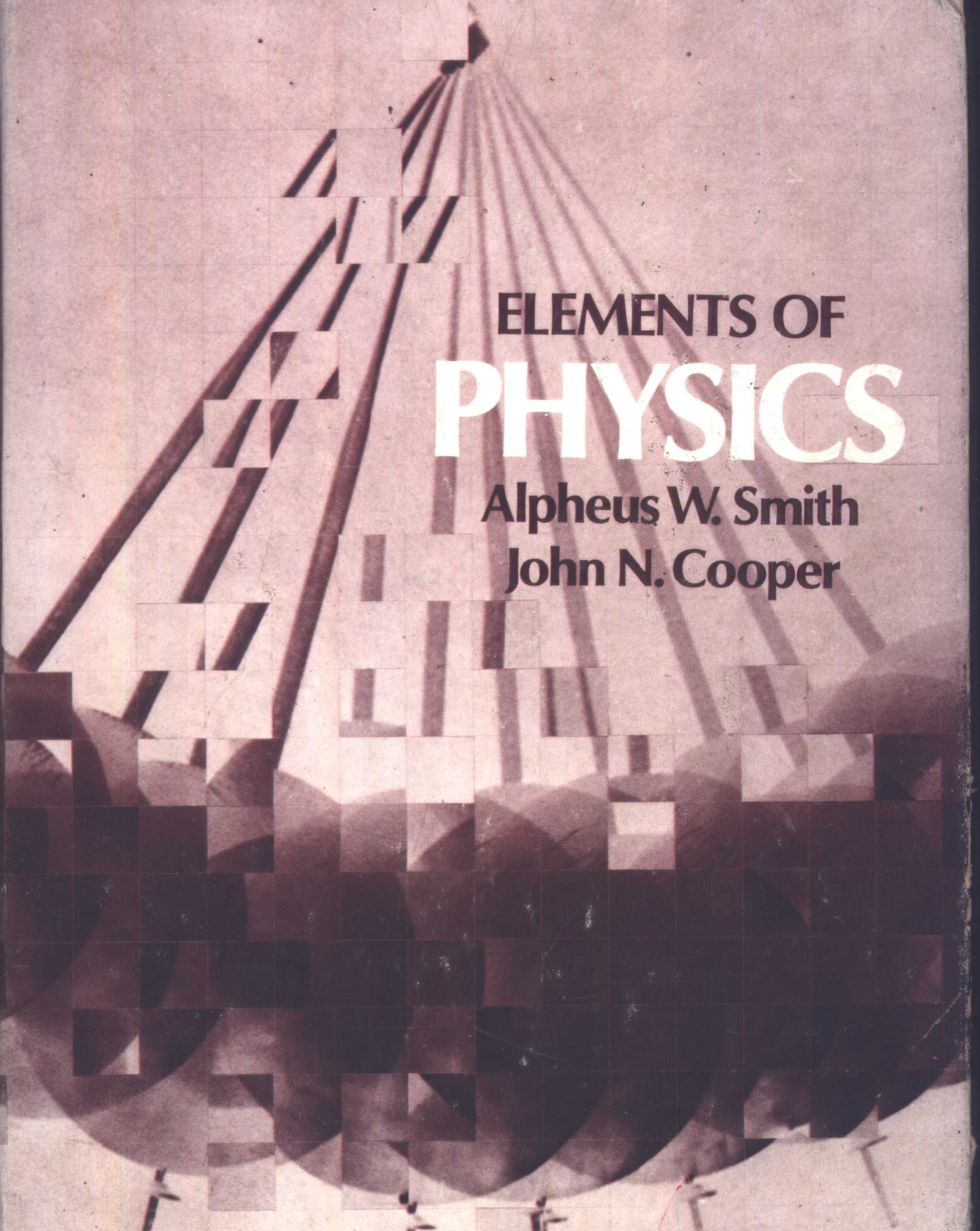

ELEMENTS OF
PHYSICS

Alpheus W. Smith
John N. Cooper

Library of Congress Cataloging in Publication Data

Smith, Alpheus Wilson, dates
Elements of physics.

Includes index.
1. Physics. I. Cooper, John N., joint author.
II. Title.
QC23.S65 1979 530 78-17919
ISBN 0-07-058634-9

ELEMENTS OF PHYSICS

234567890 DODO 78321098

This book was set in Optima with Times Roman Italic by York Graphic Services, Inc.
The editors were C. Robert Zappa and Laura D. Warner;
the designer was Elliot Epstein; the production supervisor was Dennis J. Conroy.
New drawings were done by York Graphic Services, Inc.
R. R. Donnelley & Sons Company was printer and binder.

PREFACE

Every student who enters a college or university knows a substantial amount of physics and has a broad familiarity with many physical phenomena. Some knowledge of physics is a necessity for every person who leads a normal existence. For many the information is purely qualitative and often haphazard as well. In a physics text this knowledge is organized and made quantitative. Relationships between physical observables are stated in the form of mathematical equations. Since this particular book is written for students who have not studied calculus, the equations are algebraic. The treatment of physical laws and their applications has been handled as quantitatively and rigorously as the mathematical sophistication of the prospective student permits. While there are certain situations which can be treated better by use of calculus, there are others in which careful physical reasoning can give a more penetrating understanding of a resulting equation than does the routine application of calculus. A few formulas involve definitions from trigonometry, but there is no need for a prior course because all the required relationships are developed in the text.

偶然的

予期的

常规的

The role of physics in modern life continues to expand. Since the publication of the eighth edition of *Elements of Physics* in 1972, hand-held calculators have become more numerous than slide rules in the classroom, computers have proliferated for process control and the handling of information, and the uses of laser beams have increased steadily. Innumerable other applications of physics have been made in communications, in transportation, and in industry. A knowledge of the principles of physics is increasingly imperative if one wishes to keep abreast of what is happening in the broad technological segment of human activity. It is the purpose of this book to introduce the student to the fundamental laws of physics and to give some feeling of their power and beauty. Toward this end, a wealth of applications and examples is introduced, with particular attention to the physics of everyday experience. It is our belief that an understanding of physical phenomena adds a new dimension to the beauty of the rainbow and an enriched appreciation of such scientific advances as those which permit us to view in full color events taking place thousands of kilometers away.

计算尺 滋长

绝对必要的 与—并进

The classic organization of physics into parts on mechanics, heat, sound, light, electricity and magnetism, and modern physics has been retained in this edition, but considerable rearrangement has taken place within the major divisions. In particular, the statics of a rigid body has been placed after kinematics and dynamics; teachers who prefer to discuss statics early can schedule Chapter 10 immediately after Chapter 3 and thus obtain the topic order of previous editions. There is ample material in this text for three full semesters of study. The classical physics sections alone require a full academic year for thorough coverage. For a two-semester course which includes considerable modern physics, it is possible to omit many selected chapters without seriously neglecting the background knowledge required for most subsequent chapters. Among the topics which are sometimes omitted are rotational motion, fluids, elastic properties of matter, sound, atmospheric physics, spectra and color, chemical and thermal electromotive forces, generators and motors, and alternating currents.

The Système International d'Unités (SI) has primacy everywhere in the book, but both English and cgs units are introduced because they are still in wide use. Throughout its 55 years of existence *Elements of Physics* has emphasized the physics of everyday life, and that dictates the need to relate the units in the newspaper and older scientific literature to the new international units. Of course, our practical units in electricity are a part of the international system toward which the entire world is moving.

In 1978 the United States is the only large country which is not firmly committed to the international units for general use. By 1973, 136 countries had adopted the SI and another 33 were going metric, including Canada, the United Kingdom, Australia, and New Zealand. The United States became officially metric in 1893, when the meter and the kilogram were declared the nation's "fundamental standards" of length and mass. Ever since then the yard, the pound, and other customary units have been defined as fractions of the metric standards, but these old units continued to dominate in trade and commerce. In 1968 Congress passed an act "to authorize the Secretary of Commerce to make a study to determine advantages and disadvantages of increased use of the metric systems in the United States." In 1971 the U.S. Metric Study concluded that the country should change to the metric system through a coordinated national program. Metric units are widely used in the physical sciences, pharmacy, and medicine, but in many other areas progress toward metrication has been extremely slow.

Of the many people who have been helpful in offering constructive criticism of previous editions and suggestions for improving the present one, the author can acknowledge only a few by name, but he extends his thanks to all. He is indebted to Alan F. A. Harper, Executive Member of Australia's Metric Conversion Board, for sharing his expertise regarding the best use of the SI system. Over several years Professor G. N. Koehl, of George Washington University, has done much to improve the manuscript. Colleagues at the Naval Postgraduate School have found many errors and proposed numerous improvements; among those to whom the author is grateful are Professors E. C. Crittenden, Jr., A. R. Frey, H. E. Handler, D. E. Harrison, S. H. Kalmbach, R. L. Kelly, J. R. Neighbours, L. O. Olsen, J. D. Riggin, J. V. Sanders, and W. B. Zeleny. Finally, special thanks are due to the author's wife Elaine, who typed and helped prepare the manuscript; to Elizabeth P. Richardson, who edited the entire manuscript and made many improvements; and to Laura Warner, who supervised and coordinated the editorial process, including figure production.

John N. Cooper

CONTENTS

Part One MECHANICS

Part Two KINETIC THEORY, HEAT, AND THERMODYNAMICS

Part Three WAVE MOTION AND SOUND

Part Four LIGHT

Part Five ELECTRICITY AND MAGNETISM

Part Six MODERN PHYSICS

APPENDIX

ONE

MECHANICS

1

INTRODUCTION TO PHYSICS

Every day we interact with our environment in many ways. The science of physics is concerned with the inanimate aspects of the universe and our interactions with it. How are sound and light produced, propagated, and detected? How does an automobile engine, an electric motor, or a jet engine operate? How can the motions of billiard balls, space capsules, and planets be predicted? These are all questions which can be answered in terms of the principles of physics. No one who lives a normal, active life can avoid knowing and using physics in a qualitative *way. One purpose of this book is to help you achieve a* quantitative *knowledge of many important relationships. Another is to broaden the range of physical phenomena with which you are acquainted.*

Probably no aspect of physics is more familiar than the motions of such objects as balls or automobiles, and we therefore start our study with mechanics, the branch of physics dealing with the motions of bodies and the influence of forces on these motions. To obtain precise relationships, we require quantitative measurements in terms of carefully established standards. In this first chapter we define the fundamental unit of length (the meter*), of time (the* second*), and of mass (the* kilogram*). We can express any quantity we meet in mechanics in terms of these* three basic units.

1.1 WHAT IS PHYSICS?

The word *physics* is derived from the Greek meaning *science of nature.* In a broad sense physics is the branch of knowledge which describes and explains the material world and its phenomena. In terms of this sweeping definition, other physical sciences, such as chemistry, geology, astronomy, and the engineering disciplines, are branches of the basic science *physics.* For centuries the body of knowledge we now call physics was known as *natural philosophy.*

At present, it is customary to use *physics* in a more restricted sense. Aspects of nature which are ordinarily regarded as clearly in the domain of physics are mechanics, sound, heat, electricity and magnetism, atomic and nuclear structure, and the properties of solids, liquids, gases, and plasmas. Broad areas of knowledge in which physics overlaps related sciences are described by names such as astrophysics, biophysics, chemical physics, and geophysics. Of course, these fields are not distinct; they merge into one another. Sharp distinctions between the sciences are neither necessary nor desirable.

Throughout the ages, intelligent people have endeavored to explain what went on in the world about them. There has been a never ending struggle to formulate a systematic set of concepts about the world we live in. Physics is as old as human curiosity about the environment and the wealth of processes it manifests. Early philosophers found many regularities and a great orderliness in the phenomena which impinge on our senses, suggesting that these phenomena are subject to quantitative laws. The philosophers sought to discover these laws of nature and to organize them into a logically elegant structure.

When we speak of a scientific law, we mean a *general* statement expressing some specific connection between observable quantities. For example, *Boyle's law* states how the pressure and the volume of a gas are related when the temperature is held constant; *Newton's law of universal gravitation* gives the force between two particles in terms of their masses and the distance between them. Usually a law can be written in the form of a mathematical equation. We believe that some laws are exact and are never violated; others are obeyed over a well-defined range but are not valid outside this range. As an example, *Hooke's law* states that the extension of a spring is directly proportional to the stretching force; however, if we continue to increase the force, eventually Hooke's law is no longer applicable.

Everyone is familiar with at least some of the regularities of nature. A small child soon learns that released objects fall to the floor; a more mature observer may be impressed by the regularity of the movement of the sun, moon, and stars. To find the relationship between these apparently unrelated processes required the genius of Newton. Yet many an important contribution to physics has been made by men of modest intellectual achievements. In the words of Aristotle:

> The search for Truth is in one way hard and in another easy. For it is evident that no one can master it fully nor miss it wholly. But each adds a little to our knowledge of Nature, and from all the facts assembled there arises a certain grandeur.

In the more than 2,000 years since Aristotle spoke, scientists have been adding steadily to our knowledge of nature, and today we experience the thrill of understanding many phenomena which were completely beyond the ken of the greatest scientists of earlier times. Albert Einstein, a great physicist of the early twentieth century, once said:

> The most incomprehensible fact of Nature is the fact that Nature is comprehensible.

To be sure, our knowledge is never complete, and there are always questions to which we seek answers. But many of nature's laws can be examined and understood by anyone who makes an effort to become familiar with them. The rewards are well worth the effort.

1.2 THE EVOLUTION OF PHYSICS

Physics today is a rapidly expanding science with many branches in widely varying stages of development. To appreciate the current state of the science fully it may be helpful to learn something of the historical background of physical science.

The writings of early scientists, such as Thales (640–547 B.C.) and Pythagoras (sixth century B.C.), are lost, but some of their contributions have been reported by later philosophers, of whom Aristotle (384–322 B.C.) is a prominent example. Typically the early philosophers observed naturally occurring phenomena and advanced *hypotheses* in terms of which a variety of observations could be understood. By a *hypothesis* we mean a proposal (often a pure guess) about how diverse observations in a given area can be logically related. Needless to say, many hypotheses turned out to be unacceptable. For example, about 450 B.C. Empedocles proposed the hypothesis that all material things were made from four "elements," earth, water, air, and fire. On the other hand, before 250 B.C. Aristarchus of Samos wrote that the earth revolves around the sun; this hypothesis, rejected for centuries, eventually won acceptance.

The emphasis of physical scientists before the seventeenth century was largely on qualitative aspects of physics: *How do things behave* in a given environment and *why* do they respond as they do? To be sure, early philosophers did know a great deal about the motions of the stars and the planets. Before 500 B.C. Pythagoras studied stringed musical instruments and found how the pitch depended on the length of the vibrating string (Chap. 21). About 250 B.C. Eratosthenes made a good measurement of the circumference of the earth, which he took to be a sphere (see Prob. 32). In spite of these and many other important quantitative contributions, the usual concerns of early philosophers were with describing and explaining phenomena rather than with performing experiments and making measurements. In their environment answers to quantitative questions were less important than they are in ours. Another reason is that they had few good measuring instruments. To measure time they had sundials, sand glasses, and water clocks, none of which were very good for measuring short time intervals. Nevertheless, they managed to understand many phenomena, and their contributions to modern knowledge are all too often forgotten.

As the understanding of natural phenomena expanded and the number of scientists grew, new facets of physical science became evident. Several aspects of physics, which were relatively neglected initially, came to play important roles in the evolution of modern science. These aspects are intimately related, but, interwoven as they are, it is convenient to introduce them separately.

The Experimental Method In much of early physics the scientist observed natural happenings and endeavored to explain his observations. Typically he did not cause the happenings and he did not control them. As one example, the Greek philosophers wrote about stones falling to the earth, but it was not until the time of Galileo (1564-1642) that this topic became the subject of well-controlled experiments. Galileo rolled spheres down inclined planes and made actual measurements on his system. He varied the angle of the inclined plane and studied how that affected the motion. In the laboratory environment he could repeat an experiment or refine it. Now there are laboratories all around the earth where carefully controlled experiments are carried out.

As the experimental approach grew, there was a great stimulus for new and better measuring instruments. They in turn made it possible to make better measurements and to gain further knowledge.

The Quantitative Aspect As better measuring instruments become available and better laboratory techniques develop, it becomes possible to accumulate many data. In order to formulate valid relationships between physical quantities, accurate measurements must be made. Thus, physics becomes a quantitative science. As Lord Kelvin said in 1883:

> I often say that when you can measure what you are speaking about, and express it in numbers, you know something about it; but when you cannot measure it, when you cannot express it in numbers, your knowledge is of a meager and unsatisfactory kind. It may be the beginning of knowledge, but you have scarcely, in your thoughts, advanced to the stage of science, whatever the matter may be.

The Role of Mathematics Paralleling the accelerated growth of physical knowledge which became evident in the seventeenth century was a corresponding growth in mathematical knowledge. Often the same man contributed to both; one of the most famous was Isaac Newton, but there were many others. Physics as a quantitative science rapidly became and has remained a mathematical science. The laws of physics are typically expressed in the form of mathematical expressions; as such, they are the same for physicists all over the world. Thus mathematics provides a universal language for physics and a means of rigorous, logical reasoning which is difficult to achieve in any other way.

With a growing literature of precise, reproducible measurements and new mathematical tools for manipulating ideas, it became possible to examine hypotheses more critically. If one assumed the truth of some hypothesis, one could in some cases calculate what the result of some particular experiment should be and compare this prediction with actual observations. Indeed, the treatment might suggest that some heretofore unobserved result would occur under some prescribed set of conditions. Under these circumstances the original hypothesis has become a *theory*. In general, a theory is much more than a hypothesis in that it involves not only a presumption about how nature behaves but also a mathematical formulation which gives correct quantitative values in agreement with previous experiments and correct predictions of what will be observed if some completely new experiment is performed.

An example of the transition from hypothesis to theory may help clarify :澄清 the ideas. Several Greek philosophers, including Democritus, assumed that gases (and indeed all matter) consist of small particles separated by void and that these particles are in constant motion. This kinetic hypothesis was rejected by Aristotle and others. However, Daniel Bernoulli in 1738 calculated the pressure which would be produced by huge numbers of gas "molecules" colliding with the walls of the container. Other physicists made improvements in this model, and *kinetic theory* emerged. This theory correctly predicts the velocity distribution of the molecules of any gas as a function of the temperature as well as the thermal conductivity and the viscosity of the gas. Thus the *kinetic hypothesis,* an intuitive guess about the nature of a gas, has evolved into the *kinetic theory,* a powerful tool for quantitatively understanding many kinds of phenomena exhibited by gases.

Precise Language In many areas, e.g., politics, whenever people exchange ideas, it soon becomes evident that the same words are being used by different people to express different ideas. This familiar semantic problem also arose in the earlier days of physics. A classic example lies in a sometimes bitter argument in the late seventeenth and early eighteenth centuries between the followers of Descartes and those of Leibnitz as to whether "the quantity of motion" of a body was proportional to the velocity of the body or to the square of the velocity. The lengthy disagreement evaporated into nothingness when, in 1743, d'Alembert showed that to Descartes and his partisans "quantity of motion" meant what we call "momentum" (which is indeed proportional to velocity) while to Leibnitz and his protagonists "quantity of motion" referred to what we call "kinetic energy" (which is proportional to the square of velocity). The term "quantity of motion" is no longer used as a technical term in physics, and all physicists agree on what is meant by the terms *momentum* and *kinetic energy* of a body. In modern science it is the practice to define quantities in a completely unambiguous way so that everyone using the term in a technical context means the same thing by it. Actually, in physics we use some common words like *force, power,* and *work* which have a variety of meanings, but when they are used in physics, they have a definite and precise meaning.

In many situations it is possible to express physical relationships in terms of mathematical formulas, which in turn can be manipulated in accord with established mathematical procedures to yield new mathematical relationships and to obtain new physical insights. When physical relationships can be expressed in the language of mathematics, great advantages accrue. Mathematical language is an impersonal, unemotional, objective, and universal tool, which is richly rewarding to those who put forth the effort to master it.

The Creative Aspect of Physics As we have seen, early philosophers were concerned chiefly with observing natural occurrences and explaining them. In the seventeenth century physicists became able to make careful measurements in the laboratory on phenomena which they controlled. The primary objective was to satisfy the urge to understand nature. Later scientists became interested in learning how to apply the laws of physics to achieve certain desired ends. For example in the eighteenth century scientists made great progress in understanding heat. This knowledge led to the development of heat engines, and their use opened the way for steamships, railroads, automobiles, and aircraft in our transportation system and for tractors on our farms. In the nineteenth century physicists investigated and began to understand electrical phenomena. Creative synthesis of this knowledge brought about the widespread generation and distribution of electric energy for light, heat, electric motors, and radio and television. Investigation into the discharge of electricity through gases led to the discovery of x-rays, which not only provided a vital tool for the study of crystals and atomic structure but also paved the way for revolutionary advances in the diagnosis and treatment of diseases. In the twentieth century research in physics has expanded to unprecedented levels and has given us insight into the properties of solids and into the structure of atoms and nuclei. This knowledge in turn has been utilized to develop solid-state circuits, computers, and nuclear power sources.

Progress in physics brings with it progress in commerce and industry, in medicine, and in the related sciences. Much of the difference between the way we now live in the United States and the way the Indians lived 500 years ago is associated with our greater knowledge of physical phenomena and how they can be controlled.

1.3 THE UNIT OF TIME

To formulate valid relationships between physical quantities, accurate measurements must be made. If scientists in varying parts of the world are to communicate with each other and confirm each other's findings, they must make measurements in terms of some agreed units. Time is one of the most important physical variables and we first introduce the *second* as the unit of time because it is the one fundamental unit which is common to both the metric and the British systems of units. The second (s) had its origin in the rate of rotation of the earth. The time from the instant the center of the sun is on the meridian plane (the meridian plane of an observer is a plane determined by the axis of rotation of the earth and the point at which the observer is located on the earth's surface) until the sun is centered on the meridian the following day is called a *solar day.* For several reasons solar days are not all of identical duration; the average over 1 year is called the *mean solar day.* This period is divided into 24 h, each hour into 60 min, and each minute into 60 s. Thus, a solar day contains 86,400 s. For many years the second was defined as 1/86,400 of a mean solar day.

However, the earth's rotation is subject to small variations which are not thoroughly understood. As a result, the mean solar day is not an entirely satisfactory quantity for defining a standard of time. The 1960 International Conference on Weights and Measures redefined the second as 1/31,556,925.9747 of the solar year 1900. It is evident that this definition was not very useful for measuring small time intervals with precision, and in 1968 a new definition based on an "atomic clock" was adopted. It had earlier been discovered that it is possible to excite certain atoms in such a way that they emit radiation with a very well-defined *period* (time to complete one cycle). According to the 1968 definition, *The second is the duration of 9,192,631,770 periods of the radiation corresponding to the transition between the two hyperfine levels of the fundamental state of the atom of cesium 133.*

This standard for a second has evolved over the years. As higher precision is demanded, new standards may be created, usually in such a way that they are compatible with, but better than, the displaced standard. It is not unlikely that the 1968 definition of the second may be replaced by some still more precise or useful one. For ordinary measurements the new unit would be indistinguishable from the old one; only in the most precise kind of measurements would any difference show up. In the next section we shall see that other units have also evolved as science progressed.

1.4 STANDARDS OF LENGTH AND MASS

In making measurements of physical quantities, we ordinarily perform a series of operations which involve the comparison of an unknown quantity with an accepted standard of the same kind. Thus when we say that a road is 10 meters (m) wide, we mean that a standard of length called a *meter* must be applied to it 10 times in succession in order to cover its entire width. Similarly, a body is said to have a mass of 25 kilograms (kg) if its mass is 25 times as great as the mass of a standard kilogram.

At one time the length of a king's foot or the span of his hand served as an adequate standard of length and a selected stone as a standard of mass. For example, the British yard was defined by Henry I (1068–1135) to be the distance from the point of his nose to the end of his thumb; much later it was established as the distance at 62°F between two lines ruled on a bronze bar preserved in London. The inch was defined in 1324 to be the length of three dry barleycorns laid end to end.

As commerce between countries increased, and as scientists began to make more and more accurate measurements, established standards of length and mass became of increasing importance. In 1791 the French National Assembly adopted the *metric system*, in which the standard of length was the *Meter*† *of the Archives*, a platinum bar fabricated to have a length one ten-millionth of the distance from the North Pole to the equator as then measured on the quadrant through Paris. As a standard mass, French scientists prepared a platinum cylinder, known as the *Kilogram of the Archives*, which had a mass as near as they could make it to the mass of 1,000 cubic centimeters (cm^3) of pure water at maximum density. Later measurements show that 1 kg of water at maximum density occupies 1,000.028 cm^3. A volume of exactly 1,000 cm^3 (10^{-3} m^3) is named the *liter* (L). The French system, slightly modified, is now used almost universally in scientific work and increasingly in world commerce.

Meantime in the United States a chaotic set of standards had evolved, in which a bushel basket in South Carolina held 68 $in.^3$ more than a bushel basket in New York, while a pound of meat in Massachusetts was $\frac{1}{4}$ oz lighter than a pound of meat in Maine. These facts were pointed out to the Congress in 1821 by John Quincy Adams, then Secretary of State. In his "Report on Weights and Measures" Adams wrote:

> Weights and Measures may be ranked among the necessaries of life, to every individual of human society. They enter into the economical arrangements and daily concerns of every family. They are necessary to every occupation of human industry; to the distribution and security of every species of property; to every transaction of trade and commerce; to the labors of the husbandman; to the ingenuity of the artificer; to the studies of the philosopher; to the researches of the antiquarian; to the navigation of the mariner, and the marches of the soldier; to all the exchanges of peace, and all the operations of war. The knowledge of them, as in established use, is among the first elements of education, and is often learned by those who learn nothing else, not even to read and write. This knowledge is riveted in the memory by the habitual application of it to the employments of men throughout life.

In response Congress established a bureau which later became the National Bureau of Standards, an invaluable national asset.

In 1875, representatives from many civilized countries met in Paris to discuss international standards of measurement. It was generally agreed that the French units were most suitable and that copies should be made for nations which wished to adopt the *metric system* of units. Thirty bars were made of an alloy of platinum (90 percent) and iridium (10 percent). On these bars were marked fine transverse lines separated as nearly as possible by a distance equal to the length of the Meter of the Archives. These new standards were made in 1880, and in 1889 they were distributed to the governments participating in the convention of 1875. The United States obtained two of these standard "meters," of which Bar 27 was the primary standard of length for the United States until 1960. Bar 6 was most nearly equal to the Meter of the Archives, and it was declared

---

† Meter and liter are the American spellings. Many countries, e.g., Australia, use the French spellings metre and litre.

the *International Standard Meter.* It is kept at the International Bureau of Weights and Measures at Sèvres, near Paris.

At the same time, 40 standard kilograms, with masses as nearly as possible equal to that of the Kilogram of the Archives, were constructed from the platinum-iridium alloy. The new mass which agreed most closely with the Kilogram of the Archives is now the *International Mass Standard.* The primary mass standard of the United States is Kilogram 20 (Fig. 1.1), one of the two delivered to this country in 1889. With the kilogram the legal unit of mass, the pound mass is defined to be 0.45359237 kg.

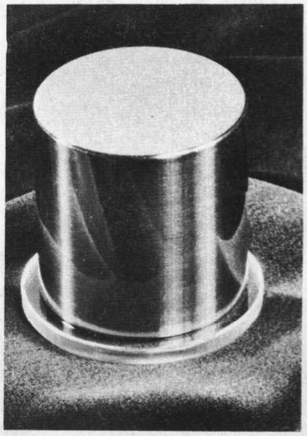

FIGURE 1.1
The mass standard of the United States is this standard kilogram, a platinum-iridium cylinder about 39 mm high and 39 mm in diameter. (*National Bureau of Standards.*)

By the middle of the twentieth century the prototype meter bar was no longer good enough as a standard of length. Secondary standards could be compared with it only to an accuracy of roughly 1 part in 10 million, while technological requirements for modern industry called for tolerances of the order of 10^{-7} m. In general, it is desirable that a master standard be at least 10 times more accurate than the scientific and industrial measuring systems which are derived from it. As a consequence, at the 1960 International Conference on Weights and Measures the meter was redefined in terms of the wavelength (Fig. 1.2) of the orange light emitted by the krypton isotope of mass 86. Krypton is found in the air, and a standard based on the light from krypton 86 has the advantage that it can never be destroyed, stolen, damaged, or lost. With this standard of length it is possible to make measurements with an accuracy of the order of 1 part in 100 million. Further, anyone with the appropriate equipment can reproduce the present standard of length, defined as follows:

The meter is a length 1,650,763.73 times the wavelength of the orange-red light given off by the pure krypton isotope of mass 86 when it is excited in an electric discharge.

The meter is the legal standard of length in the United States; however, most everyday measurements are made in British units, which are related to the meter by the definition:

One inch is 0.0254 m exactly.

1.5 THE INTERNATIONAL SYSTEM OF UNITS

The 1960 General Conference of the International Bureau of Weights and Measures established the Systême International d'Unités (SI) by selecting the *meter* as the basic unit for *length,* the *kilogram* for *mass,* the *second* for *time,* the *ampere* (Sec. 36.8) for *current,* the *kelvin* (Sec. 15.3) for *temperature,* and the *candela* (Sec. 28.1) for *luminous intensity.* Larger and smaller units are related to the standard units in terms of powers of 10. Thus the kilometer is 1,000 m, while the millimeter is 0.001 m. Table 1.1 lists the prefixes for fractions and multiples together with their abbreviations. In most scientific work metric units are used, and the SI is widely accepted although the cgs system, based on the centimeter, the gram, and the

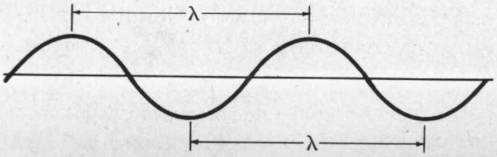

FIGURE 1.2
The wavelength λ is the distance from crest to adjacent crest (or trough to adjacent trough) of a wave.

TABLE 1.1
Fractions and Multiples (SI)

Factor	*Prefix*	*Abbreviation*
10^{-1}†	deci	d
10^{-2}†	centi	c
10^{-3}	milli	m
10^{-6}	micro	μ
10^{-9}	nano	n
10^{-12}	pico	p
10^{-15}	femto	f
10^{-18}	atto	a
10†	deka	da
10^{2}†	hecto	h
10^{3}	kilo	k
10^{6}	mega	M
10^{9}	giga	G
10^{12}	tera	T
10^{15}	peta	P
10^{18}	exa	E

† It is recommended that these factors be used only when there is a strongly felt need. Compound prefixes, for example, mμ, should be avoided.

second (together with other electrical units), retains an important following.

Many other systems have been devised. The *British absolute system* has as its fundamental units the *foot*, the *pound mass*, and the *second*. It is not necessary that the fundamental units of a system involve length, mass, and time. Indeed, as we shall see, the *British engineering system* is based on the *foot*, the *second*, and the *pound force*.

An overwhelming number of countries, and well over 90 percent of the world's population, now use the metric system, including virtually all the nations of Europe, Asia, and South America and most of those of Africa. For several years the United States has been in the process of converting to the SI.

1.6 DERIVED UNITS

When a physical observable is expressed in terms of a combination of the fundamental quantities, its units are said to be *derived*. For example, the units of area can be written as the square of units of length. Thus, we may express areas in square meters or square feet. Similarly, the dimensions of volume are lengths cubed—cubic meters, cubic feet, etc. Speed and density are examples of the many quantities in mechanics which are written in terms of derived units.

Speed The average speed of a body is defined as the ratio of the distance it travels to the time required to pass over that distance. Thus, speed is obtained by dividing a length by a time. Appropriate units of speed are meters per second, feet per second, miles per hour, etc. The speeds of ships and aircraft are often measured in *knots*. One knot is one nautical mile (1,852 m or 6,076 ft) per hour.

☐ **Example** A track man runs a measured kilometer in 2 min 27 s. Find his average speed in meters per second.

$$\text{Average speed} = \frac{\text{distance}}{\text{time}} = \frac{1{,}000\text{ m}}{147\text{ s}}$$
$$= 6.80\text{ m/s}$$

☐

Density The denisty of a body is defined as the ratio of its mass to its volume. Thus

$$d = \frac{m}{V} \tag{1.1}$$

where d is the density, m the mass, and V the volume. Among the familiar units for density are kilograms per cubic meter, slugs (Sec. 4.5) per cubic foot, and grams per cubic centimeter.

☐ **Example** A quantity of mercury has a mass of 2.05 kg and occupies a volume of 151 cm³. What is its density?

$$d = \frac{m}{V} = \frac{2.05\text{ kg}}{151\text{ cm}^3} = 0.0136\text{ kg/cm}^3$$
$$= 13.6\text{ g/cm}^3 = 13{,}600\text{ kg/m}^3$$

☐

☐ **Example** Find the mass of air in a room which is 3.00 by 8.00 by 6.00 m. The density of the air is 1.29 kg/m³.

$$m = dV = 1.29\ \text{kg/m}^3 \times 144\ \text{m}^3 = 186\ \text{kg} \qquad \square$$

The term "density" is often used in conjunction with certain other words to suggest the amount of some quantity per given amount of some other quantity. For example, we use the term *population density* to describe number of people per unit area. In electricity the term *charge density* means the ratio of electric charge to volume, and *surface charge density* is the ratio of electric charge to surface area. The ratio of the weight of an object to its volume is called its *weight density*. The ratio of the mass of a rope to its length is sometimes called its *linear density*. Whenever the word density appears in this text in any sense other than that of mass per unit volume, it will be qualified by another word.

1.7 CONVERSION OF UNITS AND SIGNIFICANT FIGURES

In the measurement of any physical quantity, the choice of units is ordinarily dictated by convenience and by the habits of the observer. In reporting any measurement, it is important to list not only the number of times the standard unit was included but also to state what this standard unit is. For example, the height of a man might be 6.08 ft, 73.0 in., or 1.85 m. The number which describes the height is meaningless unless the accompanying units are known.

We live in a country where many everyday measurements are made in the British system, but most scientific work involves metric units. Since anyone who has to deal with scientific phenomena in the United States is essentially forced to use both British and metric units, it is important to be able to transform from one system to another. To facilitate this operation an extensive list of conversion factors is presented inside the front cover.

It is convenient to convert a quantity from one unit to another in the form of the examples below. Note that one can cancel units just as though they were algebraic quantities. Note further that the factors by which one multiplies are all unity.

☐ **Example** Convert 60.0 mi/h to feet per second and meters per second.

$$\begin{aligned} 60.0\frac{\text{mi}}{\text{h}} &= 60.0\frac{\text{mi}}{\text{h}} \times \frac{1\ \text{h}}{3{,}600\ \text{s}} \times \frac{5{,}280\ \text{ft}}{1\ \text{mi}} \\ &= \frac{60.0 \times 5{,}280\ \cancel{\text{mi}}\,\cancel{\text{h}}\ \text{ft}}{3{,}600\ \cancel{\text{h}}\ \text{s}\ \cancel{\text{mi}}} = 88.0\frac{\text{ft}}{\text{s}} \\ &= 88.0\frac{\cancel{\text{ft}}}{\text{s}} \times \frac{0.3048\ \text{m}}{1\ \cancel{\text{ft}}} = 26.8\frac{\text{m}}{\text{s}} \qquad \square \end{aligned}$$

☐ **Example** The density of aluminum is 2,699 kg/m³. Convert this density to grams per cubic centimeter and to pounds per cubic foot.

$$\begin{aligned} 2{,}699\frac{\text{kg}}{\text{m}^3} &= 2{,}699\frac{\text{kg}}{\text{m}^3} \times \frac{1\ \text{m}^3}{(100\ \text{cm})^3} \times \frac{1{,}000\ \text{g}}{1\ \text{kg}} \\ &= 2.699\frac{\text{g}}{\text{cm}^3} \end{aligned}$$