FIFTH EDITION

Physics

RESNICK • HALLIDAY • KRANE

Volume 1

VOLUME ONE

PHYSICS

Fifth Edition

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SOME PHYSICAL CONSTANTS*

Speed of light in vacuum	c	3.00×10^{8} m/s
Newtonian gravitational constant	G	6.67×10^{-11} N·m²/kg²
Avogadro constant	N_A	6.02×10^{23} mol^{-1}
Molar gas constant	R	8.31 J/mol·K
Mass-energy relation	c^2	8.99×10^{16} J/kg
		931.5 MeV/u
Electric constant (permittivity)	ϵ_0	8.85×10^{-12} F/m
Magnetic constant (permeability)	μ_0	1.26×10^{-6} H/m
Planck constant	h	6.63×10^{-34} J·s
		4.14×10^{-15} eV·s
Boltzman constant	k	1.38×10^{-23} J/K
		8.62×10^{-5} eV/K
Elementary charge	e	1.60×10^{-19} C
Electron mass	m_e	9.11×10^{-31} kg
Electron rest energy	$m_e c^2$	511.0 keV
Proton mass	m_p	1.67×10^{-27} kg
Proton rest energy	$m_p c^2$	938.3 MeV
Bohr radius	a_0	5.29×10^{-11} m
Bohr magneton	μ_B	9.27×10^{-24} J/T
		5.79×10^{-5} eV/T

*For a more complete list, showing also the best experimental values, see Appendix B.

SOME CONVERSION FACTORS*

Mass

1 kg = 1000 g = 6.02×10^{26} u
1 u = 1.66×10^{-27} kg

Length

1 m = 100 cm = 39.4 in. = 3.28 ft
1 mi = 1.61 km = 5280 ft
1 in. = 2.54 cm
1 light-year = 3.26 parsec = 9.46×10^{15} m
1 Å = 0.1 nm = 100 pm = 10^{-10} m

Time

1 d = 86,400 s
1 y = $365\frac{1}{4}$ d = 3.16×10^{7} s

Volume

1 L = 1000 cm³ = 10^{-3} m³ = 1.06 quart
1 gal (U.S.) = 231 in.³ = 3.79 L

Angular measure

1 rad = 57.3° = 0.159 rev
π rad = 180° = $\frac{1}{2}$ rev

Speed

1 m/s = 3.28 ft/s = 2.24 mi/h
1 km/h = 0.621 mi/h

Force and Pressure

1 N = 10^{5} dyne = 0.225 lb
1 Pa = 1 N/m² = 10 dyne/cm² = 1.45×10^{-4} lb/in.²
1 atm = 1.01×10^{5} Pa = 14.7 lb/in.² = 76 cm-Hg

Energy and Power

1 J = 10^{7} erg = 0.239 cal = 0.738 ft·lb
1 kW·h = 3.6×10^{6} J
1 cal = 4.19 J
1 eV = 1.60×10^{-19} J
1 horsepower = 746 W = 550 ft·lb/s

Electricity and magnetism

1 T = 1 Wb/m² = 10^{4} gauss

*See Appendix G for a more complete list.

SOME PHYSICAL PROPERTIES

Air (dry, at 20 °C and 1 atm)	
Density	1.21 kg/m^3
Specific heat capacity at constant pressure	1010 J/kg · K
Ratio of specific heat capacities	1.40
Speed of sound	343 m/s
Electrical breakdown strength	3×10^6 V/m
Effective molar mass	0.0289 kg/mol
Water	
Density	1000 kg/m^3
Speed of sound	1460 m/s
Specific heat capacity at constant pressure	4190 J/kg · K
Heat of fusion (0 °C)	333 kJ/kg
Heat of vaporization (100 °C)	2260 kJ/kg
Index of refraction ($\lambda = 589$ nm)	1.33
Molar mass	0.0180 kg/mol
Earth	
Mass	5.98×10^{24} kg
Mean radius	6.37×10^6 m
Free fall acceleration at the Earth's surface	9.81 m/s^2
Standard atmosphere	1.01×10^5 Pa
Period of satellite at 100 km altitude	86.3 min
Radius of the geosynchronous orbit	42,200 km
Escape speed	11.2 km/s
Magnetic dipole moment	8.0×10^{22} A · m^2
Mean electric field at surface	150 V/m, down
Distance to:	
Moon	3.82×10^8 m
Sun	1.50×10^{11} m
Nearest star	4.04×10^{16} m
Galactic center	2.2×10^{20} m
Andromeda galaxy	2.1×10^{22} m
Edge of the observable universe	$\sim 10^{26}$ m

SUPPLEMENTS

Instructor's Supplements

Instructor's Solutions Manual by PAUL STANLEY, California Lutheran University. This manual provides worked-out solutions for all of the end-of-chapter problems.

Instructor's Manual by J. RICHARD CHRISTMAN, U.S. Coast Guard Academy. This manual includes suggested syllabi, lecture notes, a list of the problems that appear in the Student Solutions Manual, a complete list of answers to the problems, a comparison of the problems with the Fourth Edition, and a list of computer projects.

Test Bank by J. RICHARD CHRISTMAN, U.S. Coast Guard Academy. This manual includes more than 2200 multiple-choice questions. These items are also available in the Computerized Test Bank (see below).

Instructor's Resource CD. This CD contains:

- All of the *Instructor's Solutions Manual* in both LaTex and pdf files
- Computerized Test Bank, in both IBM and Macintosh versions, with full editing features to help the instructor customize tests.
- All text illustrations, suitable for both classroom projection and printing.

Wiley Physics Simulations. This CD contains 50 interactive simulations covering all major topic areas in the introductory physics course. They are programmed in Java and can be used as lecture demonstrations or as on-line student assignments.

Wiley eGrade. eGrade is a powerful on-line homework management system that allows instructors to assign and grade homework using the web.

Student's Supplements

Study Guide by J. RICHARD CHRISTMAN, U.S. Coast Guard Academy. This student study guide provides an array of study aids and problem-solving help.

Student Solutions Manual by PAUL STANLEY, California Lutheran University. This manual provides students with complete worked-out solutions to 25 percent of the problems found at the end of each chapter of the text.

VOLUME ONE

PHYSICS

PREFACE TO VOLUME 1

This is the fifth edition of the textbook first published in 1960 as *Physics for Students of Science and Engineering* by David Halliday and Robert Resnick. For four decades this book has provided the standard for the calculus-based introductory survey course and has been known for the clarity and completeness of its presentation. In the present edition we have striven to increase accessibility without sacrificing the level or the rigor of its content. The text has been substantially rewritten to make the material flow more smoothly and to ease the student's entry into new subjects. We have attempted to provide more practical examples and to proceed from the particular to the general when new topics are introduced.

This edition features significant changes in the pedagogy as well as in the order of the chapters. Those who are familiar with the fourth edition of this text will find the same topics but in a revised order. In making these revisions, we have sought the advice of users of past editions and have taken into consideration the results of physics education research. Among the changes we have made in this edition are the following:

1. We have continued the effort (begun in the previous edition) to achieve a more coherent approach to energy, especially one that bridges the gap between mechanics and thermodynamics. The need for a new approach to energy has been indicated from a variety of sources. Persistent student difficulties with energy concepts have been revealed through physics education research (for example, see the work of Lillian McDermott and co-workers*). The need to promote a greater understanding of Newton's laws has led Priscilla Laws** to propose a re-ordering of topics in introductory mechanics in which conservation of mechanical energy is introduced only after a full study of vector mechanics, including systems of particles and momentum conservation. A survey pointing out some difficulties with the conventional presentations of energy conservation has been given by Arnold Arons.*** Based in part on these ideas, in this edition we have chosen to develop the energy concept following the presentation of vector mechanics (in both translational and rotational forms). This approach allows for a more unified and coherent treatment of energy and the law of conservation of energy, and it also permits a "spiral" approach in which we can apply energy techniques to problems already solved using laws of vector mechanics. Energy concepts are introduced in this edition in Chapters 11-13, which then provide the critical background necessary for the extensive use of energy and its conservation in the remainder of this volume.

2. The chapter on vectors in the fourth edition has been eliminated. Instead, vector techniques are introduced as needed, beginning with vector addition and components of vectors in Chapter 2 (kinematics) and continuing with the cross product in Chapters 8 and 9 (rotational kinematics and dynamics) and the dot product in Chapter 11 (work and energy). In this way students find presentations of vector techniques as they are needed and immediately applied. In each case we have provided end-of-chapter exercises to help students become familiar with the concepts and techniques. A new appendix gives a summary of important vector concepts and formulas.

3. Again based in part on the findings of Priscilla Laws and other physics education researchers, we have changed the ordering of introductory topics to: one-dimensional kinematics, one-dimensional dynamics, and then two-dimensional kinematics and dynamics. We need not reproduce here the many arguments that support this change, but we feel that at minimum it helps to deal with the persistent student confusion in associating acceleration with velocity rather than with

*"Student Understanding of the Work-Energy and Impulse-Momentum Theorems," by Ronald A. Lawson and Lillian C. McDermott, *American Journal of Physics*, September 1987, p. 811.

**"A New Order for Mechanics," by Priscilla W. Laws, in *Conference on the Introductory Physics Course*, John Wiley & Sons, 1997, p. 125.

***"Development of Energy Concepts in Introductory Physics Courses," by Arnold Arons, *American Journal of Physics*, December 1999, p. 1063; see also *Teaching Introductory Physics*, by Arnold Arons, John Wiley & Sons, 1997, chapter 5.

force; for example, our new ordering allows us to introduce centripetal force upon the first presentation of uniform circular motion (rather than one or two chapters later, as in the previous ordering), and it allows the association between gravitational force and gravitational acceleration to be made at an earlier stage to dispel some of the errors that students commonly make in identifying the magnitude and direction of the acceleration in projectile motion.

4. The chapter on oscillations, which preceded gravitation and fluid mechanics in the previous edition, now follows those topics and serves as a natural introduction to wave motion.

5. The material in the fourth edition on equilibrium (Chapter 14) has been largely incorporated into the chapter on rotational dynamics (Chapter 9) in the present edition.

6. Thermodynamics, which occupied five chapters in the previous edition, has been recast into four chapters in this edition. A new chapter (22) on the molecular properties of gases incorporates topics from kinetic theory and statistical mechanics (Chapters 23 and 24 of the fourth edition) as they relate to the properties of the ideal gas. Topics relating to work and energy in the ideal gas then fall naturally into Chapter 23 of this edition (the first law of thermodynamics). Chapter 24 (entropy and the second law) differs considerably from the corresponding chapter in the fourth edition in that here we give entropy its appropriate and more prominent role as fundamental to an understanding of the second law.

7. In the fourth edition, topics from modern physics were "sprinkled" throughout the text, generally in sections labeled as "optional." In this edition we continue to use examples from modern physics where appropriate throughout the text, but the separate sections on modern physics have been consolidated into Chapter 20 (special relativity) in this volume and Chapters 45-52 in volume 2 (which treat topics from quantum physics and its applications to atoms, solids, and nuclei). We strongly believe that relativity and quantum physics are essential parts of an introductory survey course at this level, but that justice to these subjects is done better by a coherent, unified presentation rather than a collection of isolated expositions. As was the case in the fourth edition, we continue to place the chapter on special relativity among the classical mechanics chapters in volume 1, which reflects our strong belief that special relativity belongs squarely among the kinematics and mechanics chapters dealing with classical physics. (However, instructors who with to delay the presentation of this material can easily postpone coverage of Chapter 20 until later in the course.)

The end-of-chapter material in this edition differs significantly from that of the previous edition. The previous problem sets (which were all keyed to chapter sections) have been carefully edited and placed into two groups: exercises and problems. Exercises, which are keyed to text sections, generally represent direct applications of the material in the associated section. Their purpose is usually to help students become familiar with the concepts, important formulas, units and dimensions, and so forth. Problems, which are not keyed to text sections, often require use of concepts from different sections or even from previous chapters. Some problems call for the student to estimate or independently locate the data needed to solve the problem. In editing and grouping the exercises and problems, we have also eliminated some problems from the previous edition. Within the next year we shall offer a problem supplement that will incorporate most of the missing problems as well as a selection of new exercises and problems. As before, answers to odd-numbered exercises and problems are given in the text and those to the even-numbered exercises and problems can be found in the instructor's manual that accompanies the text.

Multiple-choice questions and computer problems have also been added to the end-of-chapter material. The multiple-choice questions are generally conceptual in nature and often call for unusual insights into the material. Answers to the multiple-choice questions can be found in the instructor's manual. The computer problems may require familiarity with spread-sheet techniques or with symbolic manipulation routines such as Maple or Mathematica.

We have striven to develop a textbook that offers as complete and rigorous a survey of introductory physics as is possible at this level. It is, however, important to assert that *few (if any) instructors will want to follow the entire text from start to finish,* especially in a one-year course. There are many alternate pathways through this text. The instructor who wishes to treat fewer topics in greater depth (often called the "less is more" approach) will be able to select from among these pathways. Some sections or subsections are explicitly labeled as "optional," 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 Manual, available as a companion volume, offers suggestions for abbreviating the coverage. Even so, the complete presentation remains in the text where the curious student can seek out the omitted topics and be rewarded with a broader view of the subject. We hope that the text can thus be regarded as a sort of "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 in two volumes. The present volume covers kinematics, mechanics, and thermodynamics; volume 2 covers electromagnetism, optics, and quantum physics and its applications. Supplements available include:

Instructor's Solutions Manual	Student Solutions Manual
Instructor's Manual	Student Study Guide
Instructor's Resource CD	Physics Simulations
Test Bank	eGrade Homework Management System

In preparing this edition, we have benefitted from the advice of a dedicated team of reviewers who have, individually or collectively, carefully offered comments and criticisms on nearly every page of the text:

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We would like to extend special appreciation to two individuals whose tireless efforts and exceptional contributions have been essential to the success of this project and who have set high standards for the quality of the finished product. J. Richard Christman has been a long-time contributor whose careful review of the text and contributions to the supplements have now extended over three editions. His insistence on careful explanations and correct pedagogy throughout the text has in a multitude of instances kept us on the proper track. Paul Stanley is a new addition to the team whose primary responsibility has been the end-of-chapter questions and problems. He has brought to the project a wealth of creative ideas and clever insights that will challenge students (as well as instructors) to extend their understanding of the material.

The staff at John Wiley & Sons has provided constant support for this project, for which we are exceptionally grateful. We would especially like to thank Stuart Johnson for his management of this project and his dedication to its completion. Essential contributions to the quality of this text have been made by production editor Elizabeth Swain, photo editor Hilary Newman, illustration editor Anna Melhorn, and designer Karin Kincheloe. Without the skill and efforts of these individuals this project would not have been possible.

Despite the best efforts of authors, reviewers, and editors, it is inevitable that errors may appear in the text, and we welcome communication from users with corrections or comments on the content or pedagogy. We read all of these communications and respond to as many as possible, but we regret not being able to respond to all of them. Nevertheless, we encourage readers' comments, which can be sent to www.wiley.com/college/hrk.

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CHAPTER 1

MEASUREMENT

Despite the mathematical beauty of some of its most complex and abstract theories, 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 PHYSICAL QUANTITIES, STANDARDS, AND UNITS

The laws of physics are expressed in terms of many different quantities: mass, length, time, force, speed, density, resistance, temperature, luminous intensity, magnetic field strength, and many more. Each of these terms has a precise meaning, and they form part of the common language that physicists and other scientists use to communicate with one another—when a physicist uses a term such as "kinetic energy," all other physicists will immediately understand what is meant. Each of these terms also represents a quantity that can be measured in the laboratory, and just as there must be agreement on the meaning of these terms, there must also be agreement about the units used to express their values. Without such agreement, it would not be possible for scientists to communicate their results to one another or to compare the results of experiments from different laboratories.

Such comparisons require the development and acceptance of a set of *standards* for units of measurement. For example, if a measurement of length is quoted as 4.3 meters, it means that the measured length is 4.3 times as long as the value accepted for a standard length defined to be "one meter." If two laboratories base their measurements on the same accepted standard for the meter, then presumably their results can be easily compared. For this to be possible, the accepted standards must be *accessible* to those who need to calibrate their secondary standards, and they must be *invariable* to change with the passage of time or with changes in their environment (temperature, humidity, etc.).

Maintaining and developing standards for measurement is an active branch of science. In the United States, the National Institute of Standards and Technology* (NIST) has the primary responsibility for this development. However, it is also necessary to have wide international agreement about standards, which has been accomplished through a series of international meetings of the General Conference on Weights and Measures (known by their French acroynm

* See http://physics.nist.gov/cuu for information about NIST's role in maintaining standards.

CGPM) beginning in 1889; the twenty-first meeting was held in 1999.*

Fortunately, it is not necessary to establish a measurement standard for every physical quantity—some quantities can be regarded as fundamental, and the standards for other quantities can be derived from the fundamental ones. For example, length and time were once regarded as fundamental quantities with their individual established standards (respectively the meter and the second); the measurement standard for speed (= length/time) could then be derived in terms of those standards. However, in more recent years the speed of light has been measured to a precision exceeding that of the former standard meter; as a result, today we still use a fundamental standard for the second, but we define the standard for length (the meter) in terms of the speed of light and the second (see Section 1-4). This case illustrates how measurements of increasing precision can change the established standards and how rapidly such standards evolve. Since the publication of the first edition of this textbook, the precision of the standard unit for time (the second) has improved by more than a factor of 1000.

The basic problem therefore is to choose a system involving the smallest number of physical quantities as fundamental and to agree on accessible and invariable standards for their measurement. In the next sections of this chapter we discuss the internationally accepted system and some of its fundamental quantities.

1-2 THE INTERNATIONAL SYSTEM OF UNITS**

At its various meetings, the General Conference on Weights and Measures selected as *base units* the seven quantities displayed in Table 1-1. This is the basis of the International System of Units, abbreviated SI from the French *Le Système International d'Unités.* SI is the modern form of what is known generally as the metric system.

Throughout the book we give many examples of SI derived units, such as speed, force, and electric resistance, that follow from Table 1-1. 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 3.

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 recommended the prefixes shown in Table 1-2.

TABLE 1-1 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

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. As Table 1-1 shows, the kilogram is the only SI base unit that *already* incorporates one of the prefixes displayed in Table 1-2. Thus 10^3 kg is *not* expressed as 1 kilokilogram; instead, $10^3\ \text{kg} = 10^6\ \text{g} = 1\ \text{Mg}$ (megagram).

To fortify Table 1-1 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 the Gaussian system in this book. Appendix G gives conversion factors to SI units.

The other 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. The United States continues to be the only developed country that, so far, has not adopted SI as its official unit system. However, SI is standard in all U.S. government laboratories and in many industries, especially those involved in foreign trade. The loss of the *Mars Climate Orbiter* spacecraft in September 1999 has

TABLE 1-2 SI Prefixes[a]

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

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

* See http://www.bipm.fr for the recommendations of this conference.

** 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 811 of the National Institute of Standards and Technology (1995 edition).

been traced to the fact that the manufacturer reported some of the *Orbiter*'s characteristics in British units, which the NASA navigation team mistakenly took to be SI units. Careful attention to units can be very important!

SAMPLE PROBLEM 1-1. 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.

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

$$\text{speed} = 55\,\frac{\cancel{\text{mi}}}{\cancel{\text{h}}} \times \frac{1609\text{ m}}{1\,\cancel{\text{mi}}} \times \frac{1\,\cancel{\text{h}}}{3600\text{ s}} = 25\text{ m/s}.$$

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

$$\text{volume} = 16\,\cancel{\text{gal}} \times \frac{231\,\cancel{\text{in.}}^3}{1\,\cancel{\text{gal}}} \times \left(\frac{2.54\text{ cm}}{1\,\cancel{\text{in.}}}\right)^3 = 6.1 \times 10^4\text{ cm}^3.$$

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.

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 1-3 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 with a precision of about 1 second in 200,000 years, but even this precision is not sufficient for the demands of modern science, technology, and commerce.

In 1967, the 13th General Conference on Weights and Measures adopted a definition of the second based on a characteristic frequency of the radiation emitted by a cesium atom. In particular, they stated that

TABLE 1-3 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.)	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.

The second is the duration of 9,192,631,770 vibrations of a (specified) radiation emitted by a (specified) isotope of the cesium atom.

Figure 1-1 shows the current national frequency standard, a so-called *cesium fountain clock* developed at the National Institute of Standards and Technology (NIST). Its precision is about 1 second in 20 million years.

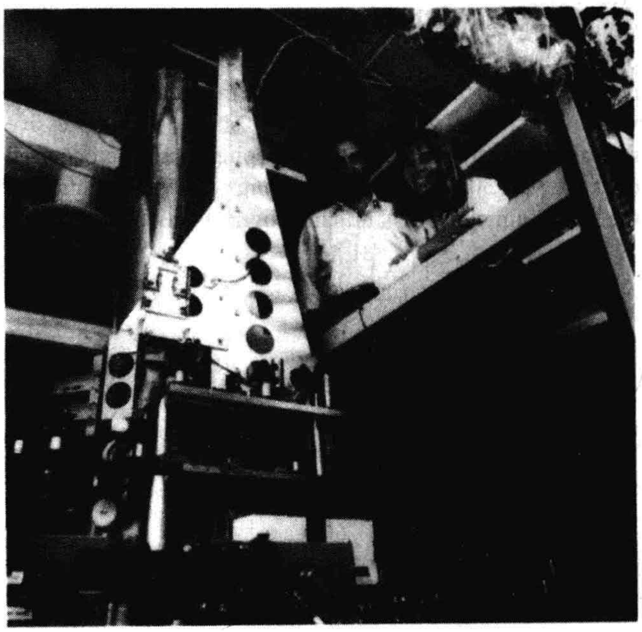

FIGURE 1-1. The National Frequency Standard NIST-F1, a so-called cesium fountain clock, developed at the National Institute of Standards and Technology. It is shown with its developers, Steve Jefferts and Dawn Meekhof. In this device extremely slow-moving cesium atoms are projected upward, covering a distance of about a meter before falling back under gravity to their launch position in about 1 second. Hence the label "fountain." The small speeds of these projected atoms make possible precise observation of the frequency of the atomic radiation that they emit. For more information, see http://www.nist.gov/public_affairs/releases/n99-22.htm.