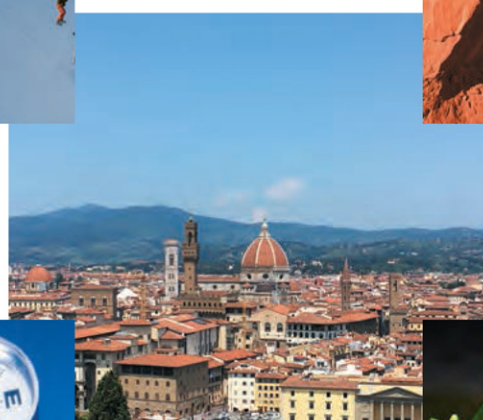
5th EDITION

PHYSICS

for SCIENTISTS and ENGINEERS



DOUGLAS

GIANCOLI

5th EDITION

PHYSICS

for SCIENTISTS and ENGINEERS

DOUGLAS GIANCOLI

Pearson

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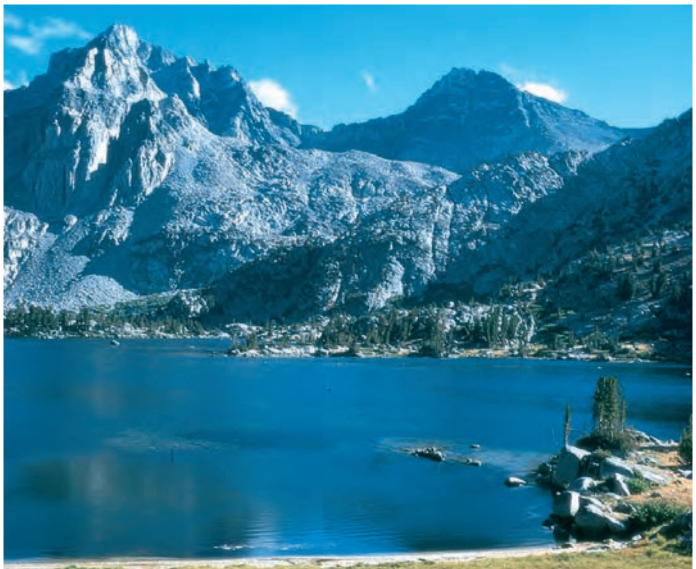
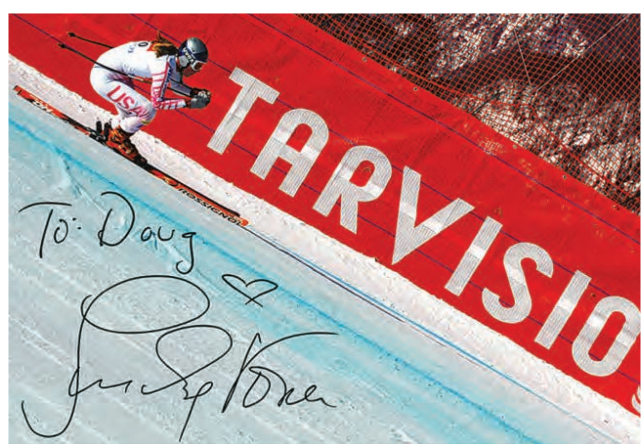
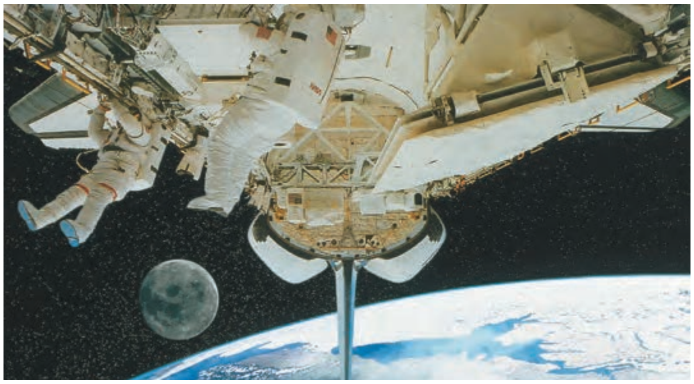
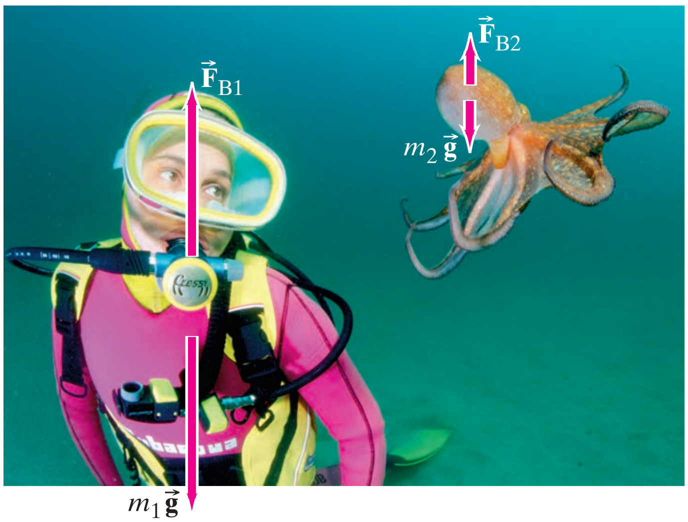


Estimate how much this lake weighs.







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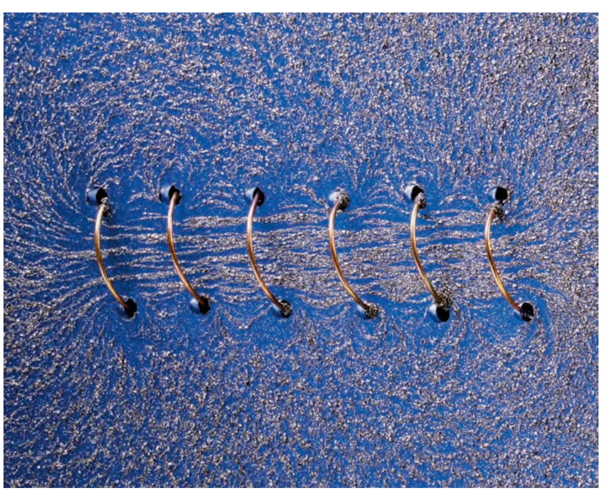

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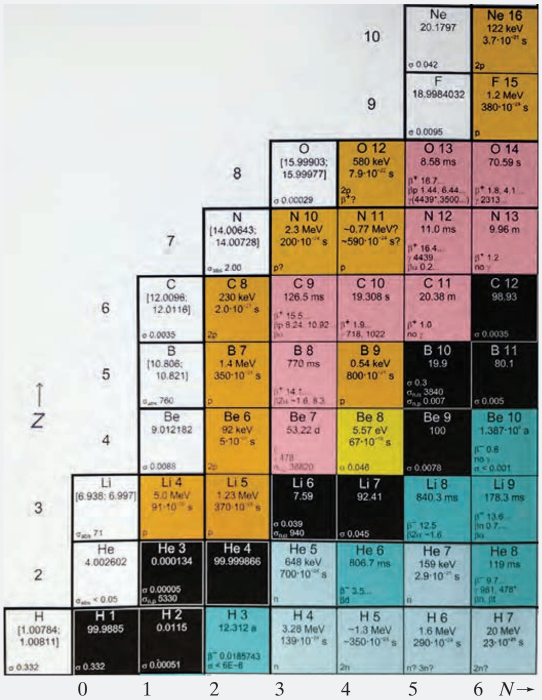
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Applications (Selected) to Medicine and Biology and to Engineering, Environment, Everyday Life, Etc.

(Entries with a star * include material new to this edition)

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

Many physics professors provided input or direct feedback on every aspect of this textbook. They are listed below, and I owe each a debt of gratitude.

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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.

D.G.

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About the Author

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 — 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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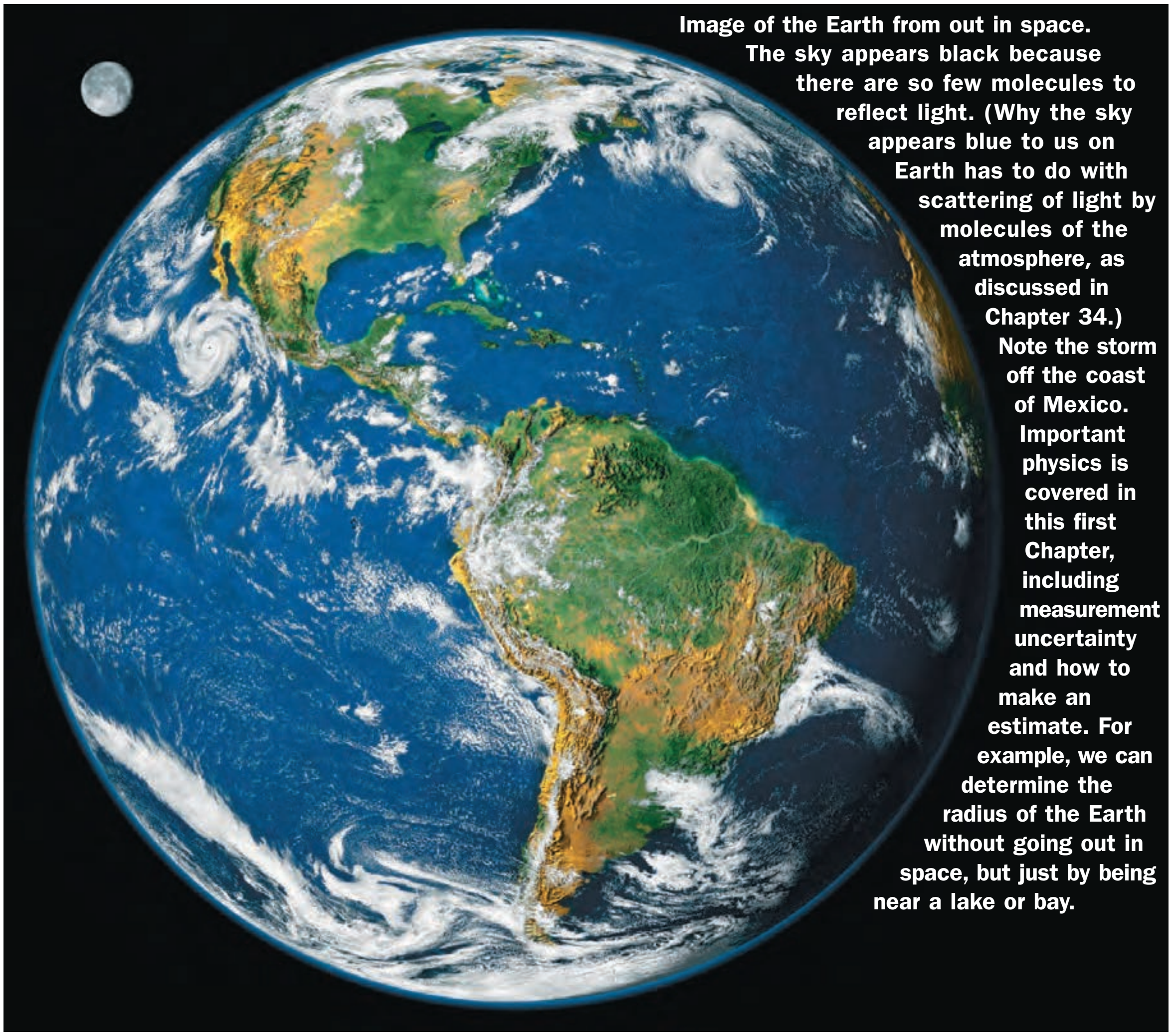


Image of the Earth from out in space. The sky appears black because there are so few molecules to reflect light. (Why the sky appears blue to us on Earth has to do with scattering of light by molecules of the atmosphere, as discussed in Chapter 34.) Note the storm off the coast of Mexico. Important physics is covered in this first Chapter, including measurement uncertainty and how to make an estimate. For example, we can determine the radius of the Earth without going out in space, but just by being near a lake or bay.

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.

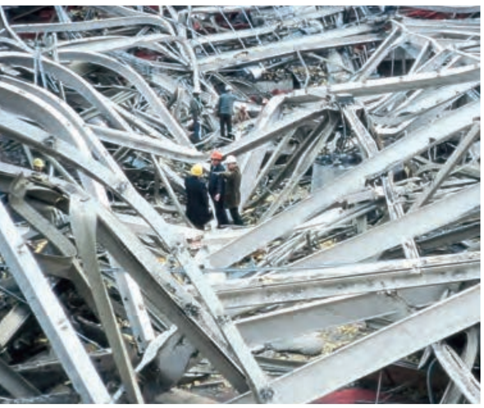
2. Suppose you wanted to actually measure the radius of the Earth, at least roughly, rather than taking other people's word for what it is. Which response below describes the best approach?

(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

(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.

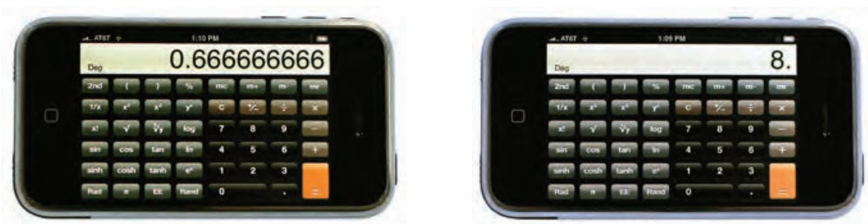
PROBLEM SOLVING
Significant figures when adding and subtracting

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)

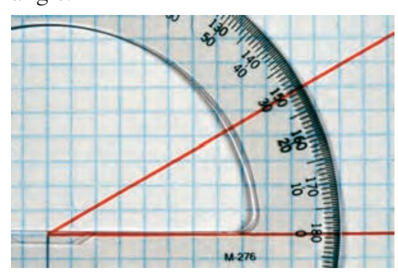
FIGURE 1–3 These two calculators show the wrong number of significant figures. In (a), 2.0 was divided by 3.0. The correct final result should be stated as 0.67. In (b), 2.5 was multiplied by 3.2. The correct result is 8.0.

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

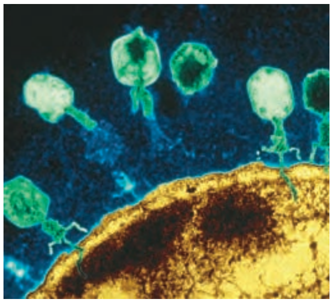
The first truly international standard was the **meter** (abbreviated m) established as the standard of **length** by the French Academy of Sciences in the 1790s. The standard meter was originally chosen to be one ten-millionth of the distance from the Earth's equator to either pole,† and a platinum 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.

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.]

New definition of the meter

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 $(24\ \text{h/day} \times 60\ \text{min/h} \times 60\ \text{s/min} = 86{,}400\ \text{s/day})$. 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**.

Systems of Units

PROBLEM SOLVING

Always use a consistent set 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, $0.304800\cdots$.) 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