

SEVENTH EDITION

VOLUME I

# PHYSICS



DOUGLAS C.

GIANCOLI

SEVENTH EDITION

# PHYSICS

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PRINCIPLES WITH APPLICATIONS

DOUGLAS C. GIANCOLI

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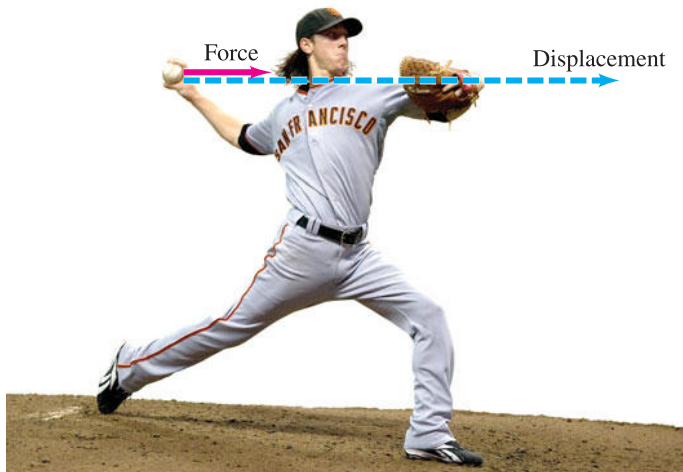
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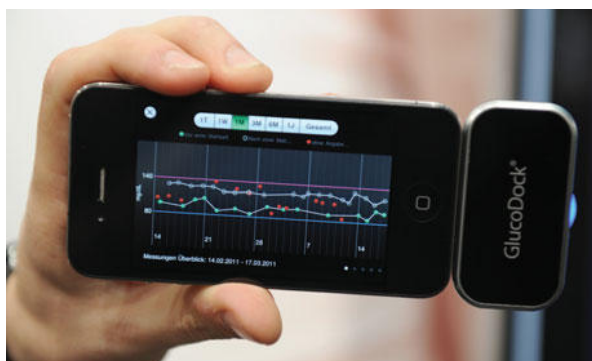
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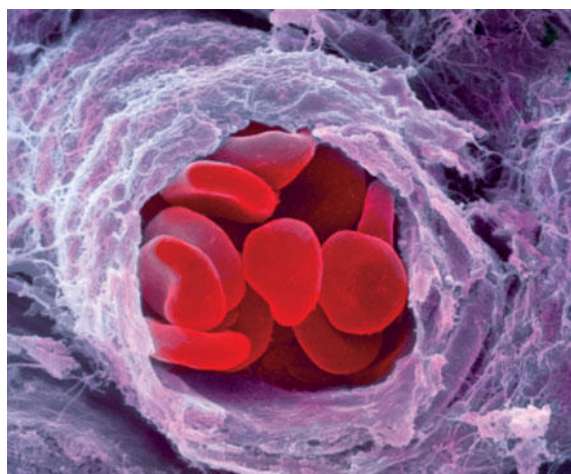
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## Student Supplements

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# Preface

## What's New?

Lots! Much is new and unseen before. Here are the big four:

1. **Multiple-choice Questions** added to the end of each Chapter. They are not the usual type. These are called **MisConceptual Questions** because the responses (*a, b, c, d*, etc.) are intended to include common student misconceptions. Thus they are as much, or more, a learning experience than simply a testing experience.
2. **Search and Learn Problems** at the very end of each Chapter, after the other Problems. Some are pretty hard, others are fairly easy. They are intended to encourage students to go back and reread some part or parts of the text, and in this search for an answer they will hopefully learn more—if only because they have to read some material again.
3. **Chapter-Opening Questions (COQ)** that start each Chapter, a sort of “stimulant.” Each is multiple choice, with responses including common misconceptions—to get preconceived notions out on the table right at the start. Where the relevant material is covered in the text, students find an Exercise asking them to return to the COQ to rethink and answer again.
4. **Digital.** Biggest of all. Crucial new applications. Today we are surrounded by digital electronics. How does it work? If you try to find out, say on the Internet, you won't find much physics: you may find shallow hand-waving with no real content, or some heavy jargon whose basis might take months or years to understand. So, for the first time, I have tried to explain
  - The basis of digital in bits and bytes, how analog gets transformed into digital, sampling rate, bit depth, quantization error, compression, noise (Section 17–10).
  - How digital TV works, including how each pixel is addressed for each frame, data stream, refresh rate (Section 17–11).
  - Semiconductor computer memory, DRAM, and flash (Section 21–8).
  - Digital cameras and sensors—revised and expanded Section 25–1.
  - New semiconductor physics, some of which is used in digital devices, including LED and OLED—how they work and what their uses are—plus more on transistors (MOSFET), chips, and technology generation as in 22-nm technology (Sections 29–9, 10, 11).

Besides those above, this new seventh edition includes

5. ***New topics, new applications, principal revisions.***
  - You can measure the Earth's radius (Section 1–7).
  - Improved graphical analysis of linear motion (Section 2–8).
  - Planets (how first seen), heliocentric, geocentric (Section 5–8).
  - The Moon's orbit around the Earth: its phases and periods with diagram (Section 5–9).
  - Explanation of lake level change when large rock thrown from boat (Example 10–11).

- Biology and medicine, including:
    - Blood measurements (flow, sugar)—Chapters 10, 12, 14, 19, 20, 21;
    - Trees help offset CO<sub>2</sub> buildup—Chapter 15;
    - Pulse oximeter—Chapter 29;
    - Proton therapy—Chapter 31;
    - Radon exposure calculation—Chapter 31;
    - Cell phone use and brain—Chapter 31.
  - Colors as seen underwater (Section 24–4).
  - Soap film sequence of colors explained (Section 24–8).
  - Solar sails (Section 22–6).
  - Lots on sports.
  - Symmetry—more emphasis and using italics or boldface to make visible.
  - Flat screens (Sections 17–11, 24–11).
  - Free-electron theory of metals, Fermi gas, Fermi level. New Section 29–6.
  - Semiconductor devices—new details on diodes, LEDs, OLEDs, solar cells, compound semiconductors, diode lasers, MOSFET transistors, chips, 22-nm technology (Sections 29–9, 10, 11).
  - Cross section (Chapter 31).
  - Length of an object is a script  $\ell$  rather than normal  $l$ , which looks like 1 or  $I$  (moment of inertia, current), as in  $F = I\ell B$ . Capital  $L$  is for angular momentum, latent heat, inductance, dimensions of length [ $L$ ].
6. **New photographs** taken by students and instructors (we asked).
  7. **Page layout:** More than in previous editions, serious attention to how each page is formatted. Important derivations and Examples are on facing pages: no turning a page back in the middle of a derivation or Example. Throughout, readers see, on two facing pages, an important slice of physics.
  8. **Greater clarity:** No topic, no paragraph in this book was overlooked in the search to improve the clarity and conciseness of the presentation. Phrases and sentences that may slow down the principal argument have been eliminated: keep to the essentials at first, give the elaborations later.
  9. Much use has been made of physics education research. See the new powerful pedagogic features listed first.
  10. **Examples modified:** More math steps are spelled out, and many new Examples added. About 10% of all Examples are Estimation Examples.
  11. **This Book is Shorter** than other complete full-service books at this level. Shorter explanations are easier to understand and more likely to be read.
  12. **Cosmological Revolution:** With generous help from top experts in the field, readers have the latest results.

## See the World through Eyes that Know Physics

I was motivated from the beginning to write a textbook different from the others which present physics as a sequence of facts, like a catalog: “Here are the facts and you better learn them.” Instead of beginning formally and dogmatically, I have sought to begin each topic with concrete observations and experiences students can relate to: start with specifics, and after go to the great generalizations and the more formal aspects of a topic, showing *why* we believe what we believe. This approach reflects how science is actually practiced.

The ultimate aim is to give students a thorough understanding of the basic concepts of physics in all its aspects, from mechanics to modern physics. A second objective 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, architecture, and more.

Also, much effort has gone into techniques and approaches for solving problems: worked-out Examples, Problem Solving sections (Sections 2–6, 3–6, 4–7, 4–8, 6–7, 6–9, 8–6, 9–2, 13–7, 14–4, and 16–6), and Problem Solving Strategies (pages 30, 57, 60, 88, 115, 141, 158, 184, 211, 234, 399, 436, 456, 534, 568, 594, 655, 666, and 697).

This textbook is especially suited for students taking a one-year introductory course in physics that uses algebra and trigonometry but not calculus.<sup>†</sup> Many of these students are majoring in biology or premed, as well as architecture, technology, and the earth and environmental sciences. Many applications to these fields are intended to answer that common student query: “Why must I study physics?” The answer is that physics is fundamental to a full understanding of these fields, and here they can see how. Physics is everywhere around us in the everyday world. It is the goal of this book to help students “see the world through eyes that know physics.”

A major effort has been made to not throw too much material at students reading the first few chapters. The basics have to be learned first. Many aspects can come later, when students are less overloaded and more prepared. If we don’t overwhelm students with too much detail, especially at the start, maybe they can find physics interesting, fun, and helpful—and those who were afraid may lose their fear.

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. Converting units and being able to make rapid *estimates* are also basic.

*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 trigonometry, are incorporated in the text where first needed, so they come with a context rather than in a scary introductory Chapter. Appendices contain a review of algebra and geometry (plus a few advanced topics).

*Color* is used pedagogically to bring out the physics. Different types of vectors are given different colors (see the chart on page xix).

Sections marked with a star \* are considered optional. These contain slightly more advanced physics material, or material not usually covered in typical courses and/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 1, 10, 12, 22, 28, 29, 32, and selected parts of Chapters 7, 8, 9, 15, 21, 24, 25, 31. Topics not covered in class can be a valuable resource for later study by students. Indeed, this text can serve as a useful reference for years because of its wide range of coverage.

<sup>†</sup>It is fine to take a calculus course. But mixing calculus with physics for these students may often mean not learning the physics because of stumbling over the calculus.



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Douglas C. 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 and Donald Glaser.

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

Doug's favorite spare-time activity is the outdoors, especially climbing peaks. He says climbing peaks is like learning physics: it takes effort and the rewards are great.



## To Students

### HOW TO STUDY

1. Read the Chapter. Learn new vocabulary and notation. Try to respond to questions and exercises as they occur.
2. Attend all class meetings. Listen. Take notes, especially about aspects you do not remember seeing in the book. 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 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 (\*) are considered **optional**. 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:  $\vec{F}$ .
3. Few equations are valid in all situations. Where practical, the **limitations** 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**. 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. **Search and Learn Problems** at the end are meant to encourage you to return to parts of the text to find needed detail, and at the same time help you to learn.
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 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 1–7); (c) **Problem Solving Strategies** placed throughout the text to suggest a step-by-step approach to problem solving for a particular topic—but remember that 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 (point 4 above).
6. **Conceptual Examples** pose a question which hopefully starts you to think and come up with 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 ( $\vec{D}$ , $\vec{r}$ )     |  |
| Velocity ( $\vec{v}$ )                     |  |
| Acceleration ( $\vec{a}$ )                 |  |
| Force ( $\vec{F}$ )                        |  |
| Force on second object                     |  |
| or third object in same figure             |  |
| Momentum ( $\vec{p}$ or $m\vec{v}$ )       |  |
| Angular momentum ( $\vec{L}$ )             |  |
| Angular velocity ( $\vec{\omega}$ )        |  |
| Torque ( $\vec{\tau}$ )                    |  |
| Electric field ( $\vec{E}$ )               |  |
| Magnetic field ( $\vec{B}$ )               |  |

### 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<br>(dashed)              |  |
| Virtual image<br>(dashed and paler) |  |

### Other

|                                   |  |
|-----------------------------------|--|
| Energy level<br>(atom, etc.)      |  |
| Measurement lines                 |  |
| Path of a moving<br>object        |  |
| Direction of motion<br>or current |  |



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Image of the Earth from a NASA satellite. The sky appears black from out in space 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 24.) Note the storm off the coast of Mexico.

CHAPTER  
**1**

# Introduction, Measurement, Estimating

## CHAPTER-OPENING QUESTIONS—Guess now!

1. How many  $\text{cm}^3$  are in  $1.0 \text{ m}^3$ ?  
(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 step ladder, 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 usually get another chance at the Question(s) 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 The Nature of Science
- 1-2 Physics and its Relation to Other Fields
- 1-3 Models, Theories, and Laws
- 1-4 Measurement and Uncertainty; Significant Figures
- 1-5 Units, Standards, and the SI System
- 1-6 Converting Units
- 1-7 Order of Magnitude: Rapid Estimating
- \*1-8 Dimensions and Dimensional Analysis

**P**hysics 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, quantum theory, 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 fundamental particles and the cosmos. But before we begin on the physics itself, we take a brief look at how this overall activity called “science,” including physics, is actually practiced.

## 1-1 The Nature of Science

The principal aim of all sciences, including physics, is generally considered to be the search for order in our observations of the world around us. Many people think that science is a mechanical process of collecting facts and devising theories. But it is not so simple. Science is a creative activity that in many respects resembles other creative activities of the human mind.

One important aspect of science is **observation** of events, which includes the design and carrying out of experiments. But observation and experiments require imagination, because scientists can never include everything in a description of what they observe. Hence, 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.; Fig. 1-1) and Galileo (1564–1642; Fig. 2-18), interpreted motion along a horizontal surface. Aristotle noted that objects given an initial push along the ground (or on a tabletop) always slow down and stop. Consequently, Aristotle argued, the natural state of an object is to be at rest. Galileo, the first true experimentalist, reexamined horizontal motion in the 1600s. 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 way of thinking about the same data, 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.

**FIGURE 1-1** Aristotle is the central figure (dressed in blue) at the top of the stairs (the figure next to him is Plato) in this famous Renaissance portrayal of *The School of Athens*, painted by Raphael around 1510. Also in this painting, considered one of the great masterpieces in art, are Euclid (drawing a circle at the lower right), Ptolemy (extreme right with globe), Pythagoras, Socrates, and Diogenes.





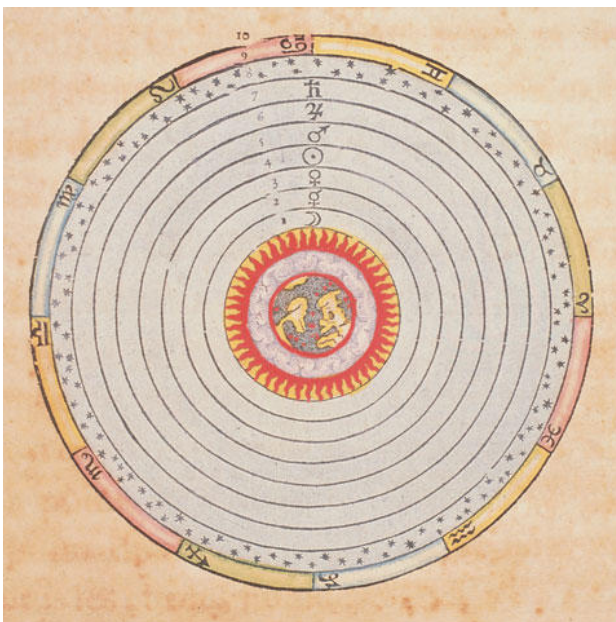
Observation, with careful experimentation and measurement, is one side of the scientific process. The other side is the invention or creation of **theories** to explain and order the observations. Theories are never derived directly from observations. Observations may help inspire a theory, and theories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

Theories are inspirations that come from the minds of human beings. For example, the idea that matter is made up of atoms (the atomic theory) was not arrived at by direct observation of atoms—we can't see atoms directly. 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.

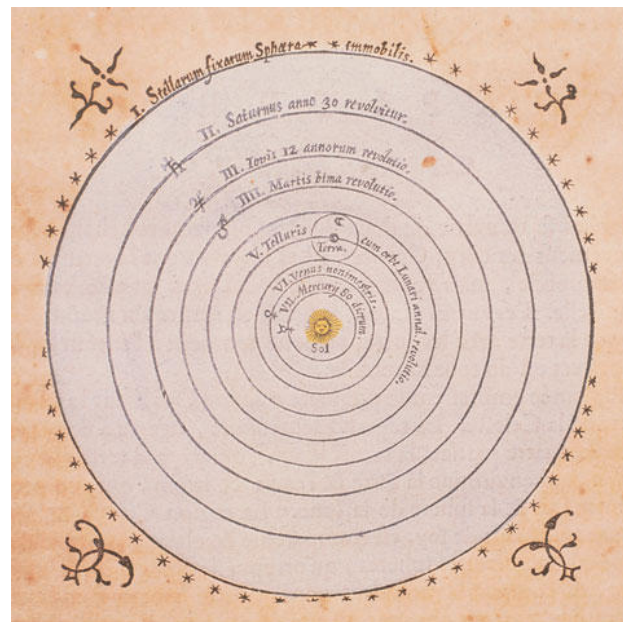
The great theories of science may be compared, as creative achievements, with great works of art or literature. But how does science differ from these other creative activities? One important difference is that science requires **testing** of its ideas or theories to see if their predictions are borne 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 for every possible set of circumstances. Hence a theory cannot be absolutely verified. Indeed, the history of science tells us that long-held theories can sometimes be replaced by new ones, particularly when new experimental techniques provide new or contradictory data.

A new theory is accepted by scientists in some cases because its predictions are quantitatively in better agreement with experiment than those of the older theory. But in many cases, a new theory is accepted only if it explains a greater *range* of phenomena than does the older one. Copernicus's Sun-centered theory of the universe (Fig. 1–2b), for example, was originally no more accurate than Ptolemy's Earth-centered theory (Fig. 1–2a) for predicting the motion of heavenly bodies (Sun, Moon, planets). But Copernicus's theory had consequences that Ptolemy's did not, such as predicting the moonlike phases of Venus. A simpler and richer theory, one which unifies and explains a greater variety of phenomena, is more useful and beautiful to a scientist. And this aspect, as well as quantitative agreement, plays a major role in the acceptance of a theory.

**FIGURE 1–2** (a) Ptolemy's geocentric view of the universe. Note at the center the four elements of the ancients: Earth, water, air (clouds around the Earth), and fire; then the circles, with symbols, for the Moon, Mercury, Venus, Sun, Mars, Jupiter, Saturn, the fixed stars, and the signs of the zodiac. (b) An early representation of Copernicus's heliocentric view of the universe with the Sun at the center. (See Chapter 5.)



(a)



(b)



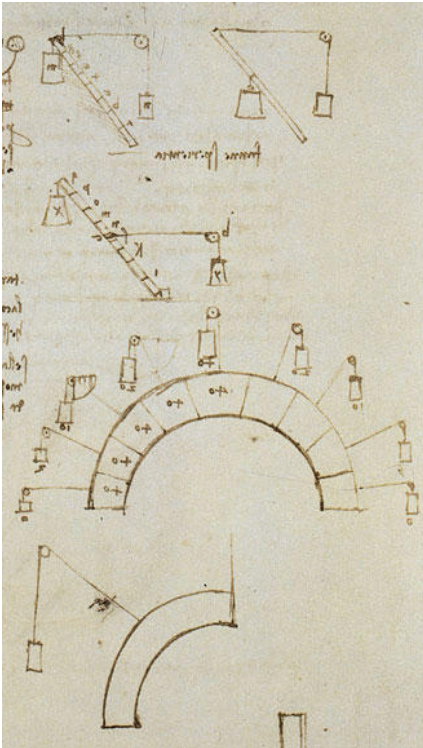
An important aspect of any theory is how well it can quantitatively predict phenomena, and from this point of view a new theory may often seem to be only a minor advance over the old one. For example, Einstein's theory of relativity gives predictions that differ very little from the older theories of Galileo and Newton in nearly all everyday situations. Its predictions are better mainly in the extreme case of very high speeds close to the speed of light. But quantitative prediction is not the only important outcome of a theory. Our view of the world is affected as well. As a result of Einstein's theory of relativity, for example, our concepts of space and time have been completely altered, and we have come to see mass and energy as a single entity (via the famous equation  $E = mc^2$ ).

## 1-2 Physics and its Relation to Other Fields

For a long time science was more or less a united whole known as natural philosophy. Not until a century or two ago did the distinctions between physics and chemistry and even the life sciences become prominent. Indeed, the sharp distinction we now see between the arts and the sciences is itself only a few centuries old. It is no wonder then that the development of physics has both influenced and been influenced by other fields. For example, the notebooks (Fig. 1-3) of Leonardo da Vinci, the great Renaissance artist, researcher, and engineer, contain the first references to the forces acting within a structure, a subject we consider as physics today; but then, as now, it has great relevance to architecture and building.

Early work in electricity that led to the discovery of the electric battery and electric current was done by an eighteenth-century physiologist, Luigi Galvani (1737–1798). He noticed the twitching of frogs' legs in response to an electric spark and later that the muscles twitched when in contact with two dissimilar metals (Chapter 18). At first this phenomenon was known as “animal electricity,” but it shortly became clear that electric current itself could exist in the absence of an animal.

Physics is used in many fields. A zoologist, for example, may find physics useful in understanding how prairie dogs and other animals can live underground without suffocating. A physical therapist will be more effective if aware of the principles of center of gravity and the action of forces within the human body. A knowledge of the operating principles of optical and electronic equipment is helpful in a variety of fields. Life scientists and architects alike will be interested in the nature of heat loss and gain in human beings and the resulting comfort or discomfort. Architects may have to calculate the dimensions of the pipes in a heating system or the forces involved in a given structure to determine if it will remain standing (Fig. 1-4). They must know physics principles in order to make realistic designs and to communicate effectively with engineering consultants and other specialists.



**FIGURE 1-3** Studies on the forces in structures by Leonardo da Vinci (1452–1519).

**FIGURE 1-4** (a) This bridge over the River Tiber in Rome was built 2000 years ago and still stands. (b) The 2007 collapse of a Mississippi River highway bridge built only 40 years before.



(a)



(b)

From the aesthetic or psychological point of view, too, architects must be aware of the forces involved in a structure—for example instability, even if only illusory, can be discomfiting to those who must live or work in the structure.

The list of ways in which physics relates to other fields is extensive. In the Chapters that follow we will discuss many such applications as we carry out our principal aim of explaining basic physics.

## 1–3 Models, Theories, and Laws

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When scientists are trying to understand a particular set of phenomena, they often make use of a **model**. A model, in the scientific sense, is a kind of analogy or mental image of the phenomena in terms of something else we are already 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. Models often give us a deeper understanding: the analogy to a known system (for instance, the water waves above) 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, however, not to confuse a model or a theory with the real system or the phenomena themselves.

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

Statements that we call laws are usually 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” for a more general picture of the phenomena dealt with.

Scientific laws are different from political laws in that the latter 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 cases, 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.

## 1–4 Measurement and Uncertainty; Significant Figures

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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.



**FIGURE 1–5** Measuring the width of a board with a centimeter ruler. Accuracy is about  $\pm 1$  mm.

Among the most important sources of uncertainty, other than blunders, are the limited accuracy of every measuring instrument and the inability to read an instrument 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. 1–5), 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  $8.8 \pm 0.1$  cm. The  $\pm 0.1$  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 cm 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, the

**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 8.8 cm, the uncertainty is assumed to be about 0.1 cm or 0.2 cm. It is important in this case that you do not write 8.80 cm, because this implies an uncertainty on the order of 0.01 cm; it assumes that the length is probably between 8.79 cm and 8.81 cm, when actually you believe it is between 8.7 and 8.9 cm.

**CONCEPTUAL EXAMPLE 1–1** **Is the diamond yours?** A friend asks to borrow your precious diamond for a day to show her family. You are a bit worried, so you carefully have your diamond weighed on a scale which reads 8.17 grams. The scale’s accuracy is claimed to be  $\pm 0.05$  gram. The next day you weigh the returned diamond again, getting 8.09 grams. Is this your diamond?

**RESPONSE** The scale readings are measurements and are not perfect. They do not necessarily give the “true” value of the mass. Each measurement could have been high or low by up to 0.05 gram or so. The actual mass of your diamond lies most likely between 8.12 grams and 8.22 grams. The actual mass of the returned diamond is most likely between 8.04 grams and 8.14 grams. These two ranges overlap, so the data do not give you a strong reason to doubt that the returned diamond is yours.

### 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 is 80 km within an accuracy of about 1 or 2 km, and then the 80 has two significant figures. If it is precisely 80 km, to within  $\pm 0.1$  km, then we write 80.0 km (three significant figures).



When making measurements, or when doing calculations, you should avoid the temptation to keep more digits in the final answer than is justified: see boldface statement on previous page. For example, to calculate the area of a rectangle 11.3 cm by 6.8 cm, the result of multiplication would be  $76.84 \text{ cm}^2$ . But this answer can not be accurate to the implied  $0.01 \text{ cm}^2$  uncertainty, 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  $77 \text{ cm}^2$ , which implies an uncertainty of about 1 or  $2 \text{ cm}^2$ . The other two digits (in the number  $76.84 \text{ cm}^2$ ) must be dropped (rounded off) because they are not significant. As a rough general rule we can say that

*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  $76.84 \text{ cm}^2$  needs to be rounded off to  $77 \text{ cm}^2$ .

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

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.

**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. 1–6a). 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.) Note also that calculators sometimes give too few significant figures. For example, when you multiply  $2.5 \times 3.2$ , a calculator may give the answer as simply 8. But the answer is accurate to two significant figures, so the proper answer is 8.0. See Fig. 1–6b.

**CONCEPTUAL EXAMPLE 1–2 Significant figures.** Using a protractor (Fig. 1–7), you measure an angle to be  $30^\circ$ . (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  $0.1^\circ$ ). So you can quote two significant figures, namely  $30^\circ$  (not  $30.0^\circ$ ). (b) If you enter  $\cos 30^\circ$  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 Chapter 3 and Appendix A.

## Scientific Notation

We commonly write numbers in “powers of ten,” or “scientific” notation—for instance 36,900 as  $3.69 \times 10^4$ , or 0.0021 as  $2.1 \times 10^{-3}$ . One advantage of scientific notation (reviewed in Appendix A) 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 10 notation the ambiguity can be avoided: if the number is known to three significant figures, we write  $3.69 \times 10^4$ , but if it is known to four, we write  $3.690 \times 10^4$ .

**EXERCISE C** 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.



(a)

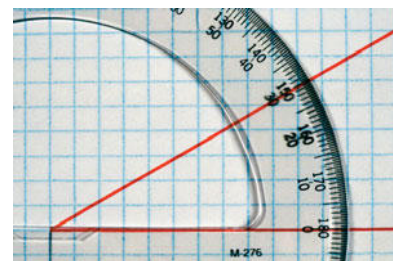


(b)

**FIGURE 1–6** These two calculations show the wrong number of significant figures. In (a), 2.0 was divided by 3.0. The correct final result would be 0.67. In (b), 2.5 was multiplied by 3.2. The correct result is 8.0.

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

**FIGURE 1–7** Example 1–2. A protractor used to measure an angle.





### \* Percent Uncertainty vs. 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  $\pm 1$  if no other uncertainty is stated. Both  $92 \pm 1$  and  $97 \pm 1$  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  $\pm 0.1$ , which is an uncertainty of about 10% ( $0.1/1.1 \approx 0.1 \approx 10\%$ ). It is better in this case to give the answer as 1.05 (which is three significant figures). Why? Because 1.05 implies an uncertainty of  $\pm 0.01$  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 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 vs. 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. 1–5 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  $\pm 0.2$  cm. Estimated uncertainty is meant to take both accuracy and precision into account.

## 1–5 Units, Standards, and the SI System

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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 with other people.

## 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,<sup>†</sup> 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 even 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.”<sup>‡</sup>

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). Other conversion factors are given in the Table on the inside of the front cover of this book. Table 1–1 presents some typical lengths, from very small to very large, rounded off to the nearest power of 10. See also Fig. 1–8. [Note that the abbreviation for inches (in.) is the only one with a period, to distinguish it from the word “in”.]

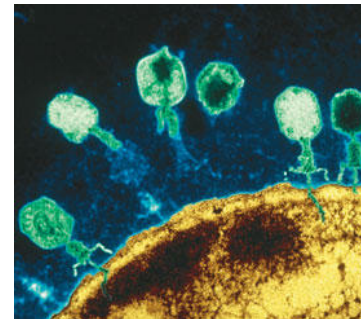
## Time

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 is now 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 defined as the time required for 9,192,631,770 oscillations of this radiation.] There are, by definition, 60 s in one minute (min) and 60 minutes in one hour (h). Table 1–2 presents a range of measured time intervals, rounded off to the nearest power of 10.

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

<sup>‡</sup>The new definition of the meter has the effect of giving the speed of light the exact value of 299,792,458 m/s.

**FIGURE 1–8** 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 above sea level, to be precise).



(a)



(b)

**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. 1–8a]                 | $10^{-7}$ 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. 1–8b] | $10^4$ 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                                     | $3 \times 10^7$ s           |
| Human life span                              | $2 \times 10^9$ s           |
| Length of recorded history                   | $10^{11}$ s                 |
| Humans on Earth                              | $10^{13}$ s                 |
| Age of Earth                                 | $10^{17}$ s                 |
| Age of Universe                              | $4 \times 10^{17}$ s        |