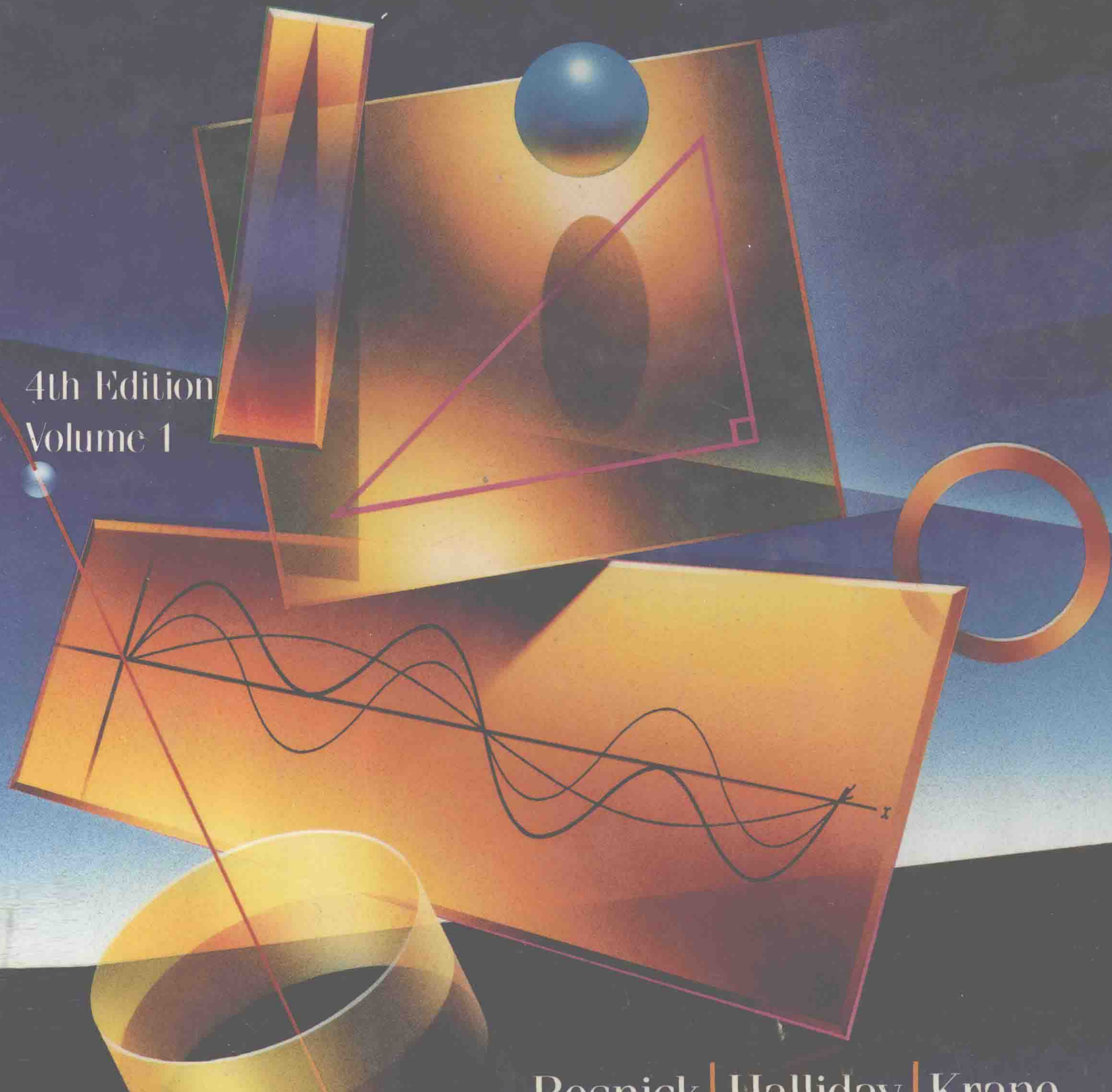
PHYSICS

4th Edition
Volume 1



Resnick | Halliday | Krane

VOLUME ONE

PHYSICS

FOURTH EDITION

ROBERT RESNICK

Professor of Physics
Rensselaer Polytechnic Institute

DAVID HALLIDAY

Professor of Physics, Emeritus
University of Pittsburgh

KENNETH S. KRANE

Professor of Physics
Oregon State University

JOHN WILEY & SONS, INC.

New York • Chichester • Brisbane • Toronto • Singapore

Acquisitions Editor *Clifford Mills*
Marketing Manager *Catherine Faduska*
Production Manager *Joe Ford*
Production Supervisor *Lucille Buonocore*
Manufacturing Manager *Lorraine Fumoso*
Copy Editing Manager *Deborah Herbert*
Photo Researcher *Jennifer Atkins*
Photo Research Manager *Stella Kupferberg*
Illustration *John Balbalis*
Text Design *Karin Gerdes Kincheloe*
Cover Design Direction *Karin Gerdes Kincheloe*
Cover Design *Lee Goldstein*
Cover Illustration *Roy Wiemann*

Library of Congress Cataloging-in-Publication Data

Halliday, David, 1916–
Physics / David Halliday, Robert Resnick, Kenneth S. Krane. -- 4th ed.
p. cm.
Includes index.
ISBN 0-471-80458-4 (lib. bdg. : v. 1)
1. Physics. I. Resnick, Robert, 1923– . II. Krane, Kenneth S.
III. Title.
QC21.2.H355 1992 91-35885
530--dc20 CIP

Printed and bound by Von Hoffmann Press, Inc.

10 9 8 7 6 5

SUPPLEMENTS

PHYSICS, FOURTH EDITION is accompanied by a complete supplementary package.

STUDY GUIDE (A Student's Companion to Physics)

J. RICHARD CHRISTMAN
U.S. Coast Guard Academy

Provides self-tests for conceptual understanding and problem solving.

SOLUTIONS MANUAL

EDWARD DERRINGH
Wentworth Institute of Technology

Provides approximately 302 of the solutions to textbook problems.

LABORATORY PHYSICS, SECOND EDITION

HARRY F. MEINERS
Rensselaer Polytechnic Institute
WALTER EPPENSTEIN
Rensselaer Polytechnic Institute
KENNETH MOORE
Rensselaer Polytechnic Institute
RALPH A. OLIVA
Texas Instruments, Inc.

This laboratory manual offers a clear introduction to procedures and instrumentation, including errors, graphing, apparatus handling, calculators, and computers, in addition to over 70 different experiments grouped by topic.

FOR THE INSTRUCTOR

A complete supplementary package of teaching and learning materials is available for instructors. Contact your local Wiley representative for further information.

Books by D. Halliday, R. Resnick, and K. Krane

Physics, Volume 1, Fourth Edition
Physics, Volume 2, Fourth Edition
Physics, Volume 2, Fourth Edition, Extended

Books by D. Halliday and R. Resnick

Fundamentals of Physics, Third Edition
Fundamentals of Physics, Third Edition, Extended

Books by R. Resnick

Introduction to Special Relativity

Books by Robert Eisberg and Robert Resnick

Quantum Physics of Atoms, Molecules, Solids, Nuclei, and Particles, Second Edition

Books by Kenneth S. Krane

Modern Physics
Introductory Nuclear Physics

PREFACE TO VOLUME 1

The first edition of *Physics for Students of Science and Engineering* appeared in 1960; the most recent edition (the third), called simply *Physics,* was published in 1977. The present fourth edition (1992) marks the addition of a new coauthor for the text.

The text has been updated to include new developments in physics and in its pedagogy. Based in part on our reading of the literature on these subjects, in part on the comments from numerous users of past editions, and in part on the advice of a dedicated group of reviewers of the manuscript of this edition, we have made a number of changes.

1. Energy is treated in a coherent way throughout the text, beginning with the work-energy theorem and continuing with thermodynamics. For example, we consistently calculate work as that done *on* a system, thus using the same sign convention for work in both mechanics and thermodynamics. Attention to such details helps the student to discern the common concepts that permeate different areas of physics.

2. Special relativity, which was treated as a Supplementary Topic in the previous edition, is integrated throughout the text. Two chapters are devoted to special relativity: one (in Volume 1) follows mechanical waves and another (in Volume 2) follows electromagnetic waves. Topics related to special relativity (for instance, relative motion, frames of reference, momentum, and energy) are treated throughout the text in chapters on kinematics, mechanics, and electromagnetism. This approach reflects our view that special relativity should be treated as part of classical physics. However, for those instructors who wish to delay special relativity until the end of the course, the material is set off in separate sections that can easily be skipped on the first reading.

3. Changes in the ordering of topics from the third edition include the interchange of Chapters 2 and 3, so that one-dimensional kinematics now precedes vectors; the consolidation of all material on angular momentum into Chapter 13 (where it follows rotational kinematics and dynamics, thus making our presentation of rotational motion more nearly parallel to that of translational motion); and a reordering and substantial rewriting of the chapters on thermodynamics, emphasizing its statistical aspects and giving the subject a more "modern" flavor.

4. In response to requests from users, several new classical topics have been added to Volume 1; these include dimensional analysis, drag forces, elasticity, surface tension, viscosity, and musical acoustics.

5. Modern applications have been "sprinkled" throughout the text: for instance, quantization of energy and angular momentum, decays of nuclei and elementary particles, chaos theory, general relativity, and quantum statistics. These are not intended to be a coherent treatment of modern physics (which is available in the additional eight chapters of the extended version of Volume 2), but instead to indicate to the student the boundaries of classical physics and the relationships between classical and modern physics.

6. We have substantially increased the number of end-of-chapter problems relative to the previous edition of Volume 1: there are now 1519 problems compared with 958 previously, an increase of 59 percent. The number of end-of-chapter questions has been similarly increased from 614 to 821 (34%). We have tried to maintain the quality and diversity of problems that have been the hallmark of previous editions of this text.

7. The number of worked examples in Volume 1 has been increased from 135 to 183 (36%). The true increase in the number of worked examples (now called sample problems) is greater than this estimate, because the previous edition occasionally introduced new topics by means of worked examples. This edition eliminates that practice; new material is presented only in the exposition of the text, and the sample problems serve only as exercises in its application.

8. Computational techniques are introduced through several worked examples and through a variety of end-of-chapter computer projects. Some program listings are given in an appendix to encourage students to adapt those methods to other applications.

9. We have increased and updated the references to articles in the literature that appear as footnotes throughout the text. Some references (often to articles in popular magazines such as *Scientific American*) are intended to broaden the student's background through interesting applications of a topic. In other cases, often involving items of pedagogic importance to which we wish to call the attention of students as well as instructors, we make reference to articles in journals such as the *American Journal of Physics* or *The Physics Teacher.*

10. The illustrations have been completely redone and their number in Volume 1 has been increased by nearly a factor of 2, from 463 to 899. We have added color to many of the drawings where the additional color enhances the clarity or the pedagogy.

11. Many of the derivations, proofs, and arguments of the previous edition have been tightened up, and any assumptions or approximations have been clarified. We have thereby improved the rigor of the text without necessarily raising its level. We are concerned about indicating to students the limit of validity of a particular argument and encouraging students to consider questions such as: Does a particular result apply always or only sometimes? What happens as we go toward the quantum or the relativistic limit?

Although we have made some efforts to eliminate material from the previous edition, the additions mentioned above contribute to a text of increasing length. *It should be emphasized that few (if any) instructors will want to follow the entire text from start to finish.* We have worked to develop a text that offers a rigorous and complete introduction to physics, but the instructor is able to follow many alternate pathways through the text. The instructor who wishes to treat fewer topics in greater depth (currently called the "less is more" approach) will be able to select from among these pathways. Some sections are explicitly labeled "optional" (and are printed in smaller type), indicating that they can be skipped without loss of continuity. Depending on the course design, other sections or even entire chapters can be skipped or treated lightly. The Instructor's Guide, available as a companion volume, offers suggestions for abbreviating the coverage. In such circumstances, the curious student who desires further study can be encouraged independently to approach the omitted topics, thereby gaining a broader view of the subject. The instructor is thus provided with a wide choice of which particular reduced set of topics to cover in a course of any given length. For instructors who wish a fuller coverage, such as in courses for physics majors or honors students or in courses of length greater than one year, this text provides the additional material needed for a challenging and comprehensive experience. We hope the text will be considered a road map through physics; many roads, scenic or direct, can be taken, and all roads need not be utilized on the first journey. The eager traveler may be encouraged to return to the map to explore areas missed on previous journeys.

The text is available as separate volumes: Volume 1 (Chapters 1 to 26) covers kinematics, mechanics, and thermodynamics, and Volume 2 (Chapters 27 to 48) covers electromagnetism and optics. An extended version of Volume 2 (Chapters 27 to 56) is available with eight additional chapters which present an introduction to quantum physics and some of its applications. The following supplements are available:

Study Guide	Solutions Manual
Laboratory Manual	Instructor's Guide

A textbook contains far more contributions to the elucidation of a subject than those made by the authors alone. We have been fortunate to have the assistance of Edward Derringh (Wentworth Institute of Technology) in preparing the problem sets and J. Richard Christman (U. S. Coast Guard Academy) in preparing the Instructor's Guide and the computer projects. We have benefited from the chapter-by-chapter comments and criticisms of a dedicated team of reviewers:

Robert P. Bauman (University of Alabama)
Truman D. Black (University of Texas, Arlington)
Edmond Brown (Rensselaer Polytechnic Institute)
J. Richard Christman (U. S. Coast Guard Academy)
Sumner Davis (University of California, Berkeley)
Roger Freedman (University of California, Santa Barbara)
James B. Gerhart (University of Washington)
Richard Thompson (University of Southern California)
David Wallach (Pennsylvania State University)
Roald K. Wangsness (University of Arizona)

We are deeply indebted to these individuals for their substantial contributions to this project.

We are grateful to the staff of John Wiley & Sons for their outstanding cooperation and support, including physics editor Cliff Mills, editorial program assistant Cathy Donovan, marketing manager Cathy Faduska, illustrator John Balbalis, editorial supervisor Deborah Herbert, designer Karin Kincheloe, production supervisor Lucille Buonocore, photo researcher Jennifer Atkins, and copy editor Christina Della Bartolomea. Word processing of the manuscript for this edition was superbly done by Christina Godfrey.

September 1991

David Halliday
Seattle, Washington

Robert Resnick
Rensselaer Polytechnic Institute
Troy, New York 12180-3590

Kenneth S. Krane
Oregon State University
Corvallis, Oregon 97331

CONTENTS

CHAPTER 6 PARTICLE DYNAMICS 103

CHAPTER 7 WORK AND ENERGY 131

CHAPTER 8 CONSERVATION OF ENERGY 151

CHAPTER 9 SYSTEMS OF PARTICLES 179

CHAPTER 10 COLLISIONS 207

CHAPTER 11 ROTATIONAL KINEMATICS 231

CHAPTER 12 ROTATIONAL DYNAMICS 245

CHAPTER 19 WAVE MOTION 417

CHAPTER 20 SOUND WAVES 445

CHAPTER 21 THE SPECIAL THEORY OF RELATIVITY 467

CHAPTER 22 TEMPERATURE 493

CHAPTER 23 KINETIC THEORY AND THE IDEAL GAS 509

CHAPTER 24 STATISTICAL MECHANICS 529

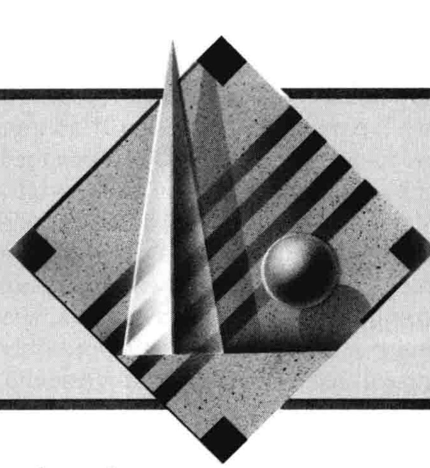
CHAPTER 25 HEAT AND THE FIRST LAW OF THERMODYNAMICS 547

CHAPTER 26 ENTROPY AND THE SECOND LAW OF THERMODYNAMICS 571

APPENDICES

CHAPTER 1

MEASUREMENT



Despite the mathematical beauty of some of its most complex and abstract theories, including those of elementary particles and general relativity, physics is above all an experimental science. It is therefore critical that those who make precise measurements be able to agree on standards in which to express the results of those measurements, so that they can be communicated from one laboratory to another and verified.

In this chapter we begin our study of physics by introducing some of the basic units of physical quantities and the standards that have been accepted for their measurement. We consider the proper way to express the results of calculations and measurements, including the appropriate dimensions and number of significant figures. We discuss and illustrate the importance of paying attention to the dimensions of the quantities that appear in our equations. Later in the text, other basic units and many derived units are introduced as they are needed.

1-1 THE PHYSICAL QUANTITIES, STANDARDS, AND UNITS

The building blocks of physics are the quantities that we use to express the laws of physics. Among these are length, mass, time, force, speed, density, resistivity, temperature, luminous intensity, magnetic field strength, and many more. Many of these words, such as length and force, are part of our everyday vocabulary. You might say, for example: "I will go to any *length* to help you as long as you do not *force* me to do so." In physics, however, we must not be misled by the everyday meanings of these words. The precise scientific definitions of length and force have no connection at all with the uses of these words in the quoted sentence.

We can define an algebraic quantity, for instance, L for length, any way we choose, and we can assume it is exactly known. However, when we try to assign a unit to a particular value of that quantity, we run into the difficulty of establishing a *standard,* so that those who have need of comparing one length with another will agree on the units of measurement. At one time, the basic unit of length was the yard, determined by the size of the king's waistline. You can easily see the problems with such a standard: it is hardly *accessible* to those who need to calibrate their own secondary standards, and it is not *invariable* to change with the passage of time.

Fortunately, it is not necessary to define and agree on standards for every physical quantity. Some elementary quantities may be easier to establish as standards, and more complex quantities can often be expressed in terms of the elementary units. *Length* and *time,* for example, were for many years among the most precisely measurable physical quantities and were generally accepted as standards. *Speed,* on the other hand, was less precisely measurable and therefore was treated as a derived unit (speed = length/time). Today, however, measurements of the speed of light have reached a precision beyond that of the former standard of length; we still treat length as a fundamental unit, but the standard for its measurement is now derived from the standards of speed and time.

The basic problem is therefore to choose the smallest possible number of physical quantities as fundamental and to agree on standards for their measurement. These standards should be both accessible and invariable, which may be difficult to satisfy simultaneously. If the standard kilogram, for instance, is to be an invariable object, it must be *in*accessible and must be kept isolated beyond the effects of handling and corrosion.

Agreement on standards has been accomplished through a series of international meetings of the General Conference on Weights and Measures beginning in 1889; the 19th meeting was held in 1991. Once a standard has been accepted, such as the *second* as a unit of *time,* then we can apply the unit to a vast range of measurements, from the lifetime of the proton (greater than 10^{40} seconds) to the lifetime of the least stable particles that can be produced in our laboratories (about 10^{-23} second). When we express such a value as 10^{40} in units of seconds, what we mean is that the *ratio* between the lifetime of the proton and the time interval that is arbitrarily defined as the standard second is 10^{40}. To accomplish such a measurement, we must have a way of comparing laboratory measuring instruments with the standard. Many of these comparisons are indirect, for no single measuring instrument is capable of operating precisely over 40 orders of magnitude. Nevertheless, it is essential to the progress of science that, when a researcher records a particular time interval with a laboratory instrument, the reading can in some way be connected to a calibration based on the standard second.

The quest for more precise or accessible standards is itself an important scientific pursuit, involving physicists and other researchers in laboratories throughout the world. In the United States, laboratories of the National Institute of Standards and Technology (formerly the National Bureau of Standards) are devoted to maintaining, developing, and testing standards for basic researchers as well as for scientists and engineers in industry. Improvements in our standards in recent years have been dramatic: since the first edition of this textbook (1960), the precision of the standard second has improved by more than a factor of 1000.

1-2 THE INTERNATIONAL SYSTEM OF UNITS*

The General Conference on Weights and Measures, at meetings during the period 1954–1971, selected as base units the seven quantities displayed in Table 1. This is the basis of the International System of Units, abbreviated SI from the French *Le Système International d'Unités.*

Throughout the book we give many examples of SI derived units, such as speed, force, and electric resistance, that follow from Table 1. For example, the SI unit of force, called the *newton* (abbreviation N), is defined in terms of the SI base units as

$$1\ \text{N} = 1\ \text{kg}\cdot\text{m/s}^2$$

as we shall make clear in Chapter 5.

TABLE 1 SI BASE UNITS

	SI Unit	
Quantity	*Name*	*Symbol*
Time	second	s
Length	meter	m
Mass	kilogram	kg
Amount of substance	mole	mol
Thermodynamic temperature	kelvin	K
Electric current	ampere	A
Luminous intensity	candela	cd

If we express physical properties such as the output of a power plant or the time interval between two nuclear events in SI units, we often find very large or very small numbers. For convenience, the General Conference on Weights and Measures, at meetings during the period 1960–1975, recommended the prefixes shown in Table 2. Thus we can write the output of a typical electrical power plant, 1.3×10^9 watts, as 1.3 gigawatts or 1.3 GW. Similarly, we can write a time interval of the size often encountered in nuclear physics, 2.35×10^{-9} seconds, as 2.35 nanoseconds or 2.35 ns. Prefixes for factors greater than unity have Greek roots, and those for factors less than unity have Latin roots (except femto and atto, which have Danish roots).

To fortify Table 1 we need seven sets of operational procedures that tell us how to produce the seven SI base units in the laboratory. We explore those for time, length, and mass in the next three sections.

Two other major systems of units compete with the International System (SI). One is the Gaussian system, in terms of which much of the literature of physics is expressed. We do not use this system in this book. Appendix G gives conversion factors to SI units.

The second is the British system, still in daily use in the United States. The basic units, in mechanics, are length (the foot), force (the pound), and time (the second). Again Appendix G gives conversion factors to SI units. We use SI units in this book, but we sometimes give the British equivalents, to help those who are unaccustomed to SI units to acquire more familiarity with them. In only three countries [Myanmar (Burma), Liberia, and the United States] is a system other than SI used as the accepted national standard of measurement.

Sample Problem 1 Any physical quantity can be multiplied by 1 without changing its value. For example, 1 min = 60 s, so 1 = 60 s/1 min; similarly, 1 ft = 12 in., so 1 = 1 ft/12 in. Using appropriate conversion factors, find (*a*) the speed in meters per second equivalent to 55 miles per hour, and (*b*) the volume in cubic centimeters of a tank that holds 16 gallons of gasoline.

* See "SI: The International System of Units," by Robert A. Nelson (American Association of Physics Teachers, 1981). The "official" U.S. guide to the SI system can be found in Special Publication 330 of the National Bureau of Standards (1986 edition).

TABLE 2 SI PREFIXES[a]

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

[a] In all cases, the first syllable is accented, as in na′-no-me′-ter. Prefixes commonly used in this book are shown in boldfaced type.

Solution (*a*) For our conversion factors, we need (see Appendix G) 1 mi = 1609 m (so that 1 = 1609 m/1 mi) and 1 h = 3600 s (so 1 = 1 h/3600 s). Thus

$$\text{speed} = 55\,\frac{\not{\text{mi}}}{\not{\text{h}}} \times \frac{1609\text{ m}}{1\ \not{\text{mi}}} \times \frac{1\ \not{\text{h}}}{3600\text{ s}} = 25\text{ m/s}.$$

(*b*) One fluid gallon is 231 cubic inches, and 1 in. = 2.54 cm. Thus

$$\text{volume} = 16\ \not{\text{gal}} \times \frac{231\ \not{\text{in.}}^3}{1\ \not{\text{gal}}} \times \left(\frac{2.54\text{ cm}}{1\ \not{\text{in.}}}\right)^3 = 6.1 \times 10^4\text{ cm}^3.$$

Note in these two calculations how the unit conversion factors are inserted so that the unwanted units appear in one numerator and one denominator, and thus cancel.

TABLE 3 SOME MEASURED TIME INTERVALS[a]

Time Interval	*Seconds*
Lifetime of proton	$>10^{40}$
Half-life of double beta decay of ^{82}Se	3×10^{27}
Age of universe	5×10^{17}
Age of pyramid of Cheops	1×10^{11}
Human life expectancy (U.S.A.)	2×10^{9}
Time of Earth's orbit around the Sun (1 year)	3×10^{7}
Time of Earth's rotation about its axis (1 day)	9×10^{4}
Period of typical low-orbit Earth satellite	5×10^{3}
Time between normal heartbeats	8×10^{-1}
Period of concert-A tuning fork	2×10^{-3}
Period of oscillation of 3-cm microwaves	1×10^{-10}
Typical period of rotation of a molecule	1×10^{-12}
Shortest light pulse produced (1990)	6×10^{-15}
Lifetime of least stable particles	$<10^{-23}$

[a] Approximate values.

1-3 THE STANDARD OF TIME*

The measurement of time has two aspects. For civil and for some scientific purposes we want to know the time of day so that we can order events in sequence. In most scientific work we want to know how long an event lasts (the time interval). Thus any time standard must be able to answer the questions "At what time does it occur?" and "How long does it last?" Table 3 shows the range of time intervals that can be measured. They vary by a factor of about 10^{63}.

We can use any phenomenon that repeats itself as a measure of time. The measurement consists of counting the repetitions, including the fractions thereof. We could use an oscillating pendulum, a mass–spring system, or a quartz crystal, for example. Of the many repetitive phenomena in nature the rotation of the Earth on its axis, which determines the length of the day, was used as a time standard for centuries. One (mean solar) second was defined to be 1/86,400 of a (mean solar) day.

Quartz crystal clocks based on the electrically sustained periodic vibrations of a quartz crystal serve well as secondary time standards. A quartz clock can be calibrated against the rotating Earth by astronomical observations and used to measure time in the laboratory. The best of these have kept time for a year with a maximum accumulated error of 5 μs, but even this precision is not sufficient for modern science and technology.

To meet the need for a better time standard, atomic clocks have been developed in several countries. Figure 1 shows such a clock, based on a characteristic frequency of the microwave radiation emitted by atoms of the element cesium. This clock, maintained at the National Institute of Standards and Technology, forms the basis in this country for Coordinated Universal Time (UTC), for which time signals are available by shortwave radio (stations WWV and WWVH) and by telephone.

Figure 2 shows, by comparison with a cesium clock, variations in the rate of rotation of the Earth over a 4-year

* For a history of timekeeping, see *Revolution in Time: Clocks and the Making of the Modern World,* by David S. Landes (Harvard University Press, 1983). Recent developments in precise timekeeping are discussed in "Precise Measurement of Time," by Norman F. Ramsey, *American Scientist,* January–February 1988, p. 42. An account of different systems for reporting time can be found in "Time and the Amateur Astronomer," by Alan M. MacRobert, *Sky and Telescope,* April 1989, p. 378.

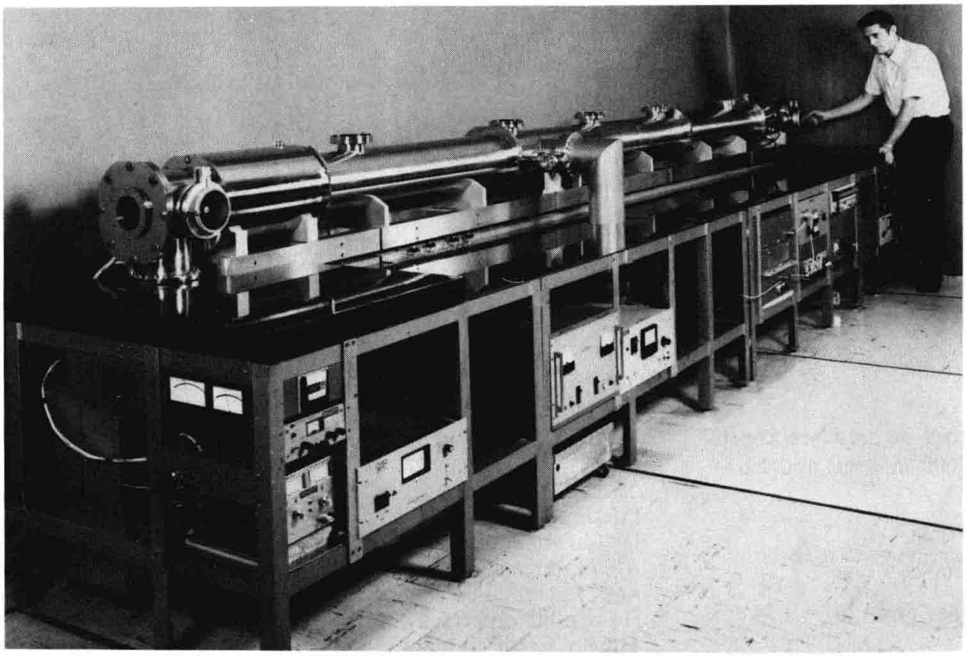


Figure 1 Cesium atomic frequency standard No. NBS-6 at the National Institute of Standards and Technology in Boulder, Colorado. This is the primary standard for the unit of time in the United States. Dial (303) 499-7111 to calibrate your watch against the standard. Dial (900) 410-8463 for Naval Observatory time signals.

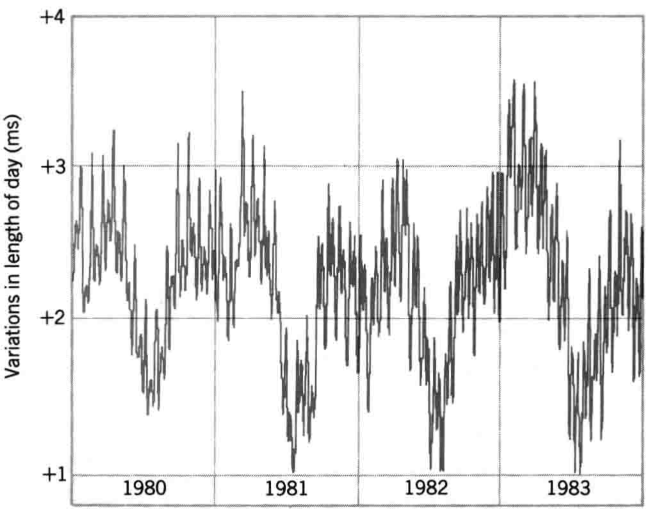


Figure 2 The variation in the length of the day over a 4-year period. Note that the vertical scale is only 3 ms = 0.003 s. See "The Earth's Rotation Rate," by John Wahr, *American Scientist,* January–February 1985, p. 41.

period. These data show what a poor time standard the Earth's rotation provides for precise work. The variations that we see in Fig. 2 can be ascribed to tidal effects caused by the Moon and seasonal variations in the atmospheric winds.

The second based on the cesium clock was adopted as the international standard by the 13th General Conference on Weights and Measures in 1967. The following definition was given:

One second is the time occupied by 9,192,631,770 vibrations of the radiation (of a specified wavelength) emitted by a cesium atom.

Two modern cesium clocks could run for 300,000 years before their readings would differ by more than 1 s. Hydrogen maser clocks have achieved the incredible precision of 1 s in 30,000,000 years. Clocks based on a single trapped atom may be able to improve on this precision by as much as 3 orders of magnitude. Figure 3 shows the impressive record of improvements in timekeeping that have occurred over the past 300 years or so, starting with the pendulum clock, invented by Christian Huygens in 1656, and ending with today's hydrogen maser.

1-4 THE STANDARD OF LENGTH*

The first international standard of length was a bar of a platinum–iridium alloy called the standard meter, which was kept at the International Bureau of Weights and Measures near Paris. The distance between two fine lines engraved near the ends of the bar, when the bar was held at a temperature of 0°C and supported mechanically in a prescribed way, was defined to be one meter. Historically, the meter was intended to be one ten-millionth of the distance from the north pole to the equator along the meridian line through Paris. However, accurate measure-

* See "The New Definition of the Meter," by P. Giacomo, *American Journal of Physics,* July 1984, p. 607.

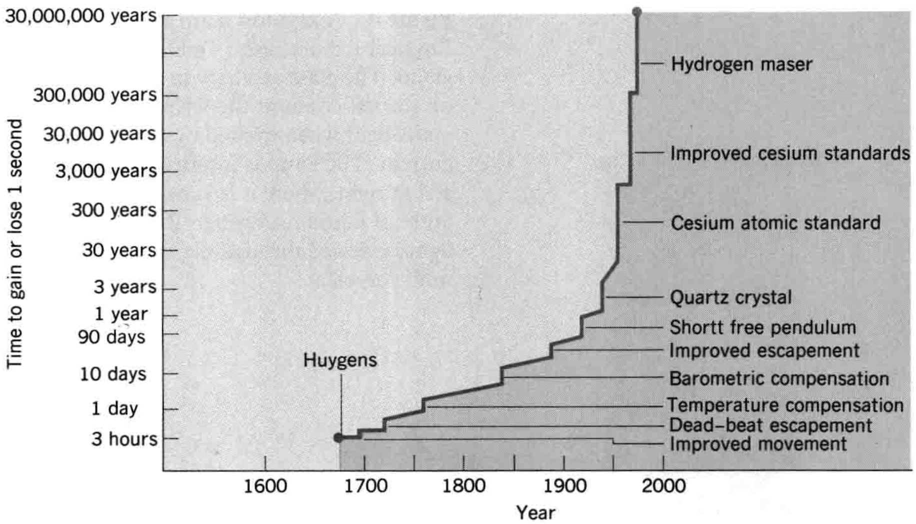


Figure 3 The improvement in timekeeping over the centuries. Early pendulum clocks gained or lost a second every few hours; present hydrogen maser clocks would do so only after 30,000,000 years.

ments showed that the standard meter bar differs slightly (about 0.023%) from this value.

Because the standard meter is not very accessible, accurate master copies of it were made and sent to standardizing laboratories throughout the world. These secondary standards were used to calibrate other, still more accessible, measuring rods. Thus, until recently, every measuring rod or device derived its authority from the standard meter through a complicated chain of comparisons using microscopes and dividing engines. Since 1959 this statement had also been true for the yard, whose legal definition in the United States was adopted in that year to be

$$1 \text{ yard} = 0.9144 \text{ meter} \quad \text{(exactly)}$$

which is equivalent to

$$1 \text{ inch} = 2.54 \text{ centimeters} \quad \text{(exactly).}$$

The accuracy with which the necessary intercomparisons of length can be made by the technique of comparing fine scratches using a microscope is no longer satisfactory for modern science and technology. A more precise and reproducible standard of length was obtained when the American physicist Albert A. Michelson in 1893 compared the length of the standard meter with the wavelength of the red light emitted by atoms of cadmium. Michelson carefully measured the length of the meter bar and found that the standard meter was equal to 1,553,163.5 of those wavelengths. Identical cadmium lamps could easily be obtained in any laboratory, and thus Michelson found a way for scientists around the world to have a precise standard of length without relying on the standard meter bar.

Despite this technological advance, the metal bar remained the official standard until 1960, when the 11th General Conference on Weights and Measures adopted an atomic standard for the meter. The wavelength in vacuum of a certain orange-red light emitted by atoms of a particular isotope of krypton*, ^{86}Kr, in electrical discharge was chosen (see Fig. 4). Specifically, one meter was defined to be 1,650,763.73 wavelengths of this light. With the ability to make length measurements to a fraction of a wavelength, scientists could use this new standard to make comparisons of lengths to a precision below 1 part in 10^9.

The choice of an atomic standard offers advantages other than increased precision in length measurements. The ^{86}Kr atoms are available everywhere, are identical, and emit light of the same wavelength. The particular wavelength chosen is uniquely characteristic of ^{86}Kr and is sharply defined. The isotope can readily be obtained in pure form.

By 1983, the demands for higher precision had reached such a point that even the ^{86}Kr standard could not meet them and in that year a bold step was taken. The meter was redefined as the distance traveled by a light wave in a specified time interval. In the words of the 17th General Conference on Weights and Measures:

> *The meter is the length of the path traveled by light in vacuum during a time interval of 1/299,792,458 of a second.*

This is equivalent to saying that the speed of light c is now *defined* as

$$c = 299{,}792{,}458 \text{ m/s} \quad \text{(exactly).}$$

---

* The superscript 86 in ^{86}Kr gives the *mass number* (the number of protons plus neutrons in the nucleus) of this isotope of krypton. Naturally occurring krypton gas contains isotopes with mass numbers 78, 80, 82, 83, 84, and 86. The wavelength of the chosen radiation will differ in these different isotopes by about 1 part in 10^5, which is unacceptably large compared with the precision of the standard, about 1 part in 10^9. In the case of the cesium clock, there is only one naturally occurring isotope of cesium, which has mass number 133.