aids to problem solving: (a) worked-out **Examples**, including an Approach and a Solution, which should be studied as an integral part of the text; (b) some of the worked-out Examples are **Estimation Examples**,which show how rough or approximate results can be obtained even if the given data are sparse (see Section 1-6); (c) **Problem Solving Strategies** placed throughout the text to suggest a step-by-step approach to problem solving for a particular topic—but the basics remain the same; most of these "Strategies" are followed by an Example that is solved by explicitly following the suggested steps; (d) special problem-solving Sections; (e) "Problem Solving" marginal notes which refer to hints within the text for solving Problems; (f) **Exercises** within the text that you should work out immediately, and then check your response against the answer given at the bottom of the last page of that Chapter; (g) the Problems themselves at the end of each Chapter.
6. **Conceptual Examples** pose a question which hopefully starts you to think about a response. Give yourself a little time to come up with your own response before reading the Response given.
7. Math review, plus additional topics, are found in **Appendices**. **Useful data**, **conversion factors**, and math **formulas** are found inside the front and back covers.

USE OF COLOR

Vectors

- A general vector
  - resultant vector (sum) is slightly thicker
  - components of any vector are dashed
- Displacement ($\vec{\mathbf{D}}, \vec{\mathbf{r}}$)
- Velocity ($\vec{\mathbf{v}}$)
- Acceleration ($\vec{\mathbf{a}}$)
- Force ($\vec{\mathbf{F}}$)
  - Force on second object
  - or third object in same figure
- Momentum ($\vec{\mathbf{p}}$ or $m\vec{\mathbf{v}}$)
- Angular momentum ($\vec{\mathbf{L}}$)
- Angular velocity ($\vec{\boldsymbol{\omega}}$)
- Torque ($\vec{\boldsymbol{\tau}}$)
- Electric field ($\vec{\mathbf{E}}$)
- Magnetic field ($\vec{\mathbf{B}}$)

Electricity and magnetism

- Electric field lines
- Equipotential lines
- Magnetic field lines
- Electric charge (+) — or +
- Electric charge (–) — or –

Electric circuit symbols

- Wire, with switch S
- Resistor
- Capacitor
- Inductor
- Battery
- Ground

Optics

- Light rays
- Object
- Real image (dashed)
- Virtual image (dashed and paler)

Other

- Energy level (atom, etc.)
- Measurement lines — 1.0 m
- Path of a moving object
- Direction of motion or current

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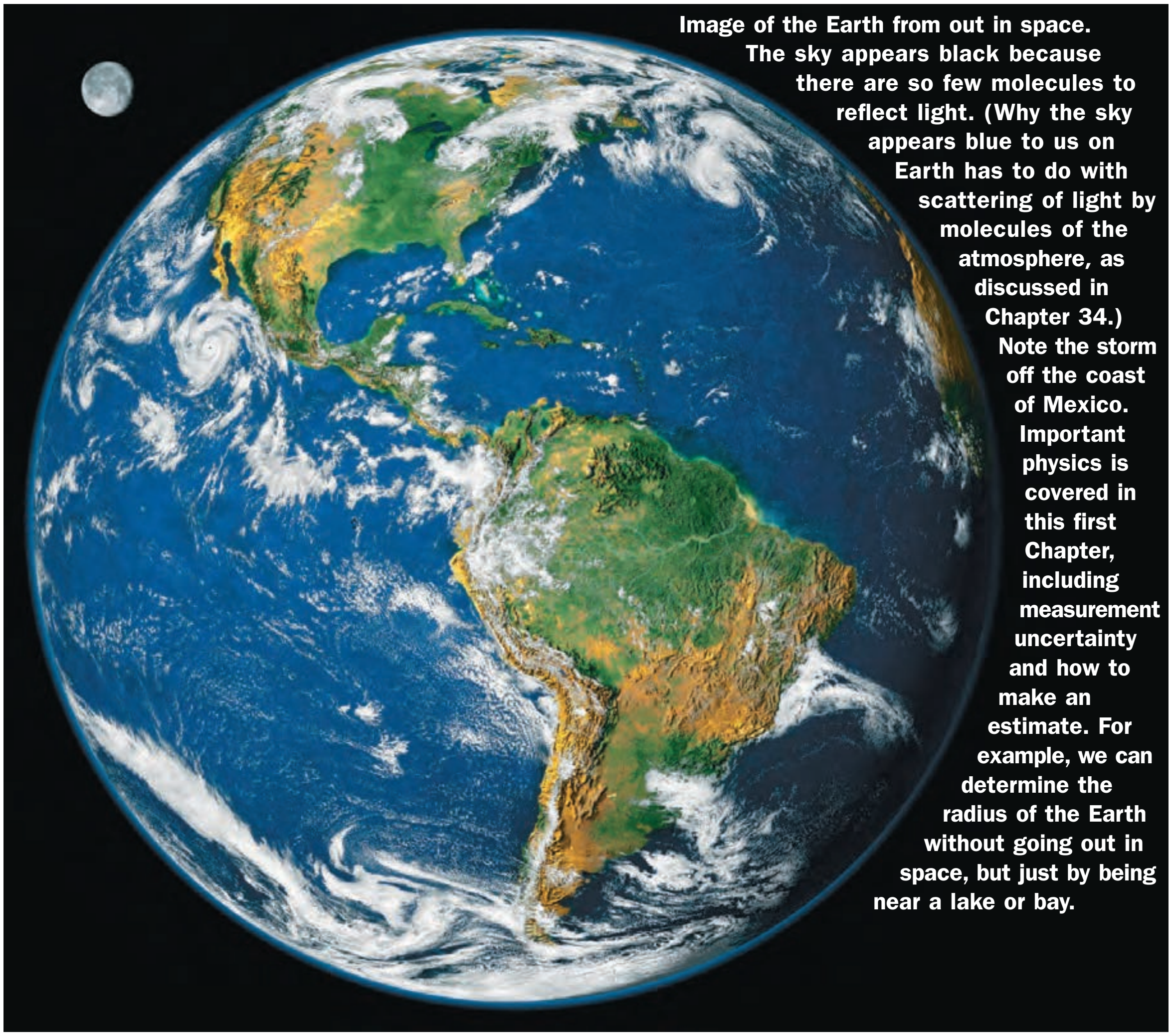


CHAPTER 1

Introduction, Measurement, Estimating

CHAPTER-OPENING QUESTIONS—Guess now!

1. How many cm^3 are in $1.0\,m^3$?

(a) 10. (b) 100. (c) 1000. (d) 10,000. (e) 100,000. (f) 1,000,000.

2. Suppose you wanted to actually measure the radius of the Earth, at least roughly, rather than taking other people's word for what it is. Which response below describes the best approach?

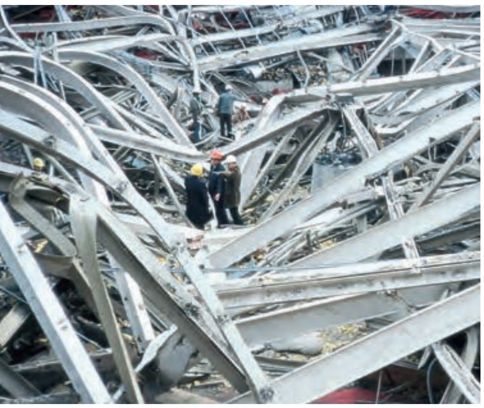
(a) Use an extremely long measuring tape.
(b) It is only possible by flying high enough to see the actual curvature of the Earth.
(c) Use a standard measuring tape, a stepladder, and a large smooth lake.
(d) Use a laser and a mirror on the Moon or on a satellite.
(e) Give up; it is impossible using ordinary means.

[*We start each Chapter with a Question—sometimes two. Try to answer right away. Don't worry about getting the right answer now—the idea is to get your preconceived notions out on the table. If they are misconceptions, we expect them to be cleared up as you read the Chapter. You will get another chance at the Question later in the Chapter when the appropriate material has been covered. These Chapter-Opening Questions will also help you see the power and usefulness of physics.*]

CONTENTS

1–1 How Science Works
1–2 Models, Theories, and Laws
1–3 Measurement and Uncertainty; Significant Figures
1–4 Units, Standards, and the SI System
1–5 Converting Units
1–6 Order of Magnitude: Rapid Estimating
*1–7 Dimensions and Dimensional Analysis

(a)



(b)

FIGURE 1–1 (a) This bridge over the River Tiber in Rome was built 2000 years ago and still stands. (b) The Hartford Civic Center collapsed in 1978, just two years after it was built.

CAUTION

Science is not static. It changes and develops

Physics is the most basic of the sciences. It deals with the behavior and structure of matter. The field of physics is usually divided into *classical physics* which includes motion, fluids, heat, sound, light, electricity and magnetism; and *modern physics* which includes the topics of relativity, atomic structure, condensed matter, nuclear physics, elementary particles, and cosmology and astrophysics. We will cover all these topics in this book, beginning with motion (or mechanics, as it is often called) and ending with the most recent results in our study of the cosmos.

An understanding of physics is wonderfully useful for anyone making a career in science or technology. Engineers, for example, must know how to calculate the forces within a structure to design it so that it remains standing (Fig. 1–1a). Indeed, in Chapter 12 we will see a worked-out Example of how a simple physics calculation—or even intuition based on understanding the physics of forces—would have saved hundreds of lives (Fig. 1–1b). We will see many examples in this book of how physics is useful in many fields, and in everyday life.

1–1 How Science Works

There is a real physical world out there. We could just walk through it, not thinking much about it. Or, we can instead examine it carefully. That is what scientists do. The aim of science is the search for order in our observations of the physical world so as to provide a deeper picture or description of this world around us. Sometimes we just want to understand how things work.

Some people seem to think that science is a mechanical process of collecting facts and devising theories. But it is not so simple. Science is a creative activity, and in many ways resembles other creative activities of the human mind.

One important aspect of science is **observation** of events (which great writers and artists also do), and includes the design and carrying out of experiments. But observation and experiment require imagination, because scientists can never include everything in a description of what they observe. In other words, scientists must make judgments about what is relevant in their observations and experiments.

Consider, for example, how two great minds, Aristotle (384–322 B.C.) and Galileo (1564–1642), interpreted motion along a horizontal surface. Aristotle noted that objects given an initial push along the ground (or on a level tabletop) always slow down and stop. Consequently, Aristotle argued, the natural state of an object is to be at rest. Galileo, in his reexamination of horizontal motion in the 1600s, had the idea that friction is a kind of force like a push or a pull; and he imagined that if friction could be eliminated, an object given an initial push along a horizontal surface would continue to move indefinitely without stopping. He concluded that for an object to be in motion was *just as natural* as for it to be at rest. By inventing a new approach, Galileo founded our modern view of motion (Chapters 2, 3, and 4), and he did so with a leap of the imagination. Galileo made this leap conceptually, without actually eliminating friction.

Observation, with careful experimentation and measurement, is one side of the scientific process. The other side is the invention or creation of **theories** to explain and order the observations. Theories are never derived directly from observations. Observations may help inspire a theory, and theories are accepted or rejected based on the results of observation and experiment.

Theories are inspirations that come from the minds of humans. For example, the idea that matter is made up of atoms (the atomic theory) was not arrived at by direct observation of atoms. Rather, the idea sprang from creative minds. The theory of relativity, the electromagnetic theory of light, and Newton's law of universal gravitation were likewise the result of human imagination.

The great theories of science may be compared, as creative achievements, with great works of art or literature. But how does science differ from these other creative activities? One important difference is that science requires **testing** of its ideas or theories to see if their predictions are borne out by experiment.

But theories are not "proved" by testing. First of all, no measuring instrument is perfect, so exact confirmation is not possible. Furthermore, it is not possible to test a theory in every single possible circumstance. Hence a theory cannot be absolutely verified.

Indeed, the history of science tells us that long-held theories can often be replaced by new ones.

1–2 Models, Theories, and Laws

When scientists are trying to understand a particular aspect of the physical world, they often make use of a **model**. A model, in the scientist's sense, is a kind of analogy or mental image of the phenomena in terms of something we are familiar with. One example is the wave model of light. We cannot see waves of light as we can water waves. But it is valuable to think of light as made up of waves because experiments indicate that light behaves in many respects as water waves do.

The purpose of a model is to give us an approximate mental or visual picture—something to hold on to—when we cannot see what actually is happening in the real world. Models often give us a deeper understanding: the analogy to a known system (for instance, water waves in the above example) can suggest new experiments to perform and can provide ideas about what other related phenomena might occur.

You may wonder what the difference is between a theory and a model. Usually a model is relatively simple and provides a structural similarity to the phenomena being studied. A **theory** is broader, more detailed, and can give quantitatively testable predictions, often with great precision.

It is important not to confuse a model or a theory with the real world and the phenomena themselves. Theories are descriptions of the physical world, and they are made up by us. Theories are *invented*—usually by very smart people.

CAUTION
Theories and laws are NOT discovered. They are invented

Scientists give the title **law** to certain concise but general statements about how nature behaves (that energy is conserved, for example). Sometimes the statement takes the form of a relationship or equation between quantities (such as Newton's second law, $F = ma$).

To be called a law, a statement must be found experimentally valid over a wide range of observed phenomena. For less general statements, the term **principle** is often used (such as Archimedes' principle). We use "theory" to describe a more general picture of a large group of phenomena.

Scientific laws are different from political laws, which are *prescriptive*: they tell us how we ought to behave. Scientific laws are *descriptive*: they do not say how nature *should* behave, but rather are meant to describe how nature *does* behave. As with theories, laws cannot be tested in the infinite variety of cases possible. So we cannot be sure that any law is absolutely true. We use the term "law" when its validity has been tested over a wide range of situations, and when any limitations and the range of validity are clearly understood.

Scientists normally do their research as if the accepted laws and theories were true. But they are obliged to keep an open mind in case new information should alter the validity of any given law or theory. In other words, laws of physics, or the "laws of nature", represent our descriptions of reality and are not inalterable facts that last forever. Laws are not lying there in nature, waiting to be discovered. We humans, the brightest humans, invent the laws using observations and intuition as a basis. And we hope our laws provide a good description of nature, and at a minimum give us a reliable approximation of how nature really behaves.

1–3 Measurement and Uncertainty; Significant Figures

In the quest to understand the world around us, scientists seek to find relationships among physical quantities that can be measured.

Uncertainty

Reliable measurements are an important part of physics. But no measurement is absolutely precise. There is an uncertainty associated with every measurement. Among the most important sources of uncertainty, other than blunders, are the limited accuracy of every measuring instrument and the inability to read

FIGURE 1–2 Measuring the width of a board with a centimeter ruler. The uncertainty is about ± 1 mm.

an instrument (such as a ruler) beyond some fraction of the smallest division shown. For example, if you were to use a centimeter ruler to measure the width of a board (Fig. 1–2), the result could be claimed to be precise to about 0.1 cm (1 mm), the smallest division on the ruler, although half of this value might be a valid claim as well. The reason is that it is difficult for the observer to estimate (or *interpolate*) between the smallest divisions. Furthermore, the ruler itself may not have been manufactured to an accuracy very much better than this.

When giving the result of a measurement, it is important to state the **estimated uncertainty** in the measurement. For example, the width of a board might be written as 8.8 ± 0.1 cm. The ± 0.1 cm ("plus or minus 0.1 cm") represents the estimated uncertainty in the measurement, so that the actual width most likely lies between 8.7 and 8.9 cm. The **percent uncertainty** is the ratio of the uncertainty to the measured value, multiplied by 100. For example, if the measurement is 8.8 and the uncertainty about 0.1 cm, the percent uncertainty is

$$\frac{0.1}{8.8} \times 100\% \approx 1\%,$$

where $\approx$ means "is approximately equal to."

Often the uncertainty in a measured value is not specified explicitly. In such cases, scientists follow a general rule that

> **uncertainty in a numerical value is assumed to be *one or a few units* in the last digit specified.**

For example, if a length is given as 5.6 cm, the uncertainty is assumed to be about 0.1 cm or 0.2 cm, or possibly 0.3 cm. It is important in this case that you do not write 5.60 cm, for this implies an uncertainty on the order of 0.01 or 0.02 cm; it assumes that the length is probably between about 5.58 cm and 5.62 cm, when actually you believe it is between about 5.4 and 5.8 cm.

Significant Figures

The number of reliably known digits in a number is called the number of **significant figures**. Thus there are four significant figures in the number 23.21 cm and two in the number 0.062 cm (the zeros in the latter are merely place holders that show where the decimal point goes). The number of significant figures may not always be clear. Take, for example, the number 80. Are there one or two significant figures? We need words here: If we say it is *roughly* 80 km between two cities, there is only one significant figure (the 8) since the zero is merely a place holder. If there is no suggestion that the 80 is a rough approximation, then we can often assume (as we will in this book) that it has two significant figures: so it is 80 km within an accuracy of about 1 or 2 km. If it is precisely 80 km, to within ± 0.1 or ± 0.2 km, then we need to write 80.0 km (three significant figures).

When specifying numerical results, you should avoid the temptation to keep more digits in the final answer than is justified: see boldface statement above. For example, to calculate the area of a rectangle 11.3 cm by 6.8 cm, the result of multiplication would be 76.84 cm^2. But this answer can not be accurate to the implied 0.01 cm^2 uncertainty. Why? Because (using the outer limits of the assumed uncertainty for each measurement) the result could be between $11.2\text{ cm} \times 6.7\text{ cm} = 75.04\text{ cm}^2$ and $11.4\text{ cm} \times 6.9\text{ cm} = 78.66\text{ cm}^2$. At best, we can quote the answer as 77 cm^2, which implies an uncertainty of about 1 or 2 cm^2. The other two digits (in the number 76.84 cm^2) must be dropped (rounded off) because they are not significant. As a rough general **significant figures rule**,

PROBLEM SOLVING

Significant figures rule: Number of significant figures in final result should be same as the least significant input value

> *the final result of a multiplication or division should have no more digits than the numerical value with the fewest significant figures.*

In our example, 6.8 cm has the least number of significant figures, namely two. Thus the result 76.84 cm^2 needs to be rounded off to 77 cm^2.

EXERCISE A The area of a rectangle 4.5 cm by 3.25 cm is correctly given by (*a*) 14.625 cm^2; (*b*) 14.63 cm^2; (*c*) 14.6 cm^2; (*d*) 15 cm^2.

When *adding* or *subtracting* numbers, the final result should contain no more decimal places than the number with the fewest decimal places. For example, the result of subtracting 0.57 from 3.6 is 3.0 (not 3.03). Similarly $36 + 8.2 = 44$, not 44.2.

Be careful not to confuse significant figures with the number of decimal places. Significant figures are related to the expected uncertainty in any measured quantity.

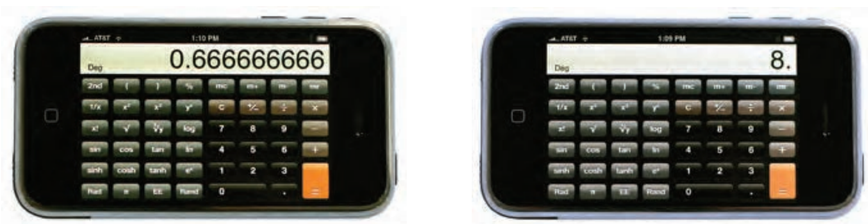
PROBLEM SOLVING
Significant figures when adding and subtracting

EXERCISE B For each of the following numbers, state the number of significant figures and the number of decimal places: (*a*) 1.23; (*b*) 0.123; (*c*) 0.0123.

Keep in mind when you use a calculator that all the digits it produces may not be significant. When you divide 2.0 by 3.0, the proper answer is 0.67, and not 0.666666666 as calculators give (Fig. 1–3a). Digits should not be quoted in a result unless they are truly significant figures. However, to obtain the most accurate result, you should normally *keep one or more extra significant figures throughout a calculation, and round off only in the final result*. (With a calculator, you can keep all its digits in intermediate results.) Calculators can also give too few significant figures. For example, when you multiply 2.5×3.2, a calculator may give the answer as simply 8. See Fig. 1–3b. But the answer is accurate to two significant figures, so the proper answer is 8.0.†

CAUTION
Calculators err with significant figures

PROBLEM SOLVING
Report only the proper number of significant figures in the final result. But keep extra digits during the calculation



(a) (b)

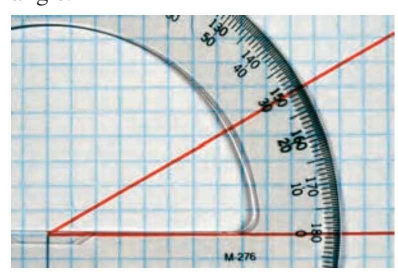
FIGURE 1–3 These two calculators show the wrong number of significant figures. In (a), 2.0 was divided by 3.0. The correct final result should be stated as 0.67. In (b), 2.5 was multiplied by 3.2. The correct result is 8.0.

CONCEPTUAL EXAMPLE 1–1 **Significant figures.** Using a protractor (Fig. 1–4), you measure an angle to be 30°. (*a*) How many significant figures should you quote in this measurement? (*b*) Use a calculator to find the cosine of the angle you measured.

RESPONSE (*a*) If you look at a protractor, you will see that the precision with which you can measure an angle is about one degree (certainly not 0.1°). So you can quote two significant figures, namely 30° (not 30.0°). (*b*) If you enter cos 30° in your calculator, you will get a number like 0.866025403. But the angle you entered is known only to two significant figures, so its cosine is correctly given by 0.87; you must round your answer to two significant figures.

NOTE Trigonometric functions, like cosine, are reviewed in Appendix A.

FIGURE 1–4 Example 1–1. A protractor used to measure an angle.



EXERCISE C Do 0.00324 and 0.00056 have the same number of significant figures?

Scientific Notation

We commonly write numbers in "powers of ten," or "scientific" notation—for instance 36,900 as 3.69×10^4, or 0.0021 as 2.1×10^{-3}. One advantage of scientific notation is that it allows the number of significant figures to be clearly expressed. For example, it is not clear whether 36,900 has three, four, or five significant figures. With powers of ten notation the ambiguity can be avoided: if the number is known to three significant figures, we write 3.69×10^4, but if it is known to four, we write 3.690×10^4.

†Be careful also about other digital read-outs. If a digital bathroom scale shows 85.6, do not assume the uncertainty is ± 0.1 or ± 0.2; the scale was likely manufactured with an accuracy of perhaps only 1% or so: that is, ± 1 or ± 2. For digital scientific instruments, also be careful: the instruction manual should state the accuracy.

EXERCISE D Write each of the following in scientific notation and state the number of significant figures for each: (*a*) 0.0258, (*b*) 42,300, (*c*) 344.50.

Percent Uncertainty versus Significant Figures

The significant figures rule is only approximate, and in some cases may underestimate the accuracy (or uncertainty) of the answer. Suppose for example we divide 97 by 92:

$$\frac{97}{92} = 1.05 \approx 1.1.$$

Both 97 and 92 have two significant figures, so the rule says to give the answer as 1.1. Yet the numbers 97 and 92 both imply an uncertainty of ± 1 if no other uncertainty is stated. Both 92 ± 1 and 97 ± 1 imply an uncertainty of about 1% $(1/92 \approx 0.01 = 1\%)$. But the final result to two significant figures is 1.1, with an implied uncertainty of ± 0.1, which is an uncertainty of $0.1/1.1 \approx 0.1 \approx 10\%$. In this case it is better to give the answer as 1.05 (which is three significant figures). Why? Because 1.05 implies an uncertainty of ± 0.01 which is $0.01/1.05 \approx 0.01 \approx 1\%$, just like the uncertainty in the original numbers 92 and 97.

SUGGESTION: Use the significant figures rule, but consider the % uncertainty too, and add an extra digit if it gives a more realistic estimate of uncertainty.

Approximations

Much of physics involves approximations, often because we do not have the means to solve a problem precisely. For example, we may choose to ignore air resistance or friction in doing a Problem even though they are present in the real world, and then our calculation is only an estimate or approximation. In doing Problems, we should be aware of what approximations we are making, and be aware that the precision of our answer may not be nearly as good as the number of significant figures given in the result.

Accuracy versus Precision

There is a technical difference between "precision" and "accuracy." **Precision** in a strict sense refers to the repeatability of the measurement using a given instrument. For example, if you measure the width of a board many times, getting results like 8.81 cm, 8.85 cm, 8.78 cm, 8.82 cm (interpolating between the 0.1 cm marks as best as possible each time), you could say the measurements give a *precision* a bit better than 0.1 cm. **Accuracy** refers to how close a measurement is to the true value. For example, if the ruler shown in Fig. 1–2 was manufactured with a 2% error, the accuracy of its measurement of the board's width (about 8.8 cm) would be about 2% of 8.8 cm or about ± 0.2 cm. Estimated uncertainty is meant to take both accuracy and precision into account.

1–4 Units, Standards, and the SI System

The measurement of any quantity is made relative to a particular standard or **unit**, and this unit must be specified along with the numerical value of the quantity. For example, we can measure length in British units such as inches, feet, or miles, or in the metric system in centimeters, meters, or kilometers. To specify that the length of a particular object is 18.6 is insufficient. The unit *must* be given, because 18.6 meters is very different from 18.6 inches or 18.6 millimeters.

For any unit we use, such as the meter for distance or the second for time, we need to define a **standard** which defines exactly how long one meter or one second is. It is important that standards be chosen that are readily reproducible so that anyone needing to make a very accurate measurement can refer to the standard in the laboratory and communicate results with other scientists.

Length

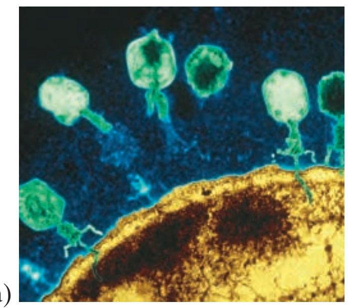
The first truly international standard was the **meter** (abbreviated m) established as the standard of **length** by the French Academy of Sciences in the 1790s. The standard meter was originally chosen to be one ten-millionth of the distance from the Earth's equator to either pole,† and a platinum rod to represent this length was made. (One meter is, very roughly, the distance from the tip of your nose to the tip of your finger, with arm and hand stretched out horizontally.) In 1889, the meter was defined more precisely as the distance between two finely engraved marks on a particular bar of platinum–iridium alloy. In 1960, to provide greater precision and reproducibility, the meter was redefined as 1,650,763.73 wavelengths of a particular orange light emitted by the gas krypton-86.

New definition of the meter

In 1983 the meter was again redefined, this time in terms of the speed of light (whose best measured value in terms of the older definition of the meter was 299,792,458 m/s, with an uncertainty of 1 m/s). The new definition reads: "The meter is the length of path traveled by light in vacuum during a time interval of 1/299,792,458 of a second." The new definition of the meter has the effect of giving the speed of light the exact value of 299,792,458 m/s. [The newer definitions provided greater precision than the 2 marks on the old platinum bar.]

British units of length (inch, foot, mile) are now defined in terms of the meter. The **inch** (in.) is defined as exactly 2.54 centimeters (cm; 1 cm = 0.01 m). One **foot** is exactly 12 in., and 1 **mile** is 5280 ft. Other conversion factors are given in the Table on the inside of the front cover of this book. Table 1–1 below presents some typical lengths, from very small to very large, rounded off to the nearest power of 10. (We call this rounded off value the **order of magnitude**.) See also Fig. 1–5. (Note that the abbreviation for inches (in.) is the only one with a period, to distinguish it from the word "in".) [The **nautical mile** = 6076 ft = 1852 km is used by ships on the open sea and was originally defined as 1/60 of a degree latitude on Earth's surface. A speed of 1 **knot** is 1 nautical mile per hour.]

FIGURE 1–5 Some lengths: (a) viruses (about 10^{-7} m long) attacking a cell; (b) Mt. Everest's height is on the order of 10^4 m (8850 m, to be precise).

(a)


(b)


Time

The standard unit of **time** is the **second** (s). For many years, the second was defined as 1/86,400 of a mean solar day (24 h/day × 60 min/h × 60 s/min = 86,400 s/day). The standard second can be defined more precisely in terms of the frequency of radiation emitted by cesium atoms when they pass between two particular states. [Specifically, one second is the time required for 9,192,631,770 periods of this radiation. This number was chosen to keep "one second" the same as in the old definition.] There are, by definition, 60 s in one minute (min) and 60 minutes in one hour (h). Table 1–2 presents a range of time intervals, rounded off to the nearest power of 10.

†Modern measurements of the Earth's circumference reveal that the intended length is off by about one-fiftieth of 1%. Not bad!

TABLE 1–1 Some Typical Lengths or Distances (order of magnitude)

Length (or Distance)	Meters (approximate)
Neutron or proton (diameter)	10^{-15} m
Atom (diameter)	10^{-10} m
Virus [see Fig. 1–5a]	10^{-7} m
Sheet of paper (thickness)	10^{-4} m
Finger width	10^{-2} m
Football field length	10^{2} m
Height of Mt. Everest [see Fig. 1–5b]	10^{4} m
Earth diameter	10^{7} m
Earth to Sun	10^{11} m
Earth to nearest star	10^{16} m
Earth to nearest galaxy	10^{22} m
Earth to farthest galaxy visible	10^{26} m

TABLE 1–2 Some Typical Time Intervals (order of magnitude)

Time Interval	Seconds (approximate)
Lifetime of very unstable subatomic particle	10^{-23} s
Lifetime of radioactive elements	10^{-22} s to 10^{28} s
Lifetime of muon	10^{-6} s
Time between human heartbeats	10^{0} s (= 1 s)
One day	10^{5} s
One year	3×10^{7} s
Human life span	2×10^{9} s
Length of recorded history	10^{11} s
Humans on Earth	10^{14} s
Life on Earth	10^{17} s
Age of Universe	4×10^{17} s

TABLE 1–3 Some Masses

Object	Kilograms (approximate)
Electron	10^{-30} kg
Proton, neutron	10^{-27} kg
DNA molecule	10^{-17} kg
Bacterium	10^{-15} kg
Mosquito	10^{-5} kg
Plum	10^{-1} kg
Human	10^{2} kg
Ship	10^{8} kg
Earth	6×10^{24} kg
Sun	2×10^{30} kg
Galaxy	10^{41} kg

Mass

The standard unit of **mass** is the **kilogram** (kg). The standard mass has been, since 1889, a particular platinum–iridium cylinder, kept at the International Bureau of Weights and Measures near Paris, France, whose mass is defined as exactly 1 kg. A range of masses is presented in Table 1–3. [For practical purposes, a 1 kg mass weighs about 2.2 pounds on Earth.]

1 metric **ton** is 1000 kg. In the British system of units, 1 ton is 2000 pounds.

When dealing with atoms and molecules, we usually use the **unified atomic mass unit** (u or amu). In terms of the kilogram,

$$1\ \text{u} = 1.6605 \times 10^{-27}\ \text{kg}.$$

(Precise values of this and other numbers are given inside the front cover.) The **density** of a uniform object is its mass divided by its volume, commonly expressed in kg/m^3.

Unit Prefixes

In the metric system, the larger and smaller units are defined in multiples of 10 from the standard unit, and this makes calculation particularly easy. Thus 1 kilometer (km) is 1000 m, 1 centimeter is $\frac{1}{100}$ m, 1 millimeter (mm) is $\frac{1}{1000}$ m or $\frac{1}{10}$ cm, and so on. The *prefixes* "centi-," "kilo-," and others are listed in Table 1–4 and can be applied not only to units of length but to units of volume, mass, or any other unit. For example, a centiliter (cL) is $\frac{1}{100}$ liter (L), and a kilogram (kg) is 1000 grams (g). An 8.2-megapixel camera has a detector with 8,200,000 pixels (individual "picture elements").

In common usage, $1\ \mu\text{m}\ (= 10^{-6}\ \text{m})$ is called 1 **micron**.

PROBLEM SOLVING
Always use a consistent set of units

Systems of Units

When dealing with the laws and equations of physics it is very important to use a consistent set of units. Several systems of units have been in use over the years. Today the most important is the **Système International** (French for International System), which is abbreviated SI. In SI units, the standard of length is the meter, the standard for time is the second, and the standard for mass is the kilogram. This system used to be called the MKS (meter-kilogram-second) system.

A second metric system is the **cgs system**, in which the centimeter, gram, and second are the standard units of length, mass, and time, as abbreviated in the title. The **British engineering system** (although more used in the U.S. than Britain) has as its standards the foot for length, the pound for force, and the second for time.

We use SI units almost exclusively in this book, although we often define the cgs and British units when a new quantity is introduced. In the SI, there have traditionally been seven *base* quantities, each defined in terms of a standard; seven is the smallest number of base quantities consistent with a full description of the physical world. See Table 1–5. All other quantities† can be defined in terms of seven base quantities; see the Table inside the front cover which lists many quantities and their units in terms of base units.

TABLE 1–4 Metric (SI) Prefixes

Prefix	Abbreviation	Value
yotta	Y	10^{24}
zetta	Z	10^{21}
exa	E	10^{18}
peta	P	10^{15}
tera	T	10^{12}
giga	G	10^{9}
mega	M	10^{6}
kilo	k	10^{3}
hecto	h	10^{2}
deka	da	10^{1}
deci	d	10^{-1}
centi	c	10^{-2}
milli	m	10^{-3}
micro†	μ	10^{-6}
nano	n	10^{-9}
pico	p	10^{-12}
femto	f	10^{-15}
atto	a	10^{-18}
zepto	z	10^{-21}
yocto	y	10^{-24}

†μ is the Greek letter "mu."

*A New SI

As always in science, new ideas and approaches can produce better precision and closer correspondence with the real world. Even for units and standards.

International organizations on units have proposed further changes that should make standards more readily available and reproducible. To cite one example, the standard kilogram (see above) has been found to have changed slightly in mass (contamination is one cause).

The new redefinition of SI standards follows the method already used for the meter as being related to the defined value of the speed of light, as we mentioned on page 7 under "Length." For example, the charge on the electron, e, instead of being a measured value, becomes *defined* as a certain value (its current value), and the unit of electric charge (the coulomb) follows from that. All units then become based on

†Some exceptions are for angle (radians—see Chapter 10), solid angle (steradian), and sound level (bel or decibel, Chapter 16).

*Some Sections of this book, such as this subsection, may be considered *optional* at the discretion of the instructor and they are marked with an asterisk (*). See the Preface for more details.

defined fundamental constants like e and the speed of light. Seven is still the number of basic standards. The new definitions maintain the values of the traditional definitions: the "new" meter is the same length as the "old" meter. The new definitions do not change our understanding of what length, time, or mass means.

For us, using this book, the difference between the new SI and the traditional SI is highly technical and does not affect the physics we study. We include the traditional SI because there is some good physics in explaining it. [The Table of Fundamental Constants inside the front cover would look slightly different using the new SI. The value of the charge e on the electron, for example, is *defined*, and so would have no uncertainty attached to it; instead, our Table inside the front cover includes the traditional SI measured uncertainty (updated) of $\pm 98 \times 10^{-29}$ C.]

TABLE 1–5 Traditional SI Base Quantities

Quantity	Unit	Unit Abbreviation
Length	meter	m
Time	second	s
Mass	kilogram	kg
Electric current	ampere	A
Temperature	kelvin	K
Amount of substance	mole	mol
Luminous intensity	candela	cd

1–5 Converting Units

Any quantity we measure, such as a length, a speed, or an electric current, consists of a number *and* a unit. Often we are given a quantity in one set of units, but we want it expressed in another set of units. For example, suppose we measure that a shelf is 21.5 inches wide, and we want to express this in centimeters. We must use a **conversion factor**, which in this case is, *by definition*, exactly

$$1\text{ in.} = 2.54\text{ cm}$$

or, written another way,

$$1 = 2.54\text{ cm/in.}$$

Since multiplying by the number one does not change anything, the width of our shelf, in cm, is

$$21.5\text{ inches} = (21.5\ \cancel{\text{in.}}) \times \left(2.54\ \frac{\text{cm}}{\cancel{\text{in.}}}\right) = 54.6\text{ cm}.$$

Note how the units (inches in this case) cancelled out (thin red lines). A Table containing many unit conversions is found inside the front cover of this book. Let's consider some Examples.

FIGURE 1–6 The world's second highest peak, K2, whose summit is considered the most difficult of the "8000-ers." Example 1–2.

EXAMPLE 1–2 The 8000-m peaks. There are only 14 peaks whose summits are over 8000 m above sea level. They are the highest peaks in the world (Fig. 1–6 and Table 1–6) and are referred to as "eight-thousanders." What is the elevation, in feet, of an elevation of 8000 m?

PHYSICS APPLIED
The world's tallest peaks

APPROACH We need to convert meters to feet, and we can start with the conversion factor 1 in. = 2.54 cm, which is exact. That is, 1 in. = 2.5400 cm to any number of significant figures, because it is *defined* to be.

SOLUTION One foot is defined to be 12 in., so we can write

$$1\text{ ft} = (12\ \cancel{\text{in.}})\left(2.54\ \frac{\text{cm}}{\cancel{\text{in.}}}\right) = 30.48\text{ cm} = 0.3048\text{ m},$$

which is exact. Note how the units cancel (colored slashes). We can rewrite this equation to find the number of feet in 1 meter:

$$1\text{ m} = \frac{1\text{ ft}}{0.3048} = 3.28084\text{ ft}.$$

(We could carry the result to 6 significant figures because 0.3048 is exact, 0.304800 · · ·.) We multiply this equation by 8000.0 (to have five significant figures):

$$8000.0\text{ m} = (8000.0\ \cancel{\text{m}})\left(3.28084\ \frac{\text{ft}}{\cancel{\text{m}}}\right) = 26{,}247\text{ ft}.$$

An elevation of 8000 m is 26,247 ft above sea level.

NOTE We could have done the unit conversions all in one line:

$$8000.0\text{ m} = (8000.0\ \cancel{\text{m}})\left(\frac{100\ \cancel{\text{cm}}}{1\ \cancel{\text{m}}}\right)\left(\frac{1\ \cancel{\text{in.}}}{2.54\ \cancel{\text{cm}}}\right)\left(\frac{1\text{ ft}}{12\ \cancel{\text{in.}}}\right) = 26{,}247\text{ ft}.$$

The key is to multiply conversion factors, each equal to one $(= 1.0000)$, and to make sure which units cancel.

TABLE 1–6 The 8000-m Peaks

Peak	Height (m)
Mt. Everest	8850
K2	8611
Kangchenjunga	8586
Lhotse	8516
Makalu	8462
Cho Oyu	8201
Dhaulagiri	8167
Manaslu	8156
Nanga Parbat	8125
Annapurna	8091
Gasherbrum I	8068
Broad Peak	8047
Gasherbrum II	8035
Shisha Pangma	8013

The first two equations in Example 1–2 on the previous page show how to change from feet to meters, or meters to feet. For practical purposes

$$1\text{ m} = 3.28\text{ ft} \approx 3.3\text{ ft}$$

which means that we can change any distance or height in meters to feet by multiplying by 3 and adding 10% (0.1). For example, a 3000-m-high peak in feet is $9000\text{ ft} + 900\text{ ft} \approx 10{,}000\text{ ft}$.

TABLE 1–6 The 8000-m Peaks

Peak	Height (m)
Mt. Everest	8850
K2	8611
Kangchenjunga	8586
Lhotse	8516
Makalu	8462
Cho Oyu	8201
Dhaulagiri	8167
Manaslu	8156
Nanga Parbat	8125
Annapurna	8091
Gasherbrum I	8068
Broad Peak	8047
Gasherbrum II	8035
Shisha Pangma	8013

EXERCISE E The names and elevations of the 14 eight-thousand-meter peaks in the world (see Example 1–2) are given in Table 1–6, repeated here. They are all in the Himalaya mountain range in India, Pakistan, Tibet, and China. Determine the elevation of the world's three highest peaks in feet.

EXAMPLE 1–3 Apartment area. You have seen a nice apartment whose floor area is 880 square feet (ft^2). What is its area in square meters?

APPROACH We use the same conversion factor, $1\text{ in.} = 2.54\text{ cm}$, but this time we have to use it twice.

SOLUTION Because $1\text{ in.} = 2.54\text{ cm} = 0.0254\text{ m}$, then

$$1\text{ ft}^2 = (12\text{ in.})^2(0.0254\text{ m/in.})^2 = 0.0929\text{ m}^2.$$

So

$$880\text{ ft}^2 = \left(880\text{ ft}^2\right)\left(0.0929\text{ m}^2/\text{ft}^2\right) \approx 82\text{ m}^2.$$

NOTE As a rule of thumb, an area given in ft^2 is roughly 10 times the number of square meters (more precisely, about 10.8×).

Rule of thumb: Floor area in ft^2 is about 10× area in m^2: $100\text{ m}^2 \approx 1000\text{ ft}^2$

EXERCISE F One **hectare** is defined as $1.000 \times 10^4\text{ m}^2$. There are 640 **acres** in a square mile. Both units are used for land area. (*a*) How many acres are in one hectare? (*b*) What would be an easy everyday rule-of-thumb conversion factor?

EXAMPLE 1–4 Speeds. Where the posted speed limit is 55 miles per hour (mi/h or mph), what is this speed (*a*) in meters per second (m/s) and (*b*) in kilometers per hour (km/h)?

APPROACH We again use the conversion factor $1\text{ in.} = 2.54\text{ cm}$, and we recall that there are 5280 feet in a mile and 12 inches in a foot; also, one hour contains $(60\text{ min/h}) \times (60\text{ s/min}) = 3600\text{ s/h}$.

SOLUTION (*a*) We can write 1 mile as

$$1\text{ mi} = (5280\text{ ft})\left(12\frac{\text{in.}}{\text{ft}}\right)\left(2.54\frac{\text{cm}}{\text{in.}}\right)\left(\frac{1\text{ m}}{100\text{ cm}}\right)$$
$$= 1609\text{ m}.$$

We also know that 1 hour contains 3600 s, so

$$55\frac{\text{mi}}{\text{h}} = \left(55\frac{\text{mi}}{\text{h}}\right)\left(1609\frac{\text{m}}{\text{mi}}\right)\left(\frac{1\text{ h}}{3600\text{ s}}\right) = 25\frac{\text{m}}{\text{s}},$$

where we rounded off to two significant figures.

(*b*) Now we use $1\text{ mi} = 1609\text{ m} = 1.609\text{ km}$; then

$$55\frac{\text{mi}}{\text{h}} = \left(55\frac{\text{mi}}{\text{h}}\right)\left(1.609\frac{\text{km}}{\text{mi}}\right) = 88\frac{\text{km}}{\text{h}}.$$

PROBLEM SOLVING
Conversion factors = 1

NOTE Each conversion factor is equal to one. You can look up most conversion factors in the Table inside the front cover.

EXERCISE G Return to the first Chapter-Opening Question, page 1, and answer it again now. Try to explain why you may have answered differently the first time.

PROBLEM SOLVING
Unit conversion is wrong if units do not cancel

When changing units, you can avoid making an error in the use of conversion factors by checking that units cancel out properly. For example, in our conversion of 1 mi to 1609 m in Example 1–4(*a*), if we had incorrectly used the factor $\left(\frac{100\text{ cm}}{1\text{ m}}\right)$ instead of $\left(\frac{1\text{ m}}{100\text{ cm}}\right)$, the centimeter units would not have cancelled out; we would not have ended up with meters.

1–6 Order of Magnitude: Rapid Estimating

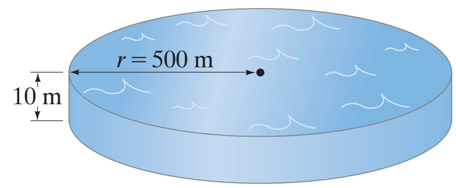
This is an exciting and powerful Section that will be useful throughout this book, and in real life. We will see how to make approximate calculations of quantities you may never have dreamed you could do.

Also, we are sometimes interested only in an approximate value for a quantity, maybe because an accurate calculation would take more time than it is worth or requires data that are not available. In other cases, we may want to make a rough estimate in order to check a calculation made on a calculator, to make sure that no blunders were made when the numbers were entered.

A rough estimate can be made by rounding off all numbers to one significant figure and its power of 10, and after the calculation is made, again keeping only one significant figure. Such an estimate is called an **order-of-magnitude estimate** and can be accurate within a factor of 10, and often better. In fact, the phrase "order of magnitude" is sometimes used to refer simply to the power of 10.

PROBLEM SOLVING
How to make a rough estimate

(a)



(b)

FIGURE 1–7 Example 1–5. (a) How much water is in this lake? (Photo is one of the Rae Lakes in the Sierra Nevada of California.) (b) Model of the lake as a cylinder. [We could go one step further and estimate the mass or weight of this lake. We will see later that water has a density of $1000\,\mathrm{kg/m^3}$, so this lake has a mass of about $(10^3\,\mathrm{kg/m^3})(10^7\,\mathrm{m^3}) \approx 10^{10}\,\mathrm{kg}$, which is about 10 billion kg or 10 million metric tons. (A metric ton is 1000 kg, about 2200 lb, slightly larger than a British ton, 2000 lb.)]

EXAMPLE 1–5 **ESTIMATE** **Volume of a lake.** Estimate how much water there is in a particular lake, Fig. 1–7a, which is roughly circular, about 1 km across, and you guess it has an average depth of about 10 m.

APPROACH No lake is a perfect circle, nor can lakes be expected to have a perfectly flat bottom. We are only estimating here. To estimate the volume, we can use a simple model of the lake as a cylinder: we multiply the average depth of the lake times its roughly circular surface area, as if the lake were a cylinder (Fig. 1–7b).

SOLUTION The volume V of a cylinder is the product of its height h times the area of its base: $V = h\pi r^2$, where r is the radius of the circular base.† The radius r is $\frac{1}{2}\,\mathrm{km} = 500\,\mathrm{m}$, so the volume is approximately

$$V = h\pi r^2 \approx (10\,\mathrm{m}) \times (3) \times (5 \times 10^2\,\mathrm{m})^2 \approx 8 \times 10^6\,\mathrm{m^3} \approx 10^7\,\mathrm{m^3},$$

where π was rounded off to 3. So the volume is on the order of $10^7\,\mathrm{m^3}$, ten million cubic meters. Because of all the estimates that went into this calculation, the order-of-magnitude estimate $(10^7\,\mathrm{m^3})$ is probably better to quote than the $8 \times 10^6\,\mathrm{m^3}$ figure.

NOTE To express our result in U.S. gallons, we see in the Table on the inside front cover that $1\ \text{liter} = 10^{-3}\,\mathrm{m^3} \approx \frac{1}{4}\,\text{gallon}$. Hence, the lake contains about $(8 \times 10^6\,\mathrm{m^3})(1\ \text{gallon}/4 \times 10^{-3}\,\mathrm{m^3}) \approx 2 \times 10^9$ gallons of water.

PHYSICS APPLIED
Estimating the volume (or mass) of a lake; see also Fig. 1–7

†Formulas like this for volume, area, etc., are found inside the back cover of this book.

FIGURE 1–8 Example 1–6. Micrometer used for measuring small thicknesses.

EXAMPLE 1–6 ESTIMATE **Thickness of a sheet of paper.** Estimate the thickness of a page of this book.

APPROACH At first you might think that a special measuring device, a micrometer (Fig. 1–8), is needed to measure the thickness of one page since an ordinary ruler can not be read so finely. But we can use a trick or, to put it in physics terms, make use of a *symmetry*: we can make the reasonable assumption that all the pages of this book are equal in thickness.

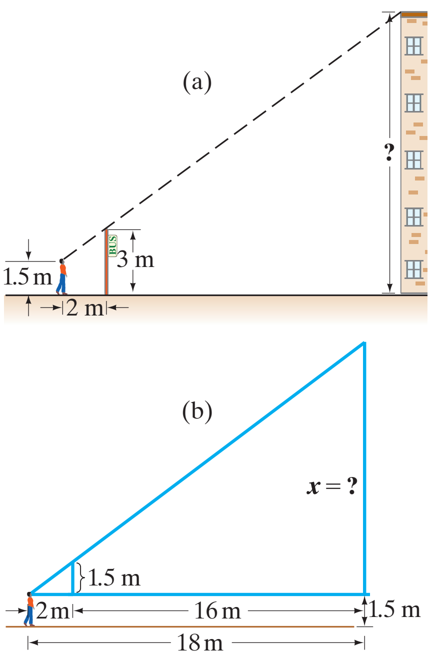
SOLUTION We can use a ruler to measure hundreds of pages at once. If you measure the thickness of the first 500 pages of this book (page 1 to page 500), you might get something like 1.5 cm. Note that 500 numbered pages, counted front and back, is 250 separate pieces of paper. So one sheet must have a thickness of about

$$\frac{1.5\text{ cm}}{250\text{ sheets}} \approx 6 \times 10^{-3}\text{ cm} = 6 \times 10^{-2}\text{ mm},$$

or less than a tenth of a millimeter (0.1 mm).

It cannot be emphasized enough how important it is to draw a diagram when solving a physics Problem, as the next Example shows.

FIGURE 1–9 Example 1–7. Diagrams are really useful!



EXAMPLE 1–7 ESTIMATE **Height by triangulation.** Estimate the height of the building shown in Fig. 1–9, by "triangulation," with the help of a bus-stop pole and a friend.

APPROACH By standing your friend next to the pole, you estimate the height of the pole to be 3 m. You next step away from the pole until the top of the pole is in line with the top of the building, Fig. 1–9a. You are 5 ft 6 in. tall, so your eyes are about 1.5 m above the ground. Your friend is taller, and when she stretches out her arms, one hand touches you and the other touches the pole, so you estimate that distance as 2 m (Fig. 1–9a). You then pace off the distance from the pole to the base of the building with big, 1-m-long steps, and you get a total of 16 steps or 16 m.

SOLUTION Now you draw, to scale, the diagram shown in Fig. 1–9b using these measurements. You can measure, right on the diagram, the last side of the triangle to be about $x \approx 13$ or 14 m. Alternatively, you can use similar triangles to obtain the height x:

$$\frac{1.5\text{ m}}{2\text{ m}} = \frac{x}{18\text{ m}},$$

so

$$x \approx 13\tfrac{1}{2}\text{ m}.$$

Finally you add in your eye height of 1.5 m above the ground to get your final result: the building is about 15 m tall.

EXAMPLE 1–8 ESTIMATE **Total number of heartbeats.** Estimate the total number of beats a typical human heart makes in a lifetime.

APPROACH A typical resting heart rate is 70 beats/min. But during exercise it can be a lot higher. A reasonable average might be 80 beats/min.

SOLUTION One year, in seconds, is $(24\text{ h/d})(3600\text{ s/h})(365\text{ d}) \approx 3 \times 10^7\text{ s}$. If an average person lives $70\text{ years} = (70\text{ yr})(3 \times 10^7\text{ s/yr}) \approx 2 \times 10^9\text{ s}$, then the total number of heartbeats would be about

$$\left(80\,\frac{\text{beats}}{\text{min}}\right)\left(\frac{1\text{ min}}{60\text{ s}}\right)(2 \times 10^9\text{ s}) \approx 3 \times 10^9,$$

or 3 billion.

EXAMPLE 1–9 ESTIMATE Estimating the radius of Earth. Believe it or not, you can estimate the radius of the Earth without having to go into space (see the photograph on page 1). If you have ever been on the shore of a large lake, you may have noticed that you cannot see the beaches, piers, or rocks at water level across the lake on the opposite shore. The lake seems to bulge out between you and the opposite shore—a good clue that the Earth is round. Suppose you climb a stepladder and discover that when your eyes are 10 ft (3.0 m) above the water, you can just see the rocks at water level on the opposite shore. From a map, you estimate the distance to the opposite shore as $d \approx 6.1$ km. Use Fig. 1–10 with $h = 3.0$ m to estimate the radius R of the Earth.

APPROACH We use simple geometry, including the theorem of Pythagoras, $c^2 = a^2 + b^2$, where c is the length of the hypotenuse of any right triangle, and a and b are the lengths of the other two sides.

SOLUTION For the right triangle of Fig. 1–10, the two sides are the radius of the Earth R and the distance $d = 6.1\text{ km} = 6100\text{ m}$. The hypotenuse is approximately the length $R + h$, where $h = 3.0$ m. By the Pythagorean theorem,

$$\begin{aligned} R^2 + d^2 &\approx (R + h)^2 \\ &\approx R^2 + 2hR + h^2. \end{aligned}$$

We solve algebraically for R, after cancelled R^2 on both sides:

$$\begin{aligned} R \approx \frac{d^2 - h^2}{2h} &= \frac{(6100\text{ m})^2 - (3.0\text{ m})^2}{6.0\text{ m}} \\ &= 6.2 \times 10^6\text{ m} \\ &= 6200\text{ km}. \end{aligned}$$

NOTE Precise measurements give 6380 km. But look at your achievement! With a few simple rough measurements and simple geometry, you made a good estimate of the Earth's radius. You did not need to go out in space, nor did you need a very long measuring tape.†

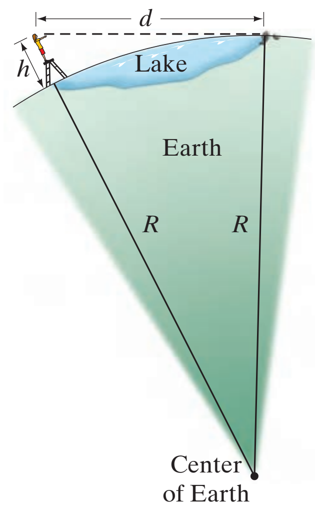
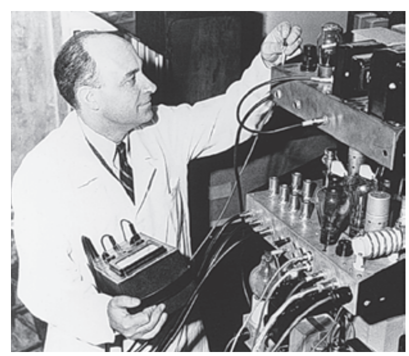


FIGURE 1–10 Example 1–9, but not to scale. You can just barely see rocks at water level on the opposite shore of a lake 6.1 km wide if you stand on a stepladder.

EXERCISE H Return to the second Chapter-Opening Question, page 1, and answer it again now. Try to explain why you may have answered differently the first time.

FIGURE 1–11 Enrico Fermi. Fermi contributed significantly to both theoretical and experimental physics, a feat almost unique in modern times.



Another type of estimate, this one made famous by Enrico Fermi (1901–1954, Fig. 1–11), was to show his students how to estimate the number of piano tuners in a city, such as Chicago or San Francisco. To get a rough order-of-magnitude estimate of the number of piano tuners today in San Francisco, a city of about 800,000 inhabitants, we can proceed by estimating the number of functioning pianos, how often each piano is tuned, and how many pianos each tuner can tune. To estimate the number of pianos in San Francisco, we note that certainly not everyone has a piano. A guess of 1 family in 3 having a piano would correspond to 1 piano per 12 persons, assuming an average family of 4 persons.

PROBLEM SOLVING *Estimating how many piano tuners there are in a city*

As an order of magnitude, let's say 1 piano per 10 people. This is certainly more reasonable than 1 per 100 people, or 1 per every person, so let's proceed with the estimate that 1 person in 10 has a piano, or about 80,000 pianos in San Francisco. Now a piano tuner needs an hour or two to tune a piano. So let's estimate that a tuner can tune 4 or 5 pianos a day. A piano ought to be tuned every 6 months or a year—let's say once each year. A piano tuner tuning 4 pianos a day, 5 days a week, 50 weeks a year can tune about 1000 pianos a year. So San Francisco, with its (very) roughly 80,000 pianos, needs about 80 piano tuners. This is, of course, only a rough estimate.‡ It tells us that there must be many more than 10 piano tuners, and surely not as many as 1000.

†As a teenager I had a summer job washing dishes at a camp located 350 m above famous Lake Tahoe in California. Starting the drive down to Lake Tahoe, the beaches across the lake were visible. But approaching the level of Lake Tahoe, the beaches across the lake were no longer visible! I realized that Lake Tahoe was bulging up in the middle, blocking the view. ("The Earth is round.")

‡A search on the internet (done after this calculation) reveals over 50 listings. Each of these listings may employ more than one tuner, but on the other hand, each may also do repairs as well as tuning. In any case, our estimate is reasonable.

*1–7 Dimensions and Dimensional Analysis

When we speak of the **dimensions** of a quantity, we are referring to the type of base units that make it up. The dimensions of area, for example, are always length squared, abbreviated $[L^2]$ using square brackets; the units can be square meters, square feet, cm^2, and so on. Velocity, on the other hand, can be measured in units of km/h, m/s, or mi/h, but the dimensions are always a length $[L]$ divided by a time $[T]$: that is, $[L/T]$.

The formula for a quantity may be different in different cases, but the dimensions remain the same. For example, the area of a triangle of base b and height h is $A = \frac{1}{2}bh$, whereas the area of a circle of radius r is $A = \pi r^2$. The formulas are different in the two cases, but the dimensions of area are always $[L^2]$.

Dimensions can be used as a help in working out relationships, a procedure referred to as **dimensional analysis**. One useful technique is the use of dimensions to check if a relationship is *incorrect*. Note that we add or subtract quantities only if they have the same dimensions (we don't add centimeters and hours); and the quantities on each side of an equals sign must have the same dimensions. (In numerical calculations, the units must also be the same on both sides of an equation.)

For example, suppose you derived the equation $v = v_0 + \frac{1}{2}at^2$, where v is the velocity of an object after a time t, v_0 is the object's initial velocity, and the object undergoes an acceleration a. Let's do a dimensional check to see if this equation could be correct or is surely incorrect. Note that numerical factors, like the $\frac{1}{2}$ here, do not affect dimensional checks. We write a dimensional equation as follows, remembering that the dimensions of velocity are $[L/T]$ and (as we shall see in Chapter 2) the dimensions of acceleration are $[L/T^2]$:

$$\left[\frac{L}{T}\right] \stackrel{?}{=} \left[\frac{L}{T}\right] + \left[\frac{L}{T^2}\right][T^2]$$
$$\stackrel{?}{=} \left[\frac{L}{T}\right] + [L].$$

The dimensions are incorrect: on the right side, we have the sum of quantities whose dimensions are not the same. Thus we conclude that an error was made in the derivation of the original equation.

A dimensional check can only tell you when a relationship is wrong. It can not tell you if it is completely right. For example, a dimensionless numerical factor (such as $\frac{1}{2}$ or 2π) could be missing.

Dimensional analysis can also be used as a quick check on an equation you are not sure about. For example, consider a simple pendulum of length ℓ. Suppose that you can't remember whether the equation for the period T (the time to make one back-and-forth swing) is $T = 2\pi\sqrt{\ell/g}$ or $T = 2\pi\sqrt{g/\ell}$, where g is the acceleration due to gravity and, like all accelerations, has dimensions $[L/T^2]$. (Do not worry about these formulas—the correct one will be derived in Chapter 11; what we are concerned about here is a person's recalling whether it contains ℓ/g or g/ℓ.) A dimensional check shows that the former (ℓ/g) is correct:

$$[T] = \sqrt{\frac{[L]}{[L/T^2]}} = \sqrt{[T^2]} = [T],$$

whereas the latter (g/ℓ) is not:

$$[T] \neq \sqrt{\frac{[L/T^2]}{[L]}} = \sqrt{\frac{1}{[T^2]}} = \frac{1}{[T]}.$$

The constant 2π has no dimensions and so can't be checked using dimensions.

Further uses of dimensional analysis are found in Appendix D.

*Some Sections of this book, such as this one, may be considered *optional* at the discretion of the instructor, and they are marked with an asterisk (*). See the Preface for more details.

EXAMPLE 1–10 **Planck length.** The smallest meaningful measure of length is called the "Planck length," and is defined in terms of three fundamental constants in nature: the speed of light $c = 3.00 \times 10^8$ m/s, the gravitational constant $G = 6.67 \times 10^{-11}\ \mathrm{m^3/kg \cdot s^2}$, and Planck's constant $h = 6.63 \times 10^{-34}\ \mathrm{kg \cdot m^2/s}$. The Planck length λ_P (λ is the Greek letter "lambda") is given by the following combination of these three constants:

$$\lambda_P = \sqrt{\frac{Gh}{c^3}}.$$

Show that the dimensions of λ_P are length $[L]$, and find the order of magnitude of λ_P.

APPROACH We rewrite the above equation in terms of dimensions. The dimensions of c are $[L/T]$, of G are $[L^3/MT^2]$, and of h are $[ML^2/T]$.

SOLUTION The dimensions of λ_P are

$$\sqrt{\frac{[L^3/MT^2][ML^2/T]}{[L^3/T^3]}} = \sqrt{[L^2]} = [L]$$

which is a length. Good. The value of the Planck length is

$$\lambda_P = \sqrt{\frac{Gh}{c^3}} = \sqrt{\frac{(6.67 \times 10^{-11}\ \mathrm{m^3/kg \cdot s^2})(6.63 \times 10^{-34}\ \mathrm{kg \cdot m^2/s})}{(3.00 \times 10^8\ \mathrm{m/s})^3}} \approx 4 \times 10^{-35}\ \mathrm{m},$$

which is on the order of 10^{-34} or 10^{-35} m.

NOTE Some recent theories (Chapters 43 and 44) suggest that the smallest particles (quarks, leptons) have sizes on the order of the Planck length, 10^{-35} m. These theories also suggest that the "Big Bang," with which the Universe is believed to have begun, started from an initial size on the order of the Planck length.

Summary

[*The Summary that appears at the end of each Chapter in this book gives a brief overview of the main ideas of the Chapter. The Summary* cannot *serve to give an understanding of the material, which can be accomplished only by a detailed reading of the Chapter.*]

Physics, like other sciences, is a creative endeavor. It is not simply a collection of facts. Important **theories** are created with the idea of explaining **observations**. To be accepted, theories are **tested** by comparing their predictions with the results of actual experiments. Note that, in general, a theory cannot be "proved" in an absolute sense.

Scientists often devise models of physical phenomena. A **model** is a kind of picture or analogy that helps to describe the phenomena in terms of something we already know about. A **theory**, often developed from a model, is usually deeper and more complex than a simple model.

A scientific **law** is a concise statement, often expressed in the form of an equation, which quantitatively describes a wide range of phenomena.

Measurements play a crucial role in physics, but can never be perfectly precise. It is important to specify the **uncertainty** of a measurement either by stating it directly using the ± notation, and/or by keeping only the correct number of **significant figures**.

Physical quantities are always specified relative to a particular standard or **unit**, and the unit used should always be stated. The commonly accepted set of units today is the **Système International** (SI), in which the standard units of length, mass, and time are the **meter**, **kilogram**, and **second**.

When converting units, check all **conversion factors** for correct cancellation of units.

Making rough, **order-of-magnitude estimates** is a very useful technique in science as well as in everyday life.

[*The **dimensions** of a quantity refer to the combination of base quantities that comprise it. Velocity, for example, has dimensions of [length/time] or $[L/T]$. Working with only the dimensions of the various quantities in a given relationship—this technique is called **dimensional analysis**—makes it possible to check a relationship for correct form.]

Questions

1. What are the merits and drawbacks of using a person's foot as a standard? Consider both (*a*) a particular person's foot, and (*b*) any person's foot. Keep in mind that it is advantageous that fundamental standards be accessible (easy to compare to), invariable (do not change), indestructible, and reproducible.
2. What is wrong with this road sign:

   Memphis 7 mi (11.263 km)?
3. Why is it incorrect to think that the more digits you include in your answer, the more accurate it is?
4. For an answer to be complete, units need to be specified. Why?
5. You measure the radius of a wheel to be 4.16 cm. If you multiply by 2 to get the diameter, should you write the result as 8 cm or as 8.32 cm? Justify your answer.
6. Express the sine of 30.0° with the correct number of significant figures.
7. List assumptions useful to estimate the number of car mechanics in (*a*) San Francisco, (*b*) your hometown, and then make the estimates.

MisConceptual Questions

[List all answers that are valid.]

1. The laws of physics
(*a*) are permanent and unalterable.
(*b*) are part of nature and are waiting to be discovered.
(*c*) can change, but only because of evidence that convinces the community of physicists.
(*d*) apply to physics but not necessarily to chemistry or other fields.
(*e*) were basically complete by 1900, and have undergone only minor revisions since.
(*f*) are accepted by all major world countries, and cannot be changed without international treaties.

2. How should we write the result of the following calculation, being careful about significant figures?

$$(3.84\text{ s})(37\text{ m/s}) + (5.3\text{ s})(14.1\text{ m/s}) =$$

(*a*) 200 m.
(*b*) 210 m.
(*c*) 216.81 m.
(*d*) 217 m.
(*e*) 220 m.

3. Four students use different instruments to measure the length of the same pen. Which measurement implies the greatest precision?
(*a*) 160.0 mm.
(*b*) 16.0 cm.
(*c*) 0.160 m.
(*d*) 0.00016 km.
(*e*) Need more information.

4. The number 0.0078 has how many significant figures?
(*a*) 1.
(*b*) 2.
(*c*) 3.
(*d*) 4.

5. How many significant figures does $1.362 + 25.2$ have?
(*a*) 2.
(*b*) 3.
(*c*) 4.
(*d*) 5.

6. Accuracy represents
(*a*) repeatability of a measurement, using a given instrument.
(*b*) how close a measurement is to the true value.
(*c*) an ideal number of measurements to make.
(*d*) how poorly an instrument is operating.

7. Precision represents
(*a*) repeatability of a measurement, using a given instrument.
(*b*) how close a measurement is to the true value.
(*c*) an ideal number of measurements to make.
(*d*) how poorly an instrument is operating.

8. To convert from ft^2 to yd^2, you should
(*a*) multiply by 3.
(*b*) multiply by 1/3.
(*c*) multiply by 9.
(*d*) multiply by 1/9.
(*e*) multiply by 6.
(*f*) multiply by 1/6.

9. Which is *not* true about an order-of-magnitude estimation?
(*a*) It gives you a rough idea of the answer.
(*b*) It can be done by keeping only one significant figure.
(*c*) It can be used to check if an exact calculation is reasonable.
(*d*) It may require making some reasonable assumptions in order to calculate the answer.
(*e*) It will always be accurate to at least two significant figures.

***10.** $[L^2]$ represents the dimensions for which of the following?
(*a*) cm^2.
(*b*) square feet.
(*c*) m^2.
(*d*) All of the above.

Problems

[*The Problems at the end of each Chapter are ranked* I, II, *or* III *according to estimated difficulty, with* (I) *Problems being easiest. Level* III *are meant as challenges for the best students. The Problems are arranged by Section, meaning that the reader should have read up to and including that Section, but not only that Section—Problems often depend on earlier material. Next is a set of "General Problems" not arranged by Section and not ranked.*]

1–3 Measurement, Uncertainty, Significant Figures

(Note: *In Problems, assume a number like* 6.4 *is accurate to* ± 0.1; *and* 950 *is accurate to* 2 *significant figures* (± 10) *unless* 950 *is said to be "precisely" or "very nearly"* 950, *in which case assume* 950 ± 1.)

1. (I) How many significant figures do each of the following numbers have: (*a*) 777, (*b*) 81.60, (*c*) 7.03, (*d*) 0.03, (*e*) 0.0086, (*f*) 6465, and (*g*) 8700?

2. (I) Write the following numbers in powers of 10 notation: (*a*) 5.859, (*b*) 21.8, (*c*) 0.0068, (*d*) 328.65, (*e*) 0.219, (*f*) 444.

3. (I) Write out the following numbers in full with the correct number of zeros: (*a*) 8.69×10^5, (*b*) 9.1×10^3, (*c*) 2.5×10^{-1}, (*d*) 4.76×10^2, and (*e*) 3.62×10^{-5}.

4. (II) What is the percent uncertainty in the measurement 3.25 ± 0.35 m?

5. (II) Time intervals measured with a physical stopwatch typically have an uncertainty of about 0.2 s, due to human reaction time at the start and stop moments. What is the percent uncertainty of a hand-timed measurement of (*a*) 4.5 s, (*b*) 45 s, (*c*) 4.5 min?

6. (II) Add $(9.2 \times 10^3\text{ s}) + (6.3 \times 10^4\text{ s}) + (0.008 \times 10^6\text{ s})$.

7. (II) Multiply 4.079×10^2 m by 0.057×10^{-1} m, taking into account significant figures.

8. (II) What, approximately, is the percent uncertainty for a measurement given as 1.27 m^2?

9. (II) For small angles θ, the numerical value of $\sin\theta$ is approximately the same as the numerical value of $\tan\theta$. Find the largest angle for which sine and tangent agree to within two significant figures.

10. (II) A report stated that "a survey of 215 students found that 37.2% had bought a sugar-rich soft drink the day before." (*a*) How many students bought a soft drink? (*b*) What is wrong with the original statement?

11. (II) A watch manufacturer claims that its watches gain or lose no more than 9 seconds in a year. How accurate are these watches, expressed as a percentage?

12. (III) What is the area, and its approximate uncertainty, of a circle of radius 5.1×10^4 cm?

13. (III) What, roughly, is the percent uncertainty in the volume of a spherical beach ball of radius $r = 0.64 \pm 0.04$ m?

1–4 and 1–5 Units, Standards, SI, Converting Units

14. (I) Write the following as full (decimal) numbers without prefixes on the units: (*a*) 286.6 mm, (*b*) 74 μV, (*c*) 430 mg, (*d*) 47.2 ps, (*e*) 22.5 nm, (*f*) 2.50 gigavolts.

15. (I) Express the following using the prefixes of Table 1–4: (*a*) 3×10^6 volts, (*b*) 2×10^{-6} meters, (*c*) 5×10^3 days, (*d*) 18×10^2 bucks, and (*e*) 9×10^{-7} seconds.

16. (I) Determine your own height in meters, and your mass in kg.

17. (II) To the correct number of significant figures, use the information inside the front cover of this book to determine the ratio of (*a*) the surface area of Earth compared to the surface area of the Moon, (*b*) the volume of Earth compared to the volume of the Moon.

18. (II) Would a driver traveling at 15 m/s in a 35 mi/h zone be exceeding the speed limit? Why or why not?

19. (II) The age of the universe is thought to be about 14 billion years. Assuming two significant figures, write this in powers of 10 in (*a*) years, (*b*) seconds.

20. (II) The Sun, on average, is 93 million miles from Earth. How many meters is this? Express (*a*) using powers of 10, and (*b*) using a metric prefix (km).

21. (II) Express the following sum with the correct number of significant figures: $1.90\,\text{m} + 142.5\,\text{cm} + 6.27 \times 10^5\,\mu\text{m}$.

22. (II) A typical atom has a diameter of about 1.0×10^{-10} m. (*a*) What is this in inches? (*b*) Approximately how many atoms are along a 1.0-cm line, assuming they just touch?

23. (II) Determine the conversion factor between (*a*) km/h and mi/h, (*b*) m/s and ft/s, and (*c*) km/h and m/s.

24. (II) What is the conversion factor between (*a*) ft^2 and yd^2, (*b*) m^2 and ft^2?

25. (II) A **light-year** is the distance light travels in one year $(\text{at speed} = 2.998 \times 10^8\,\text{m/s})$. (*a*) How many meters are there in 1.00 light-year? (*b*) An **astronomical unit** (AU) is the average distance from the Sun to Earth, 1.50×10^8 km. How many AU are there in 1.00 light-year?

26. (II) How much longer (percentage) is a one-mile race than a 1500-m race ("the metric mile")?

27. (II) How many wavelengths of orange krypton-86 light (Section 1–4) would fit into the thickness of one page of this book? See Example 1–6.

28. (II) Using the French Academy of Sciences' original definition of the meter, calculate Earth's circumference and radius in *those* meters. Give % error relative to today's accepted values (inside front cover).

29. (II) A passenger jet uses about 12 liters of fuel per km of flight. What is that value expressed as miles per gallon?

30. (II) American football uses a *field* that is 100.0 yd long, whereas a *soccer field* is 100.0 m long. Which field is longer, and by how much (give yards, meters, and percent)?

31. (II) (*a*) How many seconds are there in 1.00 year? (*b*) How many nanoseconds are there in 1.00 year? (*c*) How many years are there in 1.00 second?

32. (II) Use Table 1–3 to estimate the total number of protons or neutrons in (*a*) a bacterium, (*b*) a DNA molecule, (*c*) the human body, (*d*) our Galaxy.

33. (II) The diameter of the planet Mercury is 4879 km. (*a*) What is the surface area of Mercury? (*b*) How many times larger is the surface area of the Earth?

34. (III) A standard baseball has a circumference of approximately 23 cm. If a baseball had the same mass per unit volume (see Tables in Section 1–4) as a neutron or a proton, about what would its mass be?

1–6 Order-of-Magnitude Estimating

(Note: *Remember that for rough estimates, only round numbers are needed both as input to calculations and as final results.*)

35. (I) Estimate the order of magnitude (power of 10) of: (*a*) 3200, (*b*) 86.30×10^3, (*c*) 0.076, and (*d*) 15.0×10^8.

36. (II) Estimate how many books can be shelved in a college library with 6500 m^2 of floor space. Assume 8 shelves high, having books on both sides, with corridors 1.5 m wide. Assume books are about the size of this one, on average.

37. (II) Estimate how many hours it would take to run (at 10 km/h) across the U.S. from New York to California.

38. (II) Estimate the number of liters of water a human drinks in a lifetime.

39. (II) Estimate the number of *cells* in an adult human body, given that a typical cell has a diameter of about 10 μm, and the human body has a density of about 1000 kg/m^3.

40. (II) Estimate how long it would take one person to mow a football field using an ordinary home lawn mower (Fig. 1–12). (State your assumptions, such as the mower moves with a 1-km/h speed, and has a 0.5-m width.)

FIGURE 1–12
Problem 40.

41. (II) Estimate the number of gallons of gasoline consumed by the total of all automobile drivers in the U.S., per year.

42. (II) Estimate the number of dentists (*a*) in San Francisco and (*b*) in your town or city.

43. (II) Estimate how many kilograms of laundry soap are used in the U.S. in one year (and therefore pumped out of washing machines with the dirty water). Assume each load of laundry takes 0.1 kg of soap.

44. (II) How big is a *ton* (1000 kg)? That is, what is the volume of something that weighs a ton? To be specific, estimate the diameter of a 1-ton rock, but first make a wild guess: will it be 1 ft across, 3 ft, or the size of a car? [*Hint*: Rock has mass per volume about 3 times that of water, which is 1 kg per liter $(10^3\,\text{cm}^3)$ or 62 lb per cubic foot.]

45. (II) A hiking trail is 270 km long through varying terrain. A group of hikers cover the first 49 km in two and a half days. Estimate how much time they should allow for the rest of the trip.

46. (II) Estimate how many days it would take to walk around the circumference of the Earth, assuming 12 h walking per day at 4 km/h.

47. (II) Estimate the number of jelly beans in the jar of Fig. 1–13.

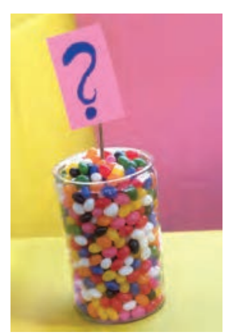


FIGURE 1–13
Problem 47. Estimate the number of jelly beans in the jar.

48. (II) Estimate the number of bus drivers (*a*) in Washington, D.C., and (*b*) in your town.

49. (III) You are in a hot air balloon, 300 m above the flat Texas plains. You look out toward the horizon. How far out can you see—that is, how far is your horizon? The Earth's radius is about 6400 km.

50. (III) I agree to hire you for 30 days. You can decide between two methods of payment: either (1) \$1000 a day, or (2) one penny on the first day, two pennies on the second day and continue to double your daily pay each day up through day 30. Use quick estimation to make your decision, and justify it.

51. (III) The rubber worn from tires mostly enters the atmosphere as *particulate pollution*. Estimate how much rubber (in kg) is put into the air in the United States every year. To get started, a good estimate for a tire tread's depth is 1 cm when new, and rubber has a mass of about 1200 kg per m^3 of volume.

52. (III) Many sailboats are docked at a marina 4.4 km away on the opposite side of a lake. You stare at one of the sailboats because, when you are lying flat at the water's edge, you can just see its deck but none of the side of the sailboat. You then go to that sailboat on the other side of the lake and measure that the deck is 1.5 m above the level of the water. Using Fig. 1–14, where $h = 1.5$ m, estimate the radius R of the Earth.

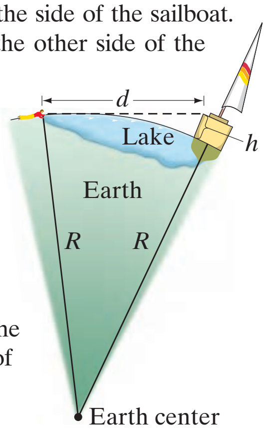


FIGURE 1–14 Problem 52. You see a sailboat across a lake (not to scale). R is the radius of the Earth. Because of the curvature of the Earth, the water "bulges out" between you and the boat.

53. (III) You are lying on a beach, your eyes 20 cm above the sand. Just as the Sun sets, fully disappearing over the horizon, you immediately jump up, your eyes now 150 cm above the sand, and you can again just see the top of the Sun. If you count the number of seconds $(= t)$ until the Sun fully disappears again, you can estimate the *Earth's radius*. But for this Problem, use the known radius of the Earth to calculate the time t.

*1–7 Dimensions

***54.** (I) What are the dimensions of density, which is mass per volume?

***55.** (II) The speed v of an object is given by the equation $v = At^3 - Bt$, where t refers to time. (*a*) What are the dimensions of A and B? (*b*) What are the SI units for the constants A and B?

***56.** (II) Three students derive the following equations in which x refers to distance traveled, v the speed, a the acceleration $(\mathrm{m/s^2})$, t the time, and the subscript zero $({}_0)$ means a quantity at time $t = 0$. Here are their equations: (*a*) $x = vt^2 + 2at$, (*b*) $x = v_0 t + \frac{1}{2}at^2$, and (*c*) $x = v_0 t + 2at^2$. Which of these could possibly be correct according to a dimensional check, and why?

***57.** (II) (*a*) Show that the following combination of the three fundamental constants of nature that we used in Example 1–10 (that is G, c, and h) forms a quantity with the dimensions of time:

$$t_P = \sqrt{\frac{Gh}{c^5}}.$$

This quantity, t_P, is called the **Planck time** and is thought to be the earliest time, after the creation of the Universe, at which the currently known laws of physics can be applied. (*b*) Estimate the order of magnitude of t_P using values given inside the front cover (or Example 1–10).

General Problems

58. **Global positioning satellites (GPS)** can be used to determine your position with great accuracy. If one of the satellites is 20,000 km from you, and you want to know your position to ± 2 m, what percent uncertainty in the distance is required? How many significant figures are needed in the distance?

59. One mole of atoms consists of 6.02×10^{23} individual atoms. If a mole of atoms were spread uniformly over the Earth's surface, how many atoms would there be per square meter?

60. **Computer chips** (Fig. 1–15) can be etched on circular silicon wafers of thickness 0.300 mm that are sliced from a solid cylindrical silicon crystal of length 25 cm. If each wafer can hold 750 chips, what is the maximum number of chips that can be produced from one entire cylinder?

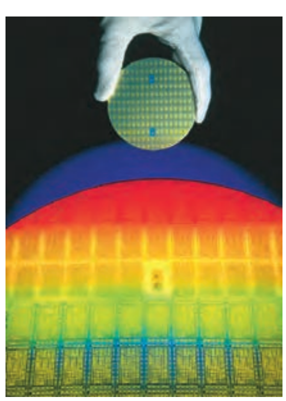


FIGURE 1–15 Problem 60. The wafer held by the hand is shown below, enlarged and illuminated by colored light. Visible are rows of integrated circuits (chips).

61. If you used only a keyboard to enter data, how many years would it take to fill up a *hard drive* in a computer that can store 1.0 terabytes $(1.0 \times 10^{12}$ bytes$)$ of data? Assume 40-hour work weeks, and that you can type 150 characters per minute, and that one byte is one keyboard character.

62. An average family of four uses roughly 1200 L (about 300 gallons) of water per day $(1\ \mathrm{L} = 1000\ \mathrm{cm^3})$. How much depth would a lake lose per year if it covered an area of 60 $\mathrm{km^2}$ with uniform depth and supplied a local town with a population of 40,000 people? Consider only population uses, and neglect evaporation, rain, creeks and rivers.

63. A certain compact disc (CD) contains 783.216 megabytes of digital information. Each byte consists of exactly 8 bits. When played, a CD player reads the CD's information at a constant rate of 1.4 megabits per second. How many minutes does it take the player to read the entire CD?

64. An *angstrom* (symbol Å) is a unit of length, defined as 10^{-10} m, which is on the order of the diameter of an atom. (*a*) How many nanometers are in 1.0 angstrom? (*b*) How many femtometers or fermis (the common unit of length in nuclear physics) are in 1.0 angstrom? (*c*) How many angstroms are in 1.0 m? (*d*) How many angstroms are in 1.0 light-year (see Problem 25)?

65. A typical adult human lung contains about 300 million tiny cavities called alveoli. Estimate the average diameter of a single alveolus.

66. Hold a pencil in front of your eye at a position where its blunt end just blocks out the Moon (Fig. 1–16). Make appropriate measurements to estimate the diameter of the Moon, given that the Earth–Moon distance is 3.8×10^5 km.

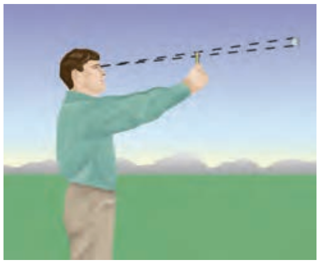


FIGURE 1–16 Problem 66. How big is the Moon?

67. A storm dumps 1.0 cm of rain on a city 5 km wide and 7 km long in a 2-h period. How many metric tons $(1 \text{ metric ton} = 10^3 \text{ kg})$ of water fell on the city? $(1 \text{ cm}^3$ of water has a mass of $1 \text{ g} = 10^{-3} \text{ kg}.)$ How many gallons of water was this?

68. Greenland's ice sheet covers over $1.7 \times 10^6 \text{ km}^2$ and is approximately 2.5 km thick. If it were to melt completely then by how much would you expect the ocean to rise? Assume $\frac{2}{3}$ of Earth's surface is ocean. See Tables inside front and back covers.

69. Noah's ark was ordered to be 300 cubits long, 50 cubits wide, and 30 cubits high. The cubit was a unit of measure equal to the length of a human forearm, elbow to the tip of the longest finger. Express the dimensions of Noah's ark in meters, and estimate its volume (m^3).

70. One liter (1000 cm^3) of oil is spilled onto a smooth lake. If the oil spreads out uniformly until it makes an oil slick just one molecule thick, with adjacent molecules just touching, estimate the diameter of the oil slick. Assume the oil molecules have a diameter of 2×10^{-10} m.

71. If you walked north along one of Earth's lines of longitude until you had changed latitude by 1 minute of arc (there are 60 minutes per degree), how far would you have walked (in miles)? This distance is a *nautical mile* (page 7).

72. Determine the percent uncertainty in θ, and in $\sin\theta$, when (*a*) $\theta = 15.0° \pm 0.5°$, (*b*) $\theta = 75.0° \pm 0.5°$.

73. Jim stands beside a wide river and wonders how wide it is. He spots a large rock on the bank directly across from him. He then walks upstream 85 strides and judges that the angle between him and the rock, which he can still see, is now at an angle of 30° downstream (Fig. 1–17). Jim measures his stride to be about 0.8 m long. Estimate the width of the river.

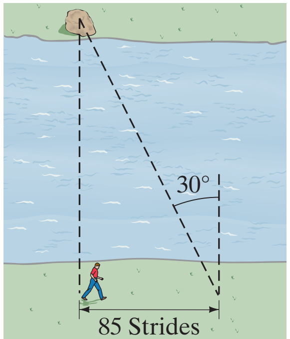


FIGURE 1–17 Problem 73.

74. Make a rough estimate of the volume of your body (in m^3).

75. Estimate the number of plumbers in San Francisco.

76. Estimate the ratio (order of magnitude) of the mass of a human to the mass of a DNA molecule. [*Hint*: Check the Tables in this Chapter.]

77. The following formula estimates an average person's lung capacity V $(\text{in liters, where } 1 \text{ L} = 10^3 \text{ cm}^3)$:

$$V = 4.1H - 0.018A - 2.7,$$

where H and A are the person's height (in meters) and age (in years), respectively. In this formula, what are the units of the numbers 4.1, 0.018, and 2.7?

78. The density of an object is defined as its mass divided by its volume. Suppose a rock's mass and volume are measured to be 6 g and 2.8325 cm^3. To the correct number of significant figures, determine the rock's density (mass/volume).

79. Recent findings in astrophysics suggest that the observable universe can be modeled as a sphere of radius $R = 13.7 \times 10^9$ light-years $= 13.0 \times 10^{25}$ m with an average total mass density of about $1 \times 10^{-26} \text{ kg/m}^3$. Only about 4% of total mass is due to "ordinary" matter (such as protons, neutrons, and electrons). Estimate how much ordinary matter (in kg) there is in the observable universe. (For the light-year, see Problem 25.)

ANSWERS TO EXERCISES

A: (*d*).
B: All three have three significant figures; the number of decimal places is (*a*) 2, (*b*) 3, (*c*) 4.
C: No: they have three and two, respectively.
D: (*a*) 2.58×10^{-2}, 3; (*b*) 4.23×10^4, 3 (probably); (*c*) 3.4450×10^2, 5.
E: Mt. Everest, 29,035 ft; K2, 28,251 ft; Kangchenjunga, 28,169 ft.
F: (*a*) 2.47 acres in 1 hectare; (*b*) $2\frac{1}{2}$ or even just 2 acres in 1 hectare.
G: (*f*) 1,000,000; that is, one million.
H: (*c*).

A space shuttle has released a parachute to reduce its speed quickly. The directions of the shuttle's velocity and acceleration are shown by the green ($\vec{\mathbf{v}}$) and gold ($\vec{\mathbf{a}}$) arrows.

Motion is described using the concepts of velocity and acceleration. In the case shown here, the velocity $\vec{\mathbf{v}}$ is to the right, in the direction of motion. The acceleration $\vec{\mathbf{a}}$ is in the opposite direction from the velocity $\vec{\mathbf{v}}$, which means the object is slowing down.

We examine in detail motion with constant acceleration, including the vertical motion of objects falling under gravity.

CHAPTER 2

Describing Motion: Kinematics in One Dimension

CONTENTS

2–1 Reference Frames and Displacement
2–2 Average Velocity
2–3 Instantaneous Velocity
2–4 Acceleration
2–5 Motion at Constant Acceleration
2–6 Solving Problems
2–7 Freely Falling Objects
*2–8 Variable Acceleration; Integral Calculus

CHAPTER-OPENING QUESTION—Guess now!

[*Don't worry about getting the right answer now—you will get another chance later in the Chapter. See also page 1 of Chapter 1 for more explanation.*]

Two small heavy balls have the same diameter but one weighs twice as much as the other. The balls are dropped from a second-story balcony at the exact same time. The time to reach the ground below will be:

(a) twice as long for the lighter ball as for the heavier one.
(b) longer for the lighter ball, but not twice as long.
(c) twice as long for the heavier ball as for the lighter one.
(d) longer for the heavier ball, but not twice as long.
(e) nearly the same for both balls.

The motion of objects—baseballs, automobiles, joggers, and even the Sun and Moon—is an obvious part of everyday life. It was not until the sixteenth and seventeenth centuries that our modern understanding of motion was established. Many individuals contributed to this understanding, particularly Galileo Galilei (1564–1642) and Isaac Newton (1642–1727).

The study of the motion of objects, and the related concepts of force and energy, form the field called **mechanics**. Mechanics is customarily divided into two parts: **kinematics**, which is the description of how objects move, and **dynamics**, which deals with force and why objects move as they do. This Chapter and the next deal with kinematics.

For now we only discuss objects that move without rotating (Fig. 2–1a). Such motion is called **translational motion**. In this Chapter we will be concerned with describing an object that moves along a straight-line path, which is one-dimensional translational motion. In Chapter 3 we will describe translational motion in two (or three) dimensions along paths that are not straight. (Rotation, shown in Fig. 2–1b, is discussed in Chapters 10 and 11.)

We will often use the concept, or *model*, of an idealized **particle** which is considered to be a mathematical **point** with no spatial extent (no size). A point particle can undergo only translational motion. The particle model is useful in many real situations where we are interested only in translational motion and the object's size is not significant. For example, we might consider a billiard ball, or even a spacecraft traveling toward the Moon, as a particle for many purposes.

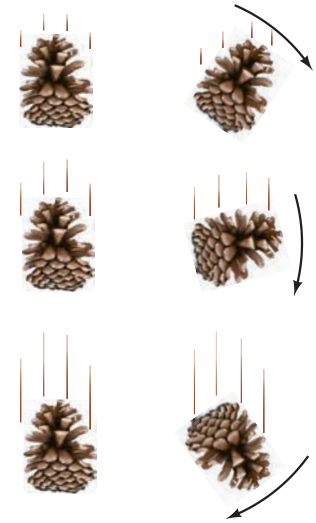


FIGURE 2–1 A falling pinecone undergoes (a) pure translation; (b) it is rotating as well as translating.

2–1 Reference Frames and Displacement

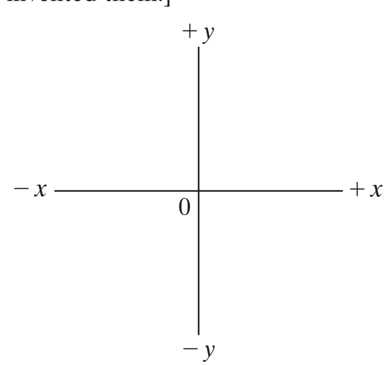
Any measurement of position, distance, or speed must be made with respect to a **reference frame**, or **frame of reference**. For example, while you are on a train traveling at 80 km/h, suppose a person walks past you toward the front of the train at a speed of, say, 5 km/h (Fig. 2–2). This 5 km/h is the person's speed with respect to the train as frame of reference. With respect to the ground, that person is moving at a speed of $80\,\text{km/h} + 5\,\text{km/h} = 85\,\text{km/h}$. It is always important to specify the frame of reference when stating a speed. In everyday life, we usually mean "with respect to the Earth" without even thinking about it, but the reference frame must be specified whenever there might be confusion.

FIGURE 2–2 A person walks toward the front of a train at 5 km/h. The train is moving at 80 km/h with respect to the ground, so the walking person's speed, relative to the ground, is 85 km/h.

When specifying the motion of an object, it is important to specify not only the speed but also the direction of motion. Often we can specify a direction by using north, east, south, and west, and by "up" and "down." In physics, we often draw a set of **coordinate axes**, as shown in Fig. 2–3, to represent a frame of reference. We can always place the origin 0, and the directions of the x and y axes, as we like for convenience. The x and y axes are always perpendicular to each other. The **origin** is where $x = 0$, $y = 0$. Objects positioned to the right of the origin of coordinates (0) on the x axis have an x coordinate which we almost always choose to be positive; objects at points to the left of 0 have a negative x coordinate. The position along the y axis is usually considered positive when above 0, and negative when below 0, although the reverse convention can be used if convenient. Any point on the xy plane can be specified by giving its x and y coordinates. In three dimensions, a z axis perpendicular to the x and y axes is added.

For one-dimensional motion, we often choose the x axis as the line along which the motion takes place. Then the **position** of an object at any moment is given by its x coordinate. If the motion is vertical, as for a dropped object, we usually use the y axis.

FIGURE 2–3 Standard set of xy coordinate axes, sometimes called "rectangular coordinates." [Also called *Cartesian coordinates*, after René Descartes (1596–1650), who invented them.]



CAUTION

The displacement may not equal the total distance traveled

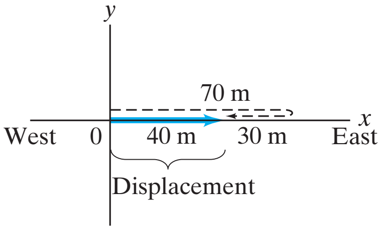


FIGURE 2–4 A person walks 70 m east, then 30 m west. The total distance traveled is 100 m (path is shown dashed in black); but the displacement, shown as a solid blue arrow, is 40 m to the east.

FIGURE 2–5 The arrow represents the displacement $x_2 - x_1$. Distances are in meters.

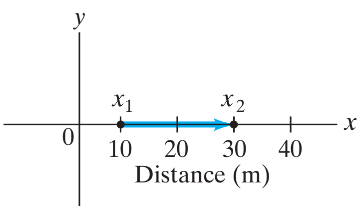
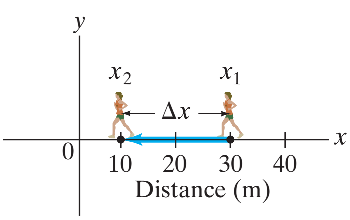


FIGURE 2–6 For the displacement $\Delta x = x_2 - x_1 = 10.0\,\text{m} - 30.0\,\text{m}$, the displacement vector points left.



We need to make a distinction between the **distance** an object has traveled and its **displacement**, which is defined as the *change in position* of the object. That is, *displacement is how far the object is from its starting point*. To see the distinction between total distance and displacement, imagine a person walking 70 m to the east and then turning around and walking back (west) a distance of 30 m (see Fig. 2–4). The total distance traveled is 70 m + 30 m = 100 m, but the displacement is only 40 m since the person is now only 40 m from the starting point.

Displacement is a quantity that has both *magnitude* and *direction*. Such quantities are called **vectors**, and are represented by arrows in diagrams. For example, in Fig. 2–4, the blue arrow represents the displacement whose magnitude is 40 m and whose direction is to the right (east).

We will deal with vectors more fully in Chapter 3. For now, we deal only with motion in one dimension, along a line. In this case, vectors which point in one direction will be positive (usually to the right along the x axis). Vectors that point in the opposite direction will have a negative sign in front of their magnitude.

Consider the motion of an object over a particular time interval. Suppose that at some initial time, call it t_1, the object is on the x axis at the position x_1 in the coordinate system shown in Fig. 2–5. At some later time, t_2, suppose the object has moved to position x_2. The displacement of our object is $x_2 - x_1$, and is represented by the arrow pointing to the right in Fig. 2–5. It is convenient to write

$$\Delta x = x_2 - x_1,$$

where the symbol Δ (Greek letter delta) means "change in." Then Δx means "the change in x," or "change in position," which is in fact the displacement. The **change in** any quantity means the *final* value of that quantity, minus the *initial* value. Suppose $x_1 = 10.0\,\text{m}$ and $x_2 = 30.0\,\text{m}$, as in Fig. 2–5. Then

$$\Delta x = x_2 - x_1 = 30.0\,\text{m} - 10.0\,\text{m} = 20.0\,\text{m},$$

so the displacement is 20.0 m in the positive direction, Fig. 2–5.

Now consider an object moving to the left as shown in Fig. 2–6. Here the object, a person, starts at $x_1 = 30.0\,\text{m}$ and walks to the left to the point $x_2 = 10.0\,\text{m}$. In this case her displacement is

$$\Delta x = x_2 - x_1 = 10.0\,\text{m} - 30.0\,\text{m} = -20.0\,\text{m},$$

and the blue arrow representing the vector displacement points to the left. For one-dimensional motion along the x axis, a vector pointing to the right is positive, whereas a vector pointing to the left has a negative sign.

EXERCISE A An ant starts at $x = 20\,\text{cm}$ on a piece of graph paper and walks along the x axis to $x = -20\,\text{cm}$. It then turns around and walks back to $x = -10\,\text{cm}$. Determine (a) the ant's displacement and (b) the total distance traveled.

2–2 Average Velocity

An important aspect of the motion of a moving object is how *fast* it is moving—its speed or velocity.

The term "speed" refers to how far an object travels in a given time interval, regardless of direction. If a car travels 240 kilometers (km) in 3 hours (h), we say its average speed was 80 km/h. In general, the **average speed** of an object is defined as *the total distance traveled along its path divided by the time it takes to travel this distance*:

$$\text{average speed} = \frac{\text{distance traveled}}{\text{time elapsed}}. \qquad \textbf{(2–1)}$$

The terms "velocity" and "speed" are often used interchangeably in ordinary language. But in physics we make a distinction between the two. Speed is simply a positive number, with units. **Velocity**, on the other hand, is used to signify both the *magnitude* (numerical value) of how fast an object is moving and also the *direction* in which it is moving. Velocity is therefore a *vector*.

There is a second difference between speed and velocity: namely, the *average velocity* is defined in terms of *displacement*, rather than total distance traveled:

$$\text{average velocity} = \frac{\text{displacement}}{\text{time elapsed}} = \frac{\text{final position} - \text{initial position}}{\text{time elapsed}}.$$

Average speed and average velocity have the same magnitude when the motion is all in one direction. In other cases, they may differ: recall the walk we described earlier, in Fig. 2–4, where a person walked 70 m east and then 30 m west. The total distance traveled was 70 m + 30 m = 100 m, but the displacement was 40 m. Suppose this walk took 70 s to complete. Then the average speed was:

$$\frac{\text{distance}}{\text{time elapsed}} = \frac{100\text{ m}}{70\text{ s}} = 1.4\text{ m/s}.$$

The magnitude of the average velocity, on the other hand, was:

$$\frac{\text{displacement}}{\text{time elapsed}} = \frac{40\text{ m}}{70\text{ s}} = 0.57\text{ m/s}.$$

In everyday life, we are usually interested in average speed. If this second equation on average velocity seems strange, we will see its usefulness in the next Section.

CAUTION
Average speed is not necessarily equal to the magnitude of the average velocity

To discuss one-dimensional motion of an object in general, suppose that at some moment in time, call it t_1, the object is on the x axis at position x_1 in a coordinate system, and at some later time, t_2, suppose it is at position x_2. The **elapsed time** (= change in time) is $\Delta t = t_2 - t_1$. During this time interval the displacement of our object is $\Delta x = x_2 - x_1$. Then the **average velocity**, defined as *the displacement divided by the elapsed time*, can be written

$$\bar{v} = \frac{x_2 - x_1}{t_2 - t_1} = \frac{\Delta x}{\Delta t}, \qquad \text{[average velocity]} \quad \textbf{(2–2)}$$

where v stands for velocity and the bar $(^{-})$ over the v is a standard symbol meaning "average."

It is always important to choose (and state) the *elapsed time*, or **time interval**, $t_2 - t_1$, the time that passes during our chosen period of observation.

CAUTION
Time interval = elapsed time

EXAMPLE 2–1 **Runner's average velocity.** The position of a runner is plotted as moving along the x axis of a coordinate system. During a 3.00-s time interval, the runner's position changes from $x_1 = 50.0\text{ m}$ to $x_2 = 30.5\text{ m}$, as shown in Fig. 2–7. What is the runner's average velocity?

APPROACH We want to find the average velocity, which is the displacement divided by the elapsed time.

SOLUTION The displacement is

$$\Delta x = x_2 - x_1 = 30.5\text{ m} - 50.0\text{ m} = -19.5\text{ m}.$$

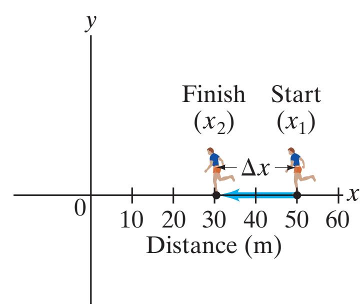
In this case the displacement is negative.

The elapsed time, or time interval, is given as $\Delta t = 3.00\text{ s}$. The average velocity (Eq. 2–2) is

$$\bar{v} = \frac{\Delta x}{\Delta t} = \frac{-19.5\text{ m}}{3.00\text{ s}} = -6.50\text{ m/s}.$$

The displacement and average velocity are negative: that is, the runner is moving to the left along the x axis, as indicated by the arrow in Fig. 2–7. The runner's average velocity is 6.50 m/s to the left.

FIGURE 2–7 Example 2–1. A person runs from $x_1 = 50.0\text{ m}$ to $x_2 = 30.5\text{ m}$. The displacement is -19.5 m.



For one-dimensional motion in the usual case of the $+x$ axis to the right, if x_2 is less than x_1, then the object is moving to the left, and $\Delta x = x_2 - x_1$ is less than zero. The sign of the displacement, and thus of the average velocity, indicates the direction: the average velocity is positive for an object moving to the right along the x axis and negative when the object moves to the left. The direction of the average velocity is always the same as the direction of the displacement.

PROBLEM SOLVING
+ or − sign can signify the direction for linear motion

EXAMPLE 2–2 **Distance a cyclist travels.** How far can a cyclist travel in 2.5 h along a straight road if her average velocity is 18 km/h?

APPROACH We want to find the distance traveled, which in this case equals the displacement Δx, so we solve Eq. 2–2 for Δx.

SOLUTION In Eq. 2–2, $\bar{v} = \Delta x/\Delta t$, we multiply both sides by Δt and obtain

$$\Delta x = \bar{v}\,\Delta t = (18\text{ km/h})(2.5\text{ h}) = 45\text{ km}.$$

EXAMPLE 2–3 **Car changes speed.** A car travels at a constant 50 km/h for 100 km. It then speeds up to 100 km/h and is driven another 100 km. What is the car's average speed for the 200-km trip?

APPROACH At 50 km/h, the car takes 2.0 h to travel 100 km. At 100 km/h, it takes only 1.0 h to travel 100 km. We use the definition of average velocity, Eq. 2–2.

SOLUTION Average velocity (Eq. 2–2) is

$$\bar{v} = \frac{\Delta x}{\Delta t} = \frac{100\text{ km} + 100\text{ km}}{2.0\text{ h} + 1.0\text{ h}} = 67\text{ km/h}.$$

NOTE Averaging the two speeds, $(50\text{ km/h} + 100\text{ km/h})/2 = 75\text{ km/h}$, gives a wrong answer. Can you see why? You must use the definition of $\bar{v}$, Eq. 2–2.

2–3 Instantaneous Velocity

FIGURE 2–8 Car speedometer showing mi/h in white, and km/h in orange.

If you drive a car along a straight road for 150 km in 2.0 h, the magnitude of your average velocity is 75 km/h. It is unlikely, though, that you were moving at precisely 75 km/h at every instant. To describe this situation we need the concept of *instantaneous velocity*, which is the velocity at any instant of time. (Its magnitude is the number, with units, indicated by a speedometer, Fig. 2–8.) More precisely, the **instantaneous velocity** at any moment is defined as *the average velocity over an infinitesimally short time interval*. That is, Eq. 2–2 is to be evaluated in the limit of Δt becoming extremely small, approaching zero. We can write the definition of instantaneous velocity, v, for one-dimensional motion as

$$v = \lim_{\Delta t \to 0} \frac{\Delta x}{\Delta t}. \qquad \text{[instantaneous velocity]} \quad \textbf{(2–3)}$$

The notation $\lim_{\Delta t \to 0}$ means the ratio $\Delta x/\Delta t$ is to be evaluated in the limit of Δt approaching zero. But we do not simply set $\Delta t = 0$ in this definition, for then Δx would also be zero, and we would not be able to evaluate it. Rather, we consider the *ratio* $\Delta x/\Delta t$, as a whole. As we let Δt approach zero, Δx approaches zero as well. But the ratio $\Delta x/\Delta t$ approaches some definite value, which is the instantaneous velocity at a given instant.

In Eq. 2–3, the limit as $\Delta t \to 0$ is written in calculus notation as dx/dt and is called the **derivative** of x with respect to t:

$$v = \lim_{\Delta t \to 0} \frac{\Delta x}{\Delta t} = \frac{dx}{dt}. \qquad \textbf{(2–4)}$$

This equation is the definition of instantaneous velocity for one-dimensional motion.

For instantaneous velocity we use the symbol v, whereas for average velocity we use $\bar{v}$, with a bar above. In the rest of this book, when we use the term "velocity" it will refer to instantaneous velocity. When we want to speak of the average velocity, we will make this clear by including the word "average."

Note that the *instantaneous speed* always equals the magnitude of the instantaneous velocity. Why? Because as the time interval becomes infinitesimally small ($\Delta t \to 0$), an object has no time to change speed or direction, and so the distance traveled and the magnitude of the displacement have to be the same.

If an object moves at a uniform (that is, constant) velocity during a particular time interval, then its instantaneous velocity at any instant is the same as its average velocity (see Fig. 2–9a). But in many situations this is not the case. For example, a car may start from rest, speed up to 50 km/h, remain at that velocity for a time, then slow down to 20 km/h in a traffic jam, and finally stop at its destination after traveling a total of 15 km in 30 min. This trip is plotted on the graph of Fig. 2–9b. Also shown on the graph is the average velocity (dashed line), which is $\bar{v} = \Delta x/\Delta t = 15\,\text{km}/0.50\,\text{h} = 30\,\text{km/h}$.

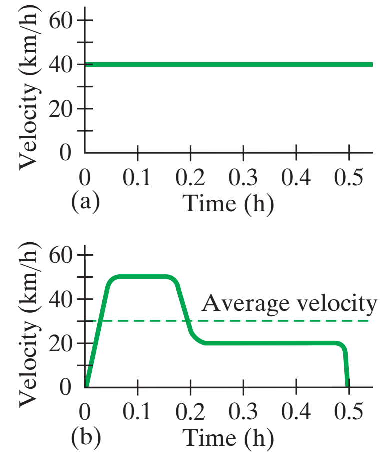
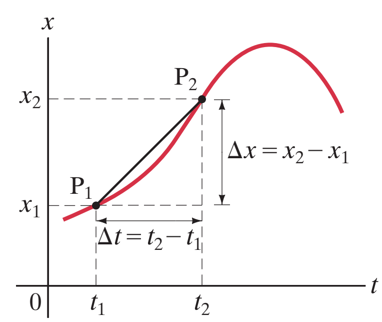


FIGURE 2–9 Velocity of a car as a function of time: (a) at constant velocity; (b) with velocity varying in time.

To better understand instantaneous velocity, let us consider a graph of the position versus time (x vs. t) of a particle moving along the x axis, as shown in Fig. 2–10. (Note that this is different from showing the "path" of a particle moving in two dimensions on an x vs. y plot.) The particle is at position x_1 at time t_1, and at position x_2 at time t_2. P_1 and P_2 represent these two points on the graph. A straight line drawn from point $P_1\left(x_1, t_1\right)$ to point $P_2\left(x_2, t_2\right)$ forms the hypotenuse of a right triangle whose sides are Δx and Δt. The ratio $\Delta x/\Delta t$ is the **slope** of the straight line P_1P_2. But $\Delta x/\Delta t$ is also the average velocity of the particle during the time interval $\Delta t = t_2 - t_1$. Therefore, we conclude that the average velocity of a particle during any time interval $\Delta t = t_2 - t_1$ is equal to the slope of the straight line (or *chord*) connecting the two points $\left(x_1, t_1\right)$ and $\left(x_2, t_2\right)$ on an x vs. t graph.

FIGURE 2–10 Graph of a particle's position x vs. time t. The slope of the straight line P_1P_2 represents the average velocity of the particle during the time interval $\Delta t = t_2 - t_1$.



Consider now a time t_i, intermediate between t_1 and t_2, at which time the particle is at x_i (Fig. 2–11). The slope of the straight line P_1P_i is less than the slope of P_1P_2 in this case. Thus the average velocity during the time interval $t_i - t_1$ is less than during the time interval $t_2 - t_1$.

Now let us imagine that we take the point P_i in Fig. 2–11 to be closer and closer to point P_1. That is, we let the interval $t_i - t_1$, which we now call Δt, become smaller and smaller. The slope of the line connecting the two points becomes closer and closer to the slope of a line tangent to the curve at point P_1. The average velocity (equal to the slope of the chord) thus approaches the slope of the tangent at point P_1. The definition of the instantaneous velocity (Eq. 2–3) is the limiting value of the average velocity as Δt approaches zero. Thus the *instantaneous velocity equals the slope of the tangent to the x vs. t curve* at that point (which we can simply call "the slope of the curve" at that point).

Because the velocity at any instant equals the slope of the tangent to the x vs. t graph at that instant, we can obtain the velocity at any instant from such a graph. For example, in Fig. 2–12 (which shows the same curve as in Figs. 2–10 and 2–11), the slope continually increases as our object moves from x_1 to x_2, so the velocity is increasing. For times after t_2, however, the slope begins to decrease and in fact reaches zero (so $v = 0$) where x has its maximum value, at point P_3 in Fig. 2–12. Beyond this point, the slope is negative, as for point P_4. The velocity is therefore negative, which makes sense since x is now decreasing—the particle is moving to the left on a standard xy plot, toward decreasing values of x.

If an object moves with constant velocity over a particular time interval, its instantaneous velocity is equal to its average velocity. The graph of x vs. t in this case will be a straight line whose slope equals the velocity. The curve of Fig. 2–10 has no straight sections, so there are no time intervals when the velocity is constant.

FIGURE 2–11 Same position vs. time curve as in Fig. 2–10, but including an intermediate time t_i. Note that the average velocity over the time interval $t_i - t_1$ (which is the slope of P_1P_i) is less than the average velocity over the time interval $t_2 - t_1$. The slope of the thin line tangent to the curve at point P_1 equals the instantaneous velocity at time t_1.

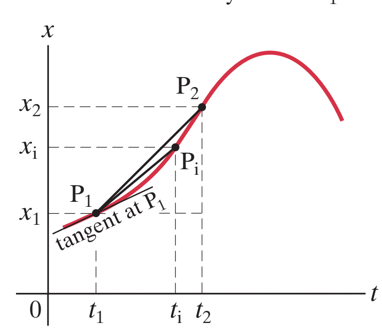
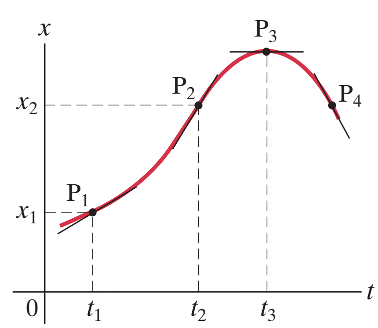


FIGURE 2–12 Same x vs. t curve as in Figs. 2–10 and 2–11, but here showing the slope at four different points: At P_3, the slope is zero, so $v = 0$. At P_4 the slope is negative, so $v < 0$.



EXERCISE B What is your speed at the instant you turn around to move in the opposite direction? (*a*) Depends on how quickly you turn around; (*b*) always zero; (*c*) always negative; (*d*) none of the above.

The derivatives of various functions are studied in calculus courses, and you can find a review in this book in Appendix B. The derivatives of polynomial functions (which we use a lot) are:

$$\frac{d}{dt}\left(Ct^n\right) = nCt^{n-1} \quad \text{and} \quad \frac{dC}{dt} = 0,$$

where C is any constant.

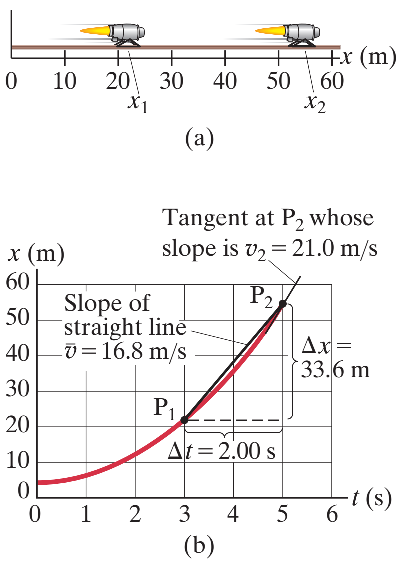


FIGURE 2–13 Example 2–4. (a) Engine traveling on a straight track. (b) Graph of x vs. t: $x = At^2 + B$.

EXAMPLE 2–4 **Given *x* as a function of *t*.** A jet engine moves along an experimental track (which we call the x axis) as shown in Fig. 2–13a. We will treat the engine as if it were a particle. Its position as a function of time is given by the equation $x = At^2 + B$, where $A = 2.10\,\text{m/s}^2$ and $B = 2.80\,\text{m}$, and this equation is plotted in Fig. 2–13b. (*a*) Determine the displacement of the engine during the time interval from $t_1 = 3.00\,\text{s}$ to $t_2 = 5.00\,\text{s}$. (*b*) Determine the average velocity during this time interval. (*c*) Determine the magnitude of the instantaneous velocity at $t = 5.00\,\text{s}$.

APPROACH (*a*) We substitute values for t_1 and t_2 in the given equation for x to obtain x_1 and x_2. (*b*) The average velocity can be found from Eq. 2–2. (*c*) To find the instantaneous velocity, we take the derivative of the given x equation with respect to t using the formulas given above.

SOLUTION (*a*) At $t_1 = 3.00\,\text{s}$, the position (point P_1 in Fig. 2–13b) is

$$x_1 = At_1^2 + B = \left(2.10\,\text{m/s}^2\right)(3.00\,\text{s})^2 + 2.80\,\text{m} = 21.7\,\text{m}.$$

At $t_2 = 5.00\,\text{s}$, the position (P_2 in Fig. 2–13b) is

$$x_2 = \left(2.10\,\text{m/s}^2\right)(5.00\,\text{s})^2 + 2.80\,\text{m} = 55.3\,\text{m}.$$

The displacement is thus

$$x_2 - x_1 = 55.3\,\text{m} - 21.7\,\text{m} = 33.6\,\text{m}.$$

(*b*) The magnitude of the average velocity can then be calculated as

$$\bar{v} = \frac{\Delta x}{\Delta t} = \frac{x_2 - x_1}{t_2 - t_1} = \frac{33.6\,\text{m}}{2.00\,\text{s}} = 16.8\,\text{m/s}.$$

This equals the slope of the straight line joining points P_1 and P_2 shown in Fig. 2–13b.

(*c*) The instantaneous velocity at $t = t_2 = 5.00\,\text{s}$ equals the slope of the tangent to the curve at point P_2 shown in Fig. 2–13b. We could measure this slope off the graph to obtain v_2. But we can calculate v more precisely for any time t, using the given formula

$$x = At^2 + B,$$

which is the engine's position x as a function of time t. We take the derivative of x with respect to time (see formulas at top of this page):

$$v = \frac{dx}{dt} = \frac{d}{dt}\left(At^2 + B\right) = 2At.$$

We are given $A = 2.10\,\text{m/s}^2$, so for $t = t_2 = 5.00\,\text{s}$,

$$v_2 = 2At = 2\left(2.10\,\text{m/s}^2\right)(5.00\,\text{s}) = 21.0\,\text{m/s}.$$

2–4 Acceleration

An object whose velocity is changing is said to be accelerating. For instance, a car whose velocity increases in magnitude from zero to 80 km/h is accelerating. Acceleration specifies how rapidly the velocity of an object is changing.

Average Acceleration

Average acceleration is defined as the change in velocity divided by the time taken to make this change:

$$\text{average acceleration} = \frac{\text{change of velocity}}{\text{time elapsed}}.$$

In symbols, the average acceleration over a time interval $\Delta t = t_2 - t_1$ during which the velocity changes by $\Delta v = v_2 - v_1$ is defined as

$$\bar{a} = \frac{v_2 - v_1}{t_2 - t_1} = \frac{\Delta v}{\Delta t}. \quad \textbf{(2–5)}$$

Because velocity is a vector, acceleration is a vector too. But for one-dimensional motion, we need only use a plus or minus sign to indicate acceleration direction relative to a chosen coordinate axis.

EXAMPLE 2–5 **Average acceleration.** A car accelerates along a straight road from rest to 90 km/h in 5.0 s, Fig. 2–14. What is the magnitude of its average acceleration?

APPROACH Average acceleration is the change in velocity divided by the elapsed time, 5.0 s. The car starts from rest, so $v_1 = 0$. The final velocity is $v_2 = 90\text{ km/h} = 90 \times 10^3\text{ m}/3600\text{ s} = 25\text{ m/s}$.

SOLUTION From Eq. 2–5, the average acceleration is

$$\bar{a} = \frac{v_2 - v_1}{t_2 - t_1} = \frac{25\text{ m/s} - 0\text{ m/s}}{5.0\text{ s}} = 5.0\,\frac{\text{m/s}}{\text{s}}.$$

This is read as "five meters per second per second" and means that, on average, the velocity changed by 5.0 m/s during each second. That is, assuming the acceleration was constant, during the first second the car's velocity increased from zero to 5.0 m/s. During the next second its velocity increased by another 5.0 m/s, reaching a velocity of 10.0 m/s at $t = 2.0$ s, and so on. See Fig. 2–14.

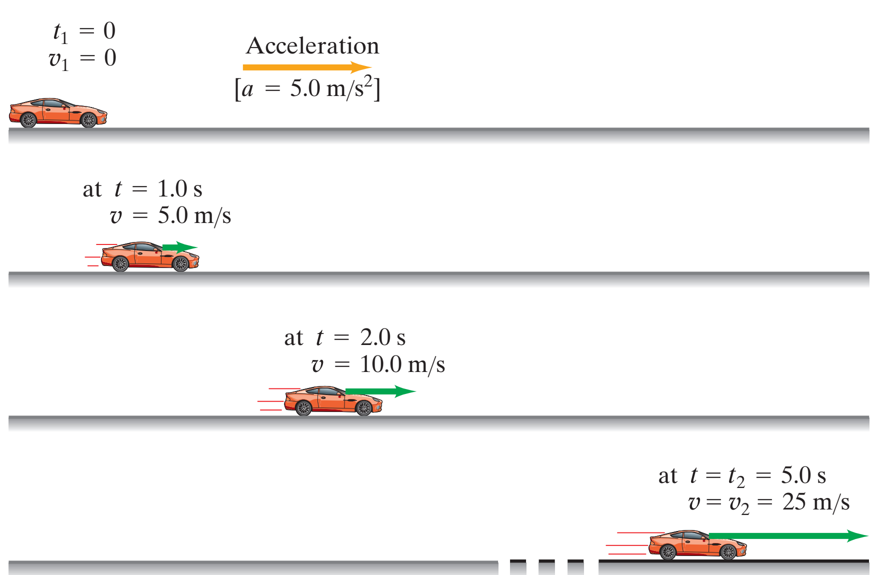


FIGURE 2–14 Example 2–5. The car is shown at the start with $v_1 = 0$ at $t_1 = 0$. The car is shown three more times, at $t = 1.0$ s, $t = 2.0$ s, and at the end of our time interval, $t_2 = 5.0$ s. The green arrows represent the velocity vectors, whose length represents the magnitude of the velocity at that moment and get longer with time. The acceleration vector is the orange arrow, whose magnitude is constant and is found to equal 5.0 m/s^2. Distances are not to scale.

We almost always write the units for acceleration as m/s^2 (meters per second squared) instead of m/s/s. This is possible because:

$$\frac{m/s}{s} = \frac{m}{s \cdot s} = \frac{m}{s^2}.$$

According to the calculation in Example 2–5, the velocity changed on average by 5.0 m/s during each second, for a total change of 25 m/s over the 5.0 s; the average acceleration was $5.0\ m/s^2$.

CAUTION
Distinguish velocity from acceleration

Note that *acceleration* tells us how quickly the *velocity* changes, whereas *velocity* tells us how quickly the *position* changes.

CAUTION
If v or a is zero, is the other zero too?

CONCEPTUAL EXAMPLE 2–6 **Velocity and acceleration.** (*a*) If the velocity of an object is zero, does it mean that the acceleration is zero? (*b*) If the acceleration is zero, does it mean that the velocity is zero? Think of some examples.

RESPONSE A zero velocity does not necessarily mean that the acceleration is zero, nor does a zero acceleration mean that the velocity is zero. (*a*) For example, when you put your foot on the gas pedal of your car which is at rest, the velocity starts from zero but the acceleration is not zero since the velocity of the car changes. (How else could your car start forward if its velocity weren't changing—that is, accelerating?) (*b*) As you cruise along a straight highway at a constant velocity of 100 km/h, your acceleration is zero: $a = 0$, $v \neq 0$.

EXERCISE C A powerful car is advertised to go from zero to 60 mi/h in 5.4 s. What does this say about the car: (*a*) it is fast (high speed); or (*b*) it accelerates well?

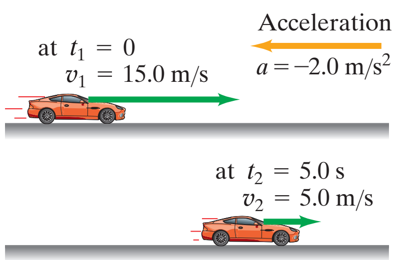


FIGURE 2–15 Example 2–7, showing the position of the car at times t_1 and t_2, as well as the car's velocity represented by the green arrows. We calculate that the acceleration vector (orange) points to the left as the car slows down while moving to the right.

EXAMPLE 2–7 **Car slowing down.** An automobile is moving to the right along a straight highway, which we choose to be the positive *x* axis (Fig. 2–15). Then the driver puts on the brakes. If the initial velocity (when the driver hits the brakes) is $v_1 = 15.0$ m/s, and it takes 5.0 s to slow down to $v_2 = 5.0$ m/s, what was the car's average acceleration?

APPROACH We put the given initial and final velocities, and the elapsed time, into Eq. 2–5 for $\bar{a}$.

SOLUTION In Eq. 2–5, we call the initial time $t_1 = 0$, and set $t_2 = 5.0$ s. (Note that our choice of $t_1 = 0$ doesn't affect the calculation of $\bar{a}$ because only $\Delta t = t_2 - t_1$ appears in Eq. 2–5.) Then

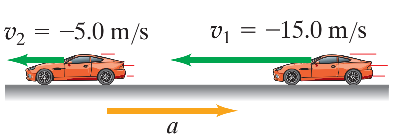
$$\bar{a} = \frac{5.0\ m/s - 15.0\ m/s}{5.0\ s} = -2.0\ m/s^2.$$

The negative sign appears because the final velocity is less than the initial velocity. In this case the direction of the acceleration is to the left (in the negative *x* direction)—even though the velocity is always pointing to the right. We say that the acceleration is $2.0\ m/s^2$ to the left, and it is shown in Fig. 2–15 as an orange arrow.

FIGURE 2–16 The car of Example 2–7, now moving to the *left* and decelerating. The acceleration is

$$a = \frac{v_2 - v_1}{\Delta t}$$

$$a = \frac{(-5.0\ m/s) - (-15.0\ m/s)}{5.0\ s} = \frac{-5.0\ m/s + 15.0\ m/s}{5.0\ s} = +2.0\ m/s^2.$$



"Deceleration"

When an object is slowing down, we sometimes say it is **decelerating**. In physics, the concept of acceleration is all we need: it can be + or −. But if the word "deceleration" is used, be careful: deceleration does *not* mean that the acceleration is necessarily negative, as in Example 2–7. The velocity of an object moving to the right along the positive *x* axis is positive; if the object is slowing down (as in Fig. 2–15), the acceleration *is* negative. But the same car moving to the left (decreasing *x*), and slowing down, has positive acceleration that points to the right, as shown in Fig. 2–16. We have a deceleration whenever the magnitude of the velocity is decreasing; thus the *velocity and acceleration point in opposite directions* when there is deceleration.

EXERCISE D A car moves along the x axis. What is the sign of the car's acceleration if it is moving in the positive x direction with (a) increasing speed or (b) decreasing speed? What is the sign of the acceleration if the car moves in the negative x direction with (c) increasing speed or (d) decreasing speed?

Instantaneous Acceleration

The **instantaneous acceleration**, a, is defined as the *limiting value of the average acceleration as we let* Δt *approach zero*:

$$a = \lim_{\Delta t \to 0} \frac{\Delta v}{\Delta t} = \frac{dv}{dt}. \qquad \textbf{(2–6)}$$

This limit, dv/dt, is the derivative of v with respect to t. We will use the term "acceleration" to refer to the instantaneous value. If we want to discuss the average acceleration, we will always include the word "average."

If we draw a graph of the velocity, v, vs. time, t, as shown in Fig. 2–17, then the *average* acceleration over a time interval $\Delta t = t_2 - t_1$ is represented by the slope of the straight line connecting the two points P_1 and P_2 in Fig. 2–17. [Compare this to the position vs. time graph of Fig. 2–10 for which the slope of the straight line represents the average velocity.] The *instantaneous* acceleration at any time, say t_1, is the slope of the tangent to the v vs. t curve at time t_1, which is also shown in Fig. 2–17. In Fig. 2–17, as we go from time t_1 to time t_2 the velocity continually increases, but the acceleration (the rate at which the velocity changes) is decreasing since the slope of the curve is decreasing.

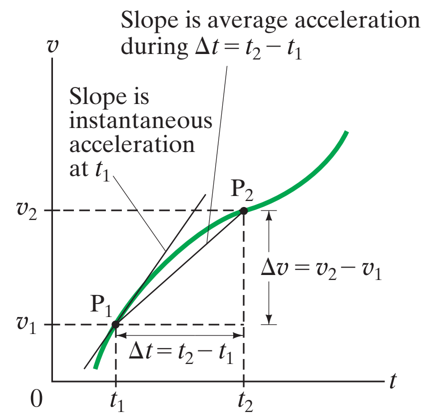


FIGURE 2–17 A graph of velocity v vs. time t. The average acceleration over a time interval $\Delta t = t_2 - t_1$ is the slope of the straight line P_1P_2: $\bar{a} = \Delta v/\Delta t$. The instantaneous acceleration at time t_1 is the slope of the v vs. t curve at that instant.

EXAMPLE 2–8 **Acceleration given $x(t)$.** A particle is moving in a straight line so that its position is given by the relation $x = (2.10\,\text{m/s}^2)t^2 + (2.80\,\text{m})$, as in Example 2–4. Calculate (a) its average acceleration during the time interval from $t_1 = 3.00\,\text{s}$ to $t_2 = 5.00\,\text{s}$, and (b) its instantaneous acceleration as a function of time.

APPROACH To determine acceleration, we first must find the velocity at t_1 and t_2 by differentiating x: $v = dx/dt$. Then we use Eq. 2–5 to find the average acceleration, and Eq. 2–6 to find the instantaneous acceleration.

SOLUTION (a) The velocity at any time t is

$$v = \frac{dx}{dt} = \frac{d}{dt}\left[(2.10\,\text{m/s}^2)t^2 + 2.80\,\text{m}\right] = (4.20\,\text{m/s}^2)t,$$

as we already saw in Example 2–4c. Therefore, at time $t_1 = 3.00\,\text{s}$, $v_1 = (4.20\,\text{m/s}^2)(3.00\,\text{s}) = 12.6\,\text{m/s}$ and at $t_2 = 5.00\,\text{s}$, $v_2 = 21.0\,\text{m/s}$. Therefore,

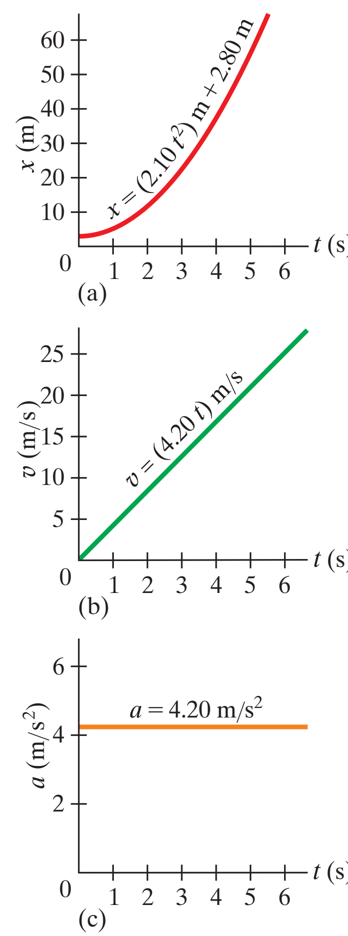
$$\bar{a} = \frac{\Delta v}{\Delta t} = \frac{21.0\,\text{m/s} - 12.6\,\text{m/s}}{5.00\,\text{s} - 3.00\,\text{s}} = 4.20\,\text{m/s}^2.$$

(b) With $v = (4.20\,\text{m/s}^2)t$, the instantaneous acceleration at any time is

$$a = \frac{dv}{dt} = \frac{d}{dt}\left[(4.20\,\text{m/s}^2)t\right] = 4.20\,\text{m/s}^2.$$

The acceleration in this case is constant; it does not depend on time. Figure 2–18 shows graphs of (a) x vs. t (the same as Fig. 2–13b), (b) v vs. t, which is linearly increasing as calculated above, and (c) a vs. t, which is a horizontal straight line because a = constant.

FIGURE 2–18 Example 2–8. Graphs of (a) x vs. t, (b) v vs. t, and (c) a vs. t for the motion $x = At^2 + B$. Note that v increases linearly with t and that the acceleration a is constant. Also, v is the slope of the x vs. t curve, whereas a is the slope of the v vs. t curve.



Like velocity, acceleration is a rate. The velocity of an object is the rate at which its displacement changes with time; its acceleration, on the other hand, is the rate at which its velocity changes with time. In a sense, acceleration is a "rate of a rate."

This can be expressed in equation form: since $a = dv/dt$ and $v = dx/dt$, then

$$a = \frac{dv}{dt} = \frac{d}{dt}\left(\frac{dx}{dt}\right) = \frac{d^2x}{dt^2}.$$

Here d^2x/dt^2 is the *second derivative* of x with respect to time: we first take the derivative of x with respect to time (dx/dt), and then we again take the derivative with respect to time, $(d/dt)(dx/dt)$, to get the acceleration.

EXERCISE E The position of a particle is given by the following equation:

$$x = (2.00\,\text{m/s}^3)t^3 + (2.50\,\text{m/s})t.$$

What is the acceleration of the particle at $t = 2.00\,\text{s}$? Choose one: (*a*) $13.0\,\text{m/s}^2$; (*b*) $22.5\,\text{m/s}^2$; (*c*) $24.0\,\text{m/s}^2$; (*d*) $2.00\,\text{m/s}^2$; (*e*) $21.0\,\text{m/s}^2$.

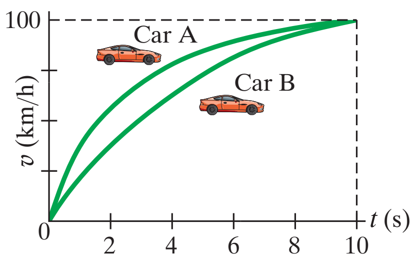


FIGURE 2–19 Example 2–9.

CONCEPTUAL EXAMPLE 2–9 **Analyzing with graphs.** Figure 2–19 shows the velocity as a function of time for two cars accelerating from 0 to 100 km/h in a time of 10.0 s. Compare for the two cars: (*a*) the average acceleration; (*b*) the instantaneous acceleration; and (*c*) the total distance traveled.

RESPONSE (*a*) Average acceleration is $\Delta v/\Delta t$. Both cars have the same Δv (100 km/h) and the same Δt (10.0 s), so the average acceleration is the same for both cars. (*b*) Instantaneous acceleration is the slope of the tangent to the v vs. t curve. For about the first 4 s, the top curve is steeper than the bottom curve, so car A has a greater instantaneous acceleration during this interval. The bottom curve is steeper during the last 6 s, so car B has the larger acceleration during this period. (*c*) Except at $t = 0$ and $t = 10.0\,\text{s}$, car A is always going faster than car B. Since it is going faster, it will go farther in the same time. Notice what marvelous information we can get from a graph.

2–5 Motion at Constant Acceleration

We now examine motion in a straight line when the magnitude of the acceleration is constant. In this case, the instantaneous and average acceleration are equal. We use the definitions of average velocity and acceleration to derive a set of valuable equations that relate x, v, a, and t when a is constant, allowing us to determine any one of these variables if we know the others.

Notation in physics varies from book to book; and different instructors use different notation. We are now going to change our notation, to simplify it a bit for our discussion here of motion at **constant acceleration**. First we choose the initial time in any discussion to be zero, and we call it t_0. That is, $t_1 = t_0 = 0$. (This is effectively starting a stopwatch at t_0.) We can then let $t_2 = t$ be the elapsed time. The initial position (x_1) and the initial velocity (v_1) of an object will now be represented by x_0 and v_0, since they represent x and v at $t = 0$. At time t the position and velocity will be called x and v (rather than x_2 and v_2). The average velocity during the time interval $t - t_0$ will be (Eq. 2–2)

$$\bar{v} = \frac{\Delta x}{\Delta t} = \frac{x - x_0}{t - t_0} = \frac{x - x_0}{t}$$

since we chose $t_0 = 0$. The acceleration, assumed constant in time, is $a = \Delta v/\Delta t$ (Eq. 2–5), so

$$a = \frac{v - v_0}{t}.$$

A common problem is to determine the velocity of an object after any elapsed time t, when we are given the object's constant acceleration. We can solve such problems by solving for v in the last equation: first we multiply both sides by t, which gives $at = v - v_0$, and then

$$v = v_0 + at. \qquad \text{[constant acceleration]} \qquad \textbf{(2–7)}$$

If an object, such as a motorcycle, starts from rest $(v_0 = 0)$ and accelerates at $4.0\,\text{m/s}^2$, then after an elapsed time $t = 6.0\,\text{s}$ its velocity will be $v = 0 + at = (4.0\,\text{m/s}^2)(6.0\,\text{s}) = 24\,\text{m/s}$.

Next, let us see how to calculate the position x of an object after a time t when it undergoes constant acceleration. The definition of average velocity (Eq. 2–2) is $\bar{v} = (x - x_0)/t$, which we can rewrite by multiplying both sides by t:

$$x = x_0 + \bar{v}t. \qquad \textbf{(2–8)}$$

Because the velocity increases at a uniform rate, the average velocity, $\bar{v}$, will be midway between the initial and final velocities:

$$\bar{v} = \frac{v_0 + v}{2}. \qquad \text{[constant acceleration]} \quad \textbf{(2–9)}$$

⚠ **CAUTION**

Average velocity, but only if $a =$ constant

(Careful: Equation 2–9 is not necessarily valid if the acceleration is not constant.) We combine the last two Equations with Eq. 2–7 and find, starting with Eq. 2–8,

$$\begin{aligned} x &= x_0 + \bar{v}t \\ &= x_0 + \left(\frac{v_0 + v}{2}\right)t \\ &= x_0 + \left(\frac{v_0 + v_0 + at}{2}\right)t \end{aligned}$$

or

$$x = x_0 + v_0 t + \tfrac{1}{2}at^2. \qquad \text{[constant acceleration]} \quad \textbf{(2–10)}$$

Equations 2–7, 2–9, and 2–10 are three of the four most useful equations for motion at constant acceleration. We now derive the fourth equation, which is useful in situations where the time t is not known. We substitute Eq. 2–9 into Eq. 2–8:

$$x = x_0 + \bar{v}t = x_0 + \left(\frac{v + v_0}{2}\right)t.$$

Next we solve Eq. 2–7 for t, obtaining

$$t = \frac{v - v_0}{a},$$

and substituting this into the previous equation we have

$$x = x_0 + \left(\frac{v + v_0}{2}\right)\left(\frac{v - v_0}{a}\right) = x_0 + \frac{v^2 - v_0^2}{2a}.$$

We solve this for v^2 and obtain

$$v^2 = v_0^2 + 2a(x - x_0), \qquad \text{[constant acceleration]} \quad \textbf{(2–11)}$$

which is the other useful equation we sought.

We now have four equations relating position, velocity, acceleration, and time, when the acceleration a is constant. We collect these *kinematic equations for constant acceleration* here in one place for further reference (the tan background is used to emphasize their importance):

$$v = v_0 + at \qquad [a = \text{constant}] \quad \textbf{(2–12a)}$$

$$x = x_0 + v_0 t + \tfrac{1}{2}at^2 \qquad [a = \text{constant}] \quad \textbf{(2–12b)}$$

$$v^2 = v_0^2 + 2a(x - x_0) \qquad [a = \text{constant}] \quad \textbf{(2–12c)}$$

$$\bar{v} = \frac{v + v_0}{2}. \qquad [a = \text{constant}] \quad \textbf{(2–12d)}$$

Kinematic equations for constant acceleration (we'll use them a lot)

These useful equations are not valid unless a is a constant. In many cases we can set $x_0 = 0$, and this simplifies the above equations a bit. Note that x represents position (not distance), and that $x - x_0$ is the displacement, whereas t is the elapsed time.

Equations 2–12 are useful also when a is approximately constant, in order to obtain reasonable estimates.

PHYSICS APPLIED
Airport design

EXAMPLE 2–10 Runway design. You are designing an airport for small planes. One kind of airplane that might use this airfield must reach a speed before takeoff of at least 27.8 m/s (100 km/h), and can accelerate at $2.00\ \text{m/s}^2$. (*a*) If the runway is 150 m long, can this airplane reach the required speed for takeoff? (*b*) If not, what minimum length must the runway have?

APPROACH Assuming the plane's acceleration is constant, we use the kinematic equations for constant acceleration. In (*a*), we want to find v, and we are given:

Known	Wanted
$x_0 = 0$	v
$v_0 = 0$	
$x = 150\ \text{m}$	
$a = 2.00\ \text{m/s}^2$	

SOLUTION (*a*) Of the four kinematic equations on page 31, Eq. 2–12c will give us v when we know v_0, a, x, and x_0:

PROBLEM SOLVING
Equations 2–12 are valid only when the acceleration is constant, which we assume in this Example

$$\begin{aligned} v^2 &= v_0^2 + 2a(x - x_0) \\ &= 0 + 2(2.00\ \text{m/s}^2)(150\ \text{m}) = 600\ \text{m}^2/\text{s}^2 \\ v &= \sqrt{600\ \text{m}^2/\text{s}^2} = 24.5\ \text{m/s}. \end{aligned}$$

This runway length is *not* sufficient, because the minimum speed is not reached.
(*b*) Now we want to find the minimum runway length, $x - x_0$, for a plane to reach $v = 27.8\ \text{m/s}$, given $a = 2.00\ \text{m/s}^2$. We again use Eq. 2–12c, but rewritten as

$$(x - x_0) = \frac{v^2 - v_0^2}{2a} = \frac{(27.8\ \text{m/s})^2 - 0}{2(2.00\ \text{m/s}^2)} = 193\ \text{m}.$$

A 200-m runway is more appropriate for this plane.

NOTE We did this Example as if the plane were a particle, so we round off our answer to 200 m.

PHYSICS APPLIED
Car safety—air bags

EXAMPLE 2–11 ESTIMATE Air bags. Suppose you want to design an air bag system that can protect the driver at a speed of 100 km/h (60 mph) if the car hits a brick wall. Estimate how fast the air bag must inflate (Fig. 2–20) to effectively protect the driver. How does the use of a seat belt help the driver?

FIGURE 2–20 Example 2–11. An air bag deploying on impact.

APPROACH We assume the acceleration is roughly constant, so we can use Eqs. 2–12. Both Eqs. 2–12a and 2–12b contain t, our desired unknown. They both contain a, so we must first find a, which we can do using Eq. 2–12c if we know the distance x over which the car crumples. A rough estimate might be about 1 meter. We choose the time interval to start at the instant of impact with the car moving at $v_0 = 100\ \text{km/h}$, and to end when the car comes to rest ($v = 0$) after traveling 1 m.

SOLUTION We convert the given initial speed to SI units: $100\ \text{km/h} = 100 \times 10^3\ \text{m}/3600\ \text{s} = 28\ \text{m/s}$. We then find the acceleration from Eq. 2–12c:

$$a = -\frac{v_0^2}{2x} = -\frac{(28\ \text{m/s})^2}{2.0\ \text{m}} = -390\ \text{m/s}^2.$$

This enormous acceleration takes place in a time given by (Eq. 2–12a):

$$t = \frac{v - v_0}{a} = \frac{0 - 28\ \text{m/s}}{-390\ \text{m/s}^2} = 0.07\ \text{s}.$$

To be effective, the air bag would need to inflate faster than this.

What does the air bag do? It spreads the force over a large area of the chest (to avoid puncture of the chest by the steering wheel). The seat belt keeps the person in a stable position directly in front of the expanding air bag.