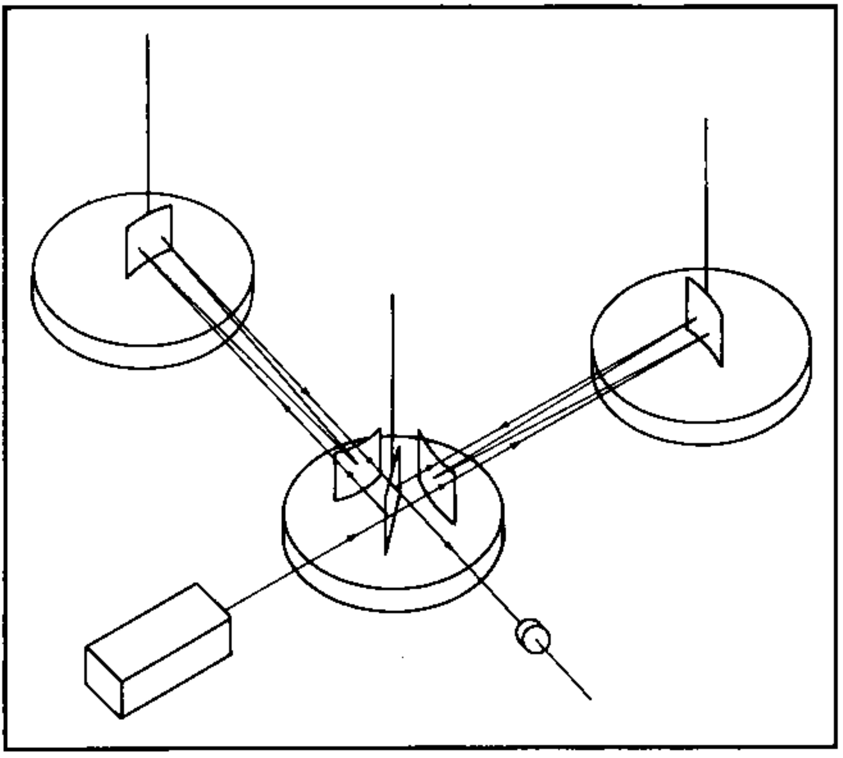
Research Concerning Metrology and Fundamental Constants (1983)

Pages
51

Size
5 x 9

ISBN
0309325749

Report Subcommittee of the Committee on Fundamental Constants; Numerical Data Advisory Board; Commission on Physical Sciences, Mathematics, and Resources; National Research Council



Schematic representation of a gravity wave detector based on a Michelson interferometer with multiple-reflection optical delay lines in each arm. The source of the beam, lower left, is a laser and the detector, lower right, is a photodiode. (See page 29.)

Research Concerning Metrology and Fundamental Constants

Report Subcommittee of the
Committee on Fundamental Constants
Commission on Physical Sciences, Mathematics,
and Resources
National Research Council

NATIONAL ACADEMY PRESS
Washington, D.C. 1983

NOTICE: The project that is the subject of this report was approved by the Governing Board of the National Research Council, whose members are drawn from the councils of the National Academy of Sciences, the National Academy of Engineering, and the Institute of Medicine. The members of the committee responsible for the report were chosen for their special competences and with regard for appropriate balance.

This report has been reviewed by a group other than the authors according to procedures approved by a Report Review Committee consisting of members of the National Academy of Sciences, the National Academy of Engineering, and the Institute of Medicine.

The National Research Council was established by the National Academy of Sciences in 1916 to associate the broad community of science and technology with the Academy's purposes of furthering knowledge and of advising the federal government. The Council operates in accordance with general policies determined by the Academy under the authority of its congressional charter of 1863, which establishes the Academy as a private, nonprofit, self-governing membership corporation. The Council has become the principal operating agency of both the National Academy of Sciences and the National Academy of Engineering in the conduct of their services to the government, the public, and the scientific and engineering communities. It is administered jointly by both Academies and the Institute of Medicine. The National Academy of Engineering and the Institute of Medicine were established in 1964 and 1970, respectively, under the charter of the National Academy of Sciences.

Available from

NUMERICAL DATA ADVISORY BOARD
National Research Council
2101 Constitution Avenue, N.W.
Washington, D.C. 20418

REPORT SUBCOMMITTEE OF THE COMMITTEE ON FUNDAMENTAL CONSTANTS

FRANCIS M. PIPKIN, Harvard University, *Chairman*
HANS G. DEHMELT, University of Washington
ROGERS C. RITTER, University of Virginia
HUGH G. ROBINSON, Duke University
WILLIAM H. WING, University of Arizona
DONALD R. YENNIE, Cornell University

COMMITTEE ON FUNDAMENTAL CONSTANTS

FRANCIS M. PIPKIN, Harvard University, *Chairman*
HANS G. DEHMELT, University of Washington
JOHN HALL, University of Colorado
ROGERS C. RITTER, University of Virginia
HUGH G. ROBINSON, Duke University
BARRY N. TAYLOR, National Bureau of Standards
WILLIAM H. WING, University of Arizona
DONALD R. YENNIE, Cornell University

STAFF

GESINA C. CARTER, *Executive Secretary*

NUMERICAL DATA ADVISORY BOARD

R. STEPHEN BERRY, University of Chicago, *Chairman*
ROBERT A. ALBERTY, Massachusetts Institute of Technology
CARL O. BOWIN, Woods Hole Oceanographic Institution
SAMUEL ETRIS, The Silver Institute
ALAN GITTELSOHN, The Johns Hopkins University
WILLIAM HAPPER, JR., Princeton University
WILLIAM W. HAVENS, JR., Columbia University
THADEUSZ B. MASSALSKI, Carnegie-Mellon University
MILTON TERRY, Bell Laboratories

GESINA C. CARTER, *Executive Secretary*

COMMISSION ON PHYSICAL SCIENCES, MATHEMATICS, AND RESOURCES

ACKNOWLEDGMENT

The Committee would like to thank many of its colleagues, in particular Peter Bender, Carlton Caves, Gerhart Friedlander, Stephen Berry, and Daniel Kleppner, for constructive comments on the manuscript.

1

OVERVIEW AND RECOMMENDATIONS

OVERVIEW

The purpose of this report is to call attention to the important role of fundamental constants and precision measurements in science and to demonstrate a requirement for increased and continuing support of this field. Precise knowledge of fundamental constants and techniques for making more accurate and reliable measurements are required to test basic theories, to extend our knowledge of the universe, and for practical applications of fundamental theories. This report demonstrates by example that research in this field, aimed in its primary goals at basic understanding, has led to profound advances that have had an impact on much of our technology-based society.

The field of fundamental constants and precision measurements is regretfully given fragmented and uncoordinated attention, resulting in a forfeiture of research opportunities that could delay significant technological advances. This report reviews the general scope of the field and makes recommendations for future research and applications.

RECOMMENDATIONS

The Committee on Fundamental Constants recommends that agencies engaged in the support of research take a broad view of their primary mission and fund research in fundamental constants and precision measurements. This research may not have an immediate payoff but will lead to significant developments over a long time period. Some of the areas that should be supported are the following:

- Efforts to determine with greater precision and with new methods fundamental quantities that form a common basis for the physical sciences and the associated theories, such as the Planck constant, the Boltzmann constant, the Faraday constant, the Avogadro constant, and the speed of light;
- Efforts to determine with greater precision the fundamental properties of matter such as the mass, charge, and magnetic moment of the electron;
- Efforts to determine quantities useful in metrology such as the acceleration of gravity at fixed points on the Earth's surface and the wavelengths of selected atomic or molecular spectral lines throughout the visible region of the spectrum;
- Efforts to improve the reference standards for measurements through the use of well-understood atomic, molecular, or solid-state systems such as standards for length, time, mass, temperature, voltage, current, and resistance;
- Efforts to improve the tools and techniques for making precision measurements;
- Efforts to disseminate new measurement technology beyond the confines of the standards laboratories;
- Efforts to produce critical compilations of valuable data;
- Efforts to improve calculational techniques for comparing theory and experiment in sensitive situations;
- Efforts to use precision measurements to test fundamental theories and set limits on the spatial and temporal variation of the fundamental constants;
- Efforts to improve theoretical predictions necessary to test fundamental theories, such as establishing the limits of the Josephson determination of $2e/h$ and the quantized Hall effect determination of e^2/h and precision quantum-electrodynamics properties such as the electron g factor anomaly, $g - 2$, and refined bound-state properties.

2

INTRODUCTION

A distinguishing characteristic of western culture is the prominent role of science. The importance of science is not only that it addresses our need to understand nature and our own origins but that it has a dramatic impact on our way of life. An essential element of science is that it rests on data from measurements that can in principle be carried out by anyone, permitting the phenomena to be independently repeated and verified. The ultimate test of a scientific theory is whether it agrees with the results of observational measurement. At its core is the recognition of what can be measured and how precisely it can be measured.

The quantification of natural phenomena requires reference quantities or standards, and procedures for making precise measurements. Basic measurements include length, time, mass, charge, voltage, and temperature; common reference units include the meter, second, kilogram, coulomb, volt, and kelvin. Within a carefully developed framework of units and standards, scientists are able to measure natural phenomena in a reproducible manner that permits intercomparisons between independent observers.

The fundamental theories of science point to the existence of constants of nature and to certain invariant relationships between measurements. These constants are important because they arise independently in different contexts, and because they have the same value no matter what phenomena are being described. These quantities are known as "fundamental constants."

Examples of one category of fundamental constants are the speed of light c in Einstein's Theory of Special Relativity, the Planck constant h in quantum theory, the Sommerfeld fine structure constant α in quantum electrodynamics, and the Weinberg angle θ_W and the masses of the weak vector bosons in the unified electro-weak-interaction theory.

A second category comprises properties of the elementary constituents of nature: the mass and charge of the electron and the mass, charge, and magnetic moment of the proton, to name but a few.

A third category of fundamental constants consists of conversion factors required to relate one set of units to another. For example, the Boltzmann constant relates temperature to mechanical energy. Such constants are, in part, artifacts of the system of measurement.

The assignment of the categories of constants is not fixed; the assignments are subject to change as the theoretical framework becomes more comprehensive and one constant sometimes is discovered to be related to others. An example is the magnetic moment of the electron. At one time, characterization of the electron required not only knowledge of the mass and charge but also the spin and magnetic moment. The Dirac theory and quantum electrodynamics eliminate the last two by predicting the spin and giving a value for the magnetic moment in terms of other constants. Similarly, the mechanical equivalent of heat was once an important theoretical link unifying the concept of energy; it is now regarded as a relatively minor conversion factor and a member of the third category of constants. There is hope that future theories will provide a value for the proton magnetic moment and the Weinberg angle in terms of more fundamental constants. A principal goal of science is the creation of unifying theories that reduce the total number of fundamental constants needed to describe physical observations.

Closely linked with measurements of the fundamental constants are precision measurements to test basic theories, for instance, the measurement of the Lamb shift in hydrogen as a test of quantum electrodynamics. These two areas interrelate closely and have as a common requirement the advancement of technology for making even more precise measurements.

Research related to fundamental constants, which provides the focal point for this unifying aspect of science, is not yet fully appreciated by the science community. It is often assumed that this research is being carried out "elsewhere" and that adequate support is made available to all the deserving individuals who wish to work in the field of fundamental constants and precision measurements. This in fact is not so. Research in this field draws from many disciplines since fundamental constants appear as unifying elements in disparate fields of science. Because of its multidisciplinary nature, the field has by and large not received focused recognition.

By clarifying and defining the field of fundamental constants and precision measurements, and by providing examples of its practical applications and its scientific excitement, this report argues for recognition of this important subject as a field in its own right, deserving of increased support. This report urges that in an era of expanding fragmentation in physics, stronger consideration be given to the need for sustaining the important connective threads of fundamental-constant research that tie together so many disciplines.

The following chapter describes the origins and development of the field to establish the flavor and general worth of the work. Chapter 4 outlines the scope of the field as it appears today. Chapter 5 points to some likely future directions for research. Chapter 6 gives a concise conclusion of the report. The Appendix summarizes the origins and history of committees and councils for constants.

3

ORIGINS AND DEVELOPMENT OF THE FIELD

Much of the progress of science has been due to inquisitive individuals who sought out and recognized regularities and attempted to quantify them in the hope that some pattern would emerge and an explanation could be developed. They were often motivated by a desire to find evidence for a particular pet theory. In this endeavor they sometimes found unanticipated regularities that later led to major changes in the way man views nature. An important ingredient is often more precise measurements of known phenomena. To illustrate this process we will give a few examples from both the early and recent histories of science and technology.

TYCHO'S MEASUREMENTS AND KEPLER'S LAWS

A good example is the work of Tycho Brahe (1546-1601).[1] When Tycho was a young man, the Copernican theory, in which it was postulated that the planets moved around the Sun in circular orbits, was generally accepted. Tycho set out to make more precise measurements of the angular positions of the planets. He built two large observatories, devised and constructed precise pretelescopic pointers, and designed a clock more accurate than any previously available. He observed the planets and stars regularly and compiled extensive catalogs and numerous records of all kinds of celestial objects.

Tycho rejected the heliocentric model as a result of his observations, because his data were not sufficiently precise to show the stellar parallax and thus prove that the Earth was moving with respect to a frame defined by the stars. Lack of precision in his measurements led him to develop a model in which the Sun moved around the stationary Earth, while all the planets and stars except the Moon moved around the Sun in circular orbits.

Although the limited accuracy of the data led Tycho to reject the heliocentric theory in which the Earth moves around the Sun in a circular orbit, the precision led Kepler to the discovery that the planets move around the Sun in elliptical orbits with the Sun at one of the foci. Tycho's data for Mars were so precise that they could not be fitted either with a circular orbit or with the conventional eccentric orbits and epicycles. The conclusion that the orbits were ellipses became the first of Kepler's three laws and was the most important clue required for the discovery of the other two laws. These three laws were an essential ingredient for the development of Newtonian mechanics and the theory of universal gravitation.

Kepler's discovery that the orbit of Mars was an ellipse highlights the importance to science of a simple increase in the accuracy of measurements. The deviation between the ellipse and the previously assumed circle causes a difference of no more than 8 minutes of arc in the longitude of the planet, but as Kepler put it, "These eight minutes alone have led to a complete renovation of astronomy" (8 minutes of arc corresponds to the angle subtended by the diameter of an ordinary pencil at 3 m and by one quarter of the diameter of the Moon).

ATOMIC SPECTRA AND BOHR'S THEORY

In the nineteenth century, scientists found that electrically excited gases produced light at characteristic wavelengths that did not display any apparent regularity. It was presumed that these wavelengths corresponded to the frequencies of vibration of some structure with elastic properties. Even though there was no readily understandable pattern, scientists developed techniques for making precise measurements of the wavelengths of the radiation characteristic of the various elements and carefully tabulated their results. Through a study of these data, a Swiss school teacher, Johann Jakob Balmer (1825-1898), found a simple but rather unorthodox formula using a single empirical constant and the sequence of integers from 2 to 6 that fit the wavelengths characteristic of hydrogen in the visible part of its spectrum. Rydberg later generalized this formula to fit series of lines observed in the spectra of other elements with two empirical constants and a sequence of integers. The Balmer formula was an essential clue used by Bohr in his development of the quantum theory for the hydrogen atom. The precision of the wavelength measurements and the accuracy with which the Bohr theory reproduced them considerably enhanced the credibility of the quantum-mechanical explanation of the characteristic wavelengths.

DENSITY OF GASES AND THE DISCOVERY OF ARGON

An instructive example of the payoff resulting from efforts to increase the precision of what might be termed routine measurements is Lord Rayleigh's discovery of argon. In words taken from Professor Richtmyer's 1931 address as retiring vice-president of section B of the American Association for the Advancement of Science, titled "The Romance of the Next Decimal Place":

"...one of the outstanding characteristics of nineteenth century physics is the extent to which the making of precise measurements, merely for the sake of securing data of greater accuracy, became a recognized part of research in physical laboratories. This point is aptly illustrated by Lord Rayleigh's determinations of the absolute density of gases in the early nineties.

"Proust's law demanded that the ratio of the respective densities of oxygen and hydrogen should be 16:1. The measurement of this ratio by Regnault as early as 1845 yielded 15.96:1, a result in agreement with Proust's law almost within experimental error. In 1888 Rayleigh attacked the problem anew, and, after a long investigation described by him as 'unusually tedious', found that the ratio was 15.882:1, thus proving untenable the theoretical value of 16:1.

"Having thus developed an improved technique for measuring the density of gases with great accuracy, Rayleigh, for no apparent purpose other than to satisfy his curiosity, decided 'before leaving the subject [to ascertain] not merely the relative but also the absolute densities of the more important gases.' In the course of this investigation he found that nitrogen, prepared from its chemical compounds and thus presumably pure, had a density of 1.2505 grams per liter, while that prepared by removing oxygen from ordinary air had a density of 1.2575 grams per liter, a difference of about 1/2 per cent which previous and less precise determinations had failed to detect. After eliminating one by one the various possible sources of contamination with known gases, Rayleigh concluded that the difference in density must be due to the presence in the atmosphere of a hitherto unknown gas more dense than nitrogen".

This clue led directly to the discovery of argon. A century earlier, Cavendish had observed that atmospheric nitrogen was 0.5 percent heavier than nitrogen prepared from nitrates and that when nitric acid was formed from the action of an electric spark on moist air there was an inert gaseous residue comprising 0.8 percent of the volume of nitrogen. Stimulated by Rayleigh's discovery, Ramsay recalled Cavendish's result and reproduced Cavendish's experiment. Ramsay then used the recently developed techniques of optical spectroscopy to establish the existence of argon. Subsequently Ramsey isolated helium, krypton, neon, and xenon.

PRECISION MEASUREMENTS AND QUANTUM ELECTRODYNAMICS

A more recent example of the significant role measurements with improved precision can play in increasing our understanding of nature is provided by the 1967 determination of 2e/h using the ac Josephson effect in superconductors. By irradiating a Josephson thin-film tunnel junction with x-band microwaves (8-12 GHz) and using the phenomenon of microwave-induced constant-voltage current steps, one can obtain a value for 2e/h. The only two precision measurements required are those of frequency and voltage. The difference between this value and the previous best value, which resulted from the 1963 least-squares adjustment of the fundamental constants of Cohen and DuMond, was 35 $\pm$ 10 ppm. It was realized subsequently that the cause of the discrepancy was the use by Cohen and DuMond in their 1963 work of a value for α derived from the early 1950s measurement of the deuterium fine-structure splitting, which subsequently turned out to be incorrect.

The Josephson 2e/h determination was especially significant because a reliable indirect value of α could be used to compare quantum-electrodynamic theory and experiment critically and unambiguously. This was in marked contrast to the situation that existed prior to 1967 when no such value was available and checks of quantum electrodynamics (QED) were mainly checks of internal consistency.

Included among the quantities that require an accurate value for α in order to compare theory and experiment are the anomalous magnetic moments of the electron and muon; the energy levels in hydrogenlike atoms, especially the n = 2 Lamb shift in hydrogen; and the ground-state hyperfine splitting in hydrogen, $^{3}He^{+}$, muonium, and positronium. Of particular interest in the late 1960s was the hydrogen hyperfine splitting. This quantity, which is essentially the energy difference between a hydrogen atom in which the electron and proton spins are parallel and one in which they are in opposite directions, can be measured to the extraordinary accuracy of 1 part in 10^{12} using the hydrogen maser. In contrast, the theoretical quantum-electrodynamical equation for the hydrogen hyperfine splitting, which involves only well-known constants and α, is limited to an accuracy of a few parts per million because of the difficulty in calculating some of the terms in the equation from theory.

The most uncertain term is δN, the contribution due to the proton polarizability, which arises from the internal structure of the proton. In the 1960s, theoretical calculations predicted $\delta N = 0 \pm 5$ ppm. This was in conflict with what was implied by the value of α accepted at that time derived from a measurement of the fine-structure splitting in deuterium. When this value of α was used to calculate a theoretical value of the hydrogen hyperfine splitting for comparison with the hydrogen-maser value, and when the difference was assumed to arise solely from the existence of a nonzero proton polarizability, it was found that $\delta N = 43 \pm 9$ ppm. This meant that the probability for δN to be as small as predicted by direct calculation was only 1 in 20,000, an obvious discrepancy. In contrast, when the value of α derived indirectly using the Josephson effect measurement of 2e/h was used in place of the value derived from the deuterium fine-structure measurements, it was found that $\delta N = 2.5 \pm 4.0$ ppm, in agreement with the theoretical calculations. In this manner the Josephson-effect value for α removed a discrepancy that during the 1960s was termed one of the major unsolved problems of QED. It was realized immediately that the cause of the discrepancy was the use by Cohen and DuMond in their 1963 work of a value of α derived from the early 1950s measurement of the deuterium fine-structure splitting, which turned out to be incorrect. This example further illustrates the overall unity of physics--a low-temperature solid-state experiment provided information about the structure of the proton--as well as how precise measurements of fundamental constants can illuminate apparent inconsistencies in our description of nature.

THE LONGITUDE PROBLEM AND THE MEASUREMENT OF TIME

The position of a ship at sea is known when its latitude and longitude have been determined.[2] The navigator can find his latitude by making measurements on the Sun or stars. However, in order to find his longitude, he must, besides making a measurement of this kind, know the time at which the observation was made. His astronomical observations give his local time, and his longitude east or west of the given fixed point is given simply by the difference between this local time and time measured by a clock synchronized with a clock set at 12 noon when the Sun crosses the prime meridian.

The early coastwise navigators were able to make their way from landmark to landmark, and it was not until long ocean voyages began to be made in the fifteenth and sixteenth centuries that the need was felt for a method of finding the longitude. The employment of a timekeeper to be carried on board ship was proposed by Gemma Frisius in 1530, but the only timekeepers of that period were foliot clocks and watches, which were incapable of approaching the accuracy necessary. As early as 1598, a large sum of money was offered by Phillip III of Spain for development of a suitable chronometer. Various astronomical methods of determining the time, such as the observation of the moons of Jupiter, were suggested, but none of these proved of sufficient accuracy.

The first timekeepers made specifically for use at sea were designed by Huygens about 1662. They were pendulum clocks and were mounted in gimbals in order to keep them upright as much as possible. When tested at sea they behaved reasonably well in calm weather, but in rough weather, their timekeeping became erratic and they frequently stopped altogether. They had no form of compensation for the effect of varying temperature, and their rate varied with the varying attraction of gravity at different places on the Earth. Huygens persisted right up to his death in 1695 in attempts to make a satisfactory marine timekeeper, but with no success.

As time progressed and long voyages became more common, the problem became more pressing. In order to encourage people to find a solution to this problem, the British Government established a special committee called the "Board of Longitude" with a prestigious membership. The Chairman was the Lord High Admiral, roughly the equivalent of our Chief of Naval Operations today; other members were the President of the Royal Society; the Astronomer Royal; the Professors of Mathematics at the Universities of Oxford, Cambridge, and London; and a number of military officers. In his statement to the Board in 1714, Sir Isaac Newton said, "for the true determining of the longitude at sea, there have been several projects that are true in the theory but difficult to execute." He went on to mention the use of the eclipses of Jupiter's satellites and the observation of the so-called lunars, that is, the relative motion of the Moon with respect to the stellar background; but with regard to all of these, he said that they simply would not work. He then discussed some of the more promising methods, and, among other things, he said, "One is by a watch to keep time exactly, but by reason of the motion of the ship, the variation of heat and cold, wet and dry, and the difference of gravity in different latitudes, such a watch hath not yet been made."

The Board of Longitude then decided to offer a prize for the development of Newton's "watch." What they did in modern terms was to issue a Request for Proposals. In 1714 the British Government offered for a method of determining a vessel's longitude at sea at the end of a voyage to the West Indies £10,000 if the accuracy was within 60',£15,000 if the accuracy was within 40', and £20,000 if within 30'. Since one degree of longitude corresponds to 4 minutes in time, an error of 30', or half a degree, corresponds to an error of 2 minutes in time, so that in order to win the full award it was necessary for a timekeeper to err by less than this amount in the 6-week voyage. This was a formidable technical requirement for those days. The clock had to be accurate to roughly 3 seconds a day or about 1 part in 30,000.

The clockmaking industry was invited to make proposals, and under certain circumstances grants were issued to the proposers in order to support the work. The British clockmaking industry was thereby mobilized to help solve this important national problem. The Royal Observatory, which already was a growing concern under government control, was used for evaluating the results of the competition. In developing the chronometer, the Board disbursed well over £100,000 in the period from 1714 to the end of the eighteenth century. This is actually a fairly large sum of money in view of the fact that a line-of-battle ship, fully equipped, in those days cost approximately £20,000. Even then research and development were not cheap. As one might expect, the Board was deluged by a large number of quack proposals.

Test facilities were established at the Royal Greenwich Observatory to check out the devices that were submitted to the Board. Eighteenth-century environmental test chambers were installed, and hundreds of clocks were tested before sea trials of the survivors of these tests were made. These environmental test chambers are still at Greenwich and can be viewed in the Naval Museum.

A timekeeper that even exceeded the specified performance was constructed by John Harrison, a Yorkshire carpenter, who devoted practically his whole life to this endeavor. Between 1728 and 1759 Harrison designed and constructed four marine timekeepers, all of entirely original design, and with the fourth of these he eventually succeeded in winning the award. The essential invention that he produced to solve the problem was the bimetallic spring, which permitted a clock to operate on a constant-tension spring independent of temperature. He also developed better bearings with constant friction under all conditions of humidity and temperature. In short, he overcame all the problems to which Newton had alluded in his testimony before the Board of Longitude.

In 1761, the fourth timekeeper was taken to Jamaica and back in H.M.S. Deptford, being tended on the way by Harrison's son William. On this voyage it more than fulfilled all expectations. On arrival at Jamaica it was found to have erred by no more than 5 seconds, corresponding to an error in longitude of only 1-1/4', or approximately 1-1/2 miles in the latitude of Jamaica. Harrison had evidently succeeded in solving the problem of determining longitude at sea. The reward of £20,000 was not paid to him at once, however, as the Board of Longitude suspected that the good performance of the chronometer might be accidental. A second test was therefore made in 1764, and William Harrison again accompanied the instrument, this time to Barbados and back. Its performance was as good as on the first test. Its total indicated error in 5 months was only 54 seconds. After corrections had been applied for its declared change of rate at different temperatures, the actual error was 15 seconds.

Harrison had shown that it was possible to construct a timekeeper that would keep sufficiently accurate time at sea, but his timekeeper was complicated and difficult to construct. It was left to his successors to design instruments that could be produced in large numbers to be available for all seagoing ships. The progress made was remarkably rapid, and by 1820 chronometer making had become an important branch of the watch trade.

The development of more precise clocks is a continuing activity that has resulted in the atomic clocks now in use throughout the world. Not only are these clocks essential components for navigation of vessels at sea, they are required for the guidance of spaceships and the precise targeting of missiles. They are essential components for long-baseline interferometry and radio astronomy. Atomic clocks are required for coordinated television transmission. Atomic clocks have been carried on airplanes making circuits in both directions around the Earth and used to verify the difference predicted by the Theory of Relativity. Atomic clocks have been sent up in rockets and used to measure the gravitational red shift and to test the predictions of general relativity. The availability of cheap, portable atomic clocks may make possible collison-free aircraft-control systems.

THE STRUCTURE OF THE SUN AND THE THEORY OF RELATIVITY

One of the most profound conceptual revolutions of the twentieth century is provided by Einstein's Theory of General Relativity. It predicts, among other things, that Euclid's laws of geometry do not describe the universe, that the orbit of a planet is not precisely an ellipse, as Kepler proposed, but an ellipse whose major axis turns slowly in the direction of the planet's revolution and that rays of starlight are bent when passing near a large mass such as the Sun. The unexplained portion of the precession of the orbit of the planet Mercury provided the first evidence for general relativity; the observation during a solar eclipse of stars nearly occulted by the Sun provided the second major piece of evidence for the theory and caused a popular sensation.

In the 1960s, it was pointed out that the Sun is not precisely round; rather, its rotation about its axis causes it to flatten at the poles and bulge at the equator, thereby modifying its gravitational field. This induced quadrupole moment could affect Mercury's orbit and thereby remove the agreement of the observed precession with the predictions of general relativity. Experiments carried out at that time indicated that the Sun was oblate. Calculations carried out using as input the observed oblateness revealed a discrepancy with the prediction of general relativity.

Other measurements carried out subsequently, using planetary radar, indicated that general relativity was correct. Therefore, another observer set out to remeasure the solar oblateness by a different method that was sensitive to minute variations in the brightness of the solar limb, or the Sun's edge, as viewed through a fine slit. These measurements cast doubt on the oblateness found in the earlier measurements but provided evidence for solar pulsations. This has contributed to the development of the new field of solar seismology, which promises to reveal much new information about the Sun's structure, about its internal processes, and, by implication, about those of other stars. These measurements may also provide a better measurement of the quadrupole moment of the Sun and hence a more definitive test of general relativity.

ATOMIC STANDARDS

In this century, one of the major motivations for a unified system of fundamental constants has come from the closer link between chemistry and physics resulting from the development of quantum mechanics. This link required precise and uniform values of the constants for interrelating the results from different laboratories and for comparison with theory. Since many chemists were unfamiliar with the details of the physics literature and had little motivation to become familiar with them, they wanted standardized values as free of ambiguity as possible. It is frustrating to compare two results when you do not know the precise standards in terms of which they were measured or the values of the constants used in reducing the data.

The suggestion to obtain natural reference standards for all measurements--rather than artificial prototype standards such as the standard kilogram, the length of the King's foot, the standard meter, or the standard pendulum clock--is an old one that dates back to the first recognition of the atomic and molecular structure of matter. Development and implementation of such standards have become technically feasible only in the twentieth century, which has seen some standards replaced by atomic standards that can be more easily transferred from one location to another. The second is now defined in terms of the frequency of oscillation of the cesium atom. The unit of length is defined in terms of the wavelength of a particular atomic transition in ^{86}Kr and will soon be defined in terms of the speed of light in vacuum and the cesium-atom second. The volt is maintained in terms of 2e/h via the ac Josephson effect. The recently discovered quantized Hall effect may make feasible a realization of the ohm in terms of the fine-structure constant and the velocity of light. The major holdout is the standard of mass. It is still the mass of the international prototype of the kilogram--a "hunk" of platinium-iridium kept in a vault at the Bureau International des Poids et Mesures (BIPM) in Sèvres, just outside Paris, France. One needs a precise count of the number of atoms in a macroscopic piece of matter to make practical a useful unit based on the mass of the atom. If the Avogadro constant, N_A, could be determined to an accuracy of a few parts in 10^9, then one could consider abandoning the present definition of the kilogram and replacing it with one based on the mass of a particular atom.

UNIVERSAL CONSTANTS

One of the most intriguing ideas for the three fundamental mechanical units is that put forward by Planck at the end of the last century. He suggested

$$\text{mass:} \quad \sqrt{\frac{\hbar c}{G}} = 2.2 \times 10^{-5} \text{ gram},$$

$$\text{length:} \quad \sqrt{\frac{\hbar G}{c^3}} = 1.6 \times 10^{-33} \text{ centimeter},$$

$$\text{time:} \quad \sqrt{\frac{\hbar G}{c^5}} = 5.4 \times 10^{-44} \text{ second}.$$

Here $\hbar$ is the Planck constant divided by 2π, G is the Newtonian gravitational constant, and c is the speed of light. The first two are sometimes referred to, respectively, as the Planck mass and the Planck length. Planck pointed out that this was the only system of units that was free, like blackbody radiation itself, of all complications of solid-state physics, molecular binding, atomic constitution, and elementary-particle structure, because it draws for its background only on the simplest and most universal principles of physics, the laws of gravitation and blackbody radiation. It is speculated that the Planck mass is related to the unification of the gravitational and strong interactions and that the Planck length is a length at which the smoothness of space breaks down and assumes a granular structure. At present the understanding of the relationship of gravitation and quantum field theory is unsatisfactory, and the relevance of these natural lengths remains uncertain. One of the important motivations behind some of the present efforts to improve the precision with which one can make measurements is to detect gravitational waves and study more thoroughly the gravitational interaction.

REFERENCES

1. The material in this section relies heavily on D. H. Menzel, F. W. Whipple, and G. deVancouleurs, Survey of the Universe (Prentice-Hall, Englewood Cliffs, New Jersey, 1970), Chap. 3.

2. The material in this section relies heavily on the following two sources: H. Mark, The Bridge, National Academy of Engineering 10, Winter 1980-81, p. 20; and F. A. B. Ward, Time Measurement (Her Majesty's Stationary Office, London, 1961), Chap. IV, p. 29.

4

SCOPE OF THE FIELD

The term "fundamental constants" describes a variety of quantities used in the physical sciences. They deal with the fundamental content of physical sciences: space and time, the four fundmental forces of nature (gravitational, electromagnetic, weak nuclear,and strong nuclear), and the matter in the universe. In one common usage the fundamental constants are a set of quantities, the knowledge of which is sufficient to predict, using appropriate theory, all the properties of matter and radiation at both a macroscopic and microscopic level. Candidates for such a set are G, the gravitational constant; h, the Planck constant; c, the speed of light, e, the charge of the electron; m_e, the mass of the electron; m_p, the mass of the proton; k, the Boltzmann constant; θ_W, the Weinberg angle, which relates the charged and neutral weak currents; G_F, the coupling constant for the weak nuclear interaction; θ_C, the Cabibbo angle, which relates the strangeness changing and nonstrangeness changing weak nuclear interactions; and Λ, the quantum chromodynamic coupling parameter, which characterizes the strong nuclear interaction. In one sense, only dimensionless numbers formed from measured constants have fundamental significance.

What we call the set of fundamental constants is both time and theory dependent. For example, at present we do not know how to predict with precision the masses of the so-called elementary particles in terms of a small set of more fundamental measurable parameters, such as the masses of the quarks and the coupling parameter of quantum chromodynamics. It is hoped that in the future we will be able to make such calculations and thus reduce the number of independent quantities required. At present we require G_F, θ_W, θ_C, and the masses of the leptons to describe weak-interaction phenomena. The Glashow-Weinberg-Salam electro-weak unification theory expresses G_F in terms of e, θ_W, and m_W, where m_W is the mass of the charged vector boson. The currently studied SU(5) grand unification theory provides an a priori prediction for θ_W. A similar simplification produced through quantum electrodynamics and the Dirac theory of the electron was the calculation in 1947 of the magnetic moment of the electron in terms of e, h, m_e, and c. There is as yet no such precise calculation of the magnetic moment of the proton.

It is an open question whether the fundamental constants change slowly with time and have slightly differing values throughout the universe. One line of questioning invokes Mach's principle, the suggestion that the inertial mass of an object depends on the distribution of matter in the universe. If this is true and the universe is expanding, then might not the gravitational force be getting weaker in time? This possibility was raised by Dirac in 1937 as the "large numbers hypothesis," which involved ratios of physical constants. This suggestion appeared to many as a numerological exercise. Recently, however, a large number of papers have appeared, putting it in a new context and showing in combination with some cosmological theories a plausible connection to a grand unified theory of all interactions.

A second use of the term fundamental constants is to refer to the properties of matter and the fundamental forces independent of whether they are related by theory. This is essentially a list of useful quantities. The Particle Properties Data Book (updated every year and published in Reviews of Modern Physics; also available from CERN and the Lawrence Berkeley Laboratory) is one such compilation. Examples are e, the elementary unit of charge; m_p, the mass of the proton; μ_μ, the magnetic moment of the muon, $\Delta\nu_H$, the hyperfine splitting for the hydrogen atom; μ_o, the permeability of the vacuum; R_∞, the Rydberg constant for infinite mass; and α, the fine structure constant. This list clearly overlaps with the first list and is distinguished primarily by the measurability and utility of the items. Some constants such as $\Delta\nu_H$, R_∞, and α are combinations of the items listed in the first two categories of fundamental constants. In one sense, α is more fundamental and e should be calculated from α, h, c, and ε_o.

Some fundamental constants have been assumed to be strictly zero. Examples are the mass of the photon (experimentally: $m_\gamma c^2 \leq 6 \times 10^{-16}$ eV) and the masses of the neutrinos (experimentally: $m_{\nu(e)}c^2 \leq 60$ eV). If the photon did have a mass, it would probably not have far-reaching consequences. A nonvanishing neutrino mass, however, would be of importance for astrophysical and cosmological questions. Modern theories expect the neutrino to have a finitie mass.

A third use of the term fundamental constants is to refer to conversion factors used to relate one system of units to another. The Boltzmann constant relates temperature as measured in terms of a rather arbitrary unit to the energy content of a thermodynamic system, the Avogadro constant relates the atomic unit of mass to the macroscopic unit of mass, the acceleration of gravity on the Earth's surface relates the gravitational force on an object to its mass. A conversion factor relates the ohm as-maintained to the SI (International System)-defined ohm. Another conversion factor relates the volt as maintained using Josephson-junction voltage steps at a given microwave frequency to the SI-defined volt. The measured wavelength of a particular line in iodine is currently used to convert measurements of wavelengths in the visible spectrum to absolute frequencies in terms of the Cs-defined second. The Faraday is essentially a conversion factor relating the charge of an electron to the number of atoms in a macroscopic piece of matter. Prior to recent developments, a conversion factor was required to relate the wavelengths of optical and x-ray transitions. Even more common conversion factors change pounds to grams, inches to centimeters, gallons to liters, and knots to kilometers/hour.

How a constant is viewed in the context of these categories may change as theory and technology advance. They should only be regarded as convenient characterizations.

The character of the work in this field spans a wide range. The principal common ingredients are efforts to improve the technology for making precise measurements, efforts to develop new methods for measuring familiar quantities, and efforts to make measurements and theoretical calculations of increased precision to test fundamental theories. The most important advances come through the development of new bases of measurement, theoretical calculations of increased precision, and new techniques. The main part of the effort is devoted to the increase in precision through the improved design of apparatus, improved methods for taking data, better understanding of sources of systematic errors, and the use of new experimental phenomena such as the Josephson effect and the quantized Hall resistance. The same fundamental constants apply in many fields, and developments in one field may have great implications for another.

The nature of the work can best be illustrated by listing some of the major advances that have been made in the last hundred years. Many of these developments, in fact, took place in the last two decades. A partial list follows:

1. The establishment of a standard of length and multiples and submultiples of that unit, first in terms of the prototype standard meter and subsequently in terms of the wavelength of suitable atomic transitions using both conventional and laser sources.
2. The development of alloys such as Invar for the construction of apparatus that is less sensitive to temperature.
3. The measurement of the gyromagnetic ratio of the proton using a calculable magnetic field derived from a carefully constructed solenoid with measurable dimensions and a known current.
4. The development of techniques for maintaining the volt in terms of the small voltage-current steps of a Josephson junction irradiated with microwaves of a known frequency.
5. The development of the triple-point temperature standard and methods of extending the temperature scale to both high and low temperatures.
6. The development of portable atomic clocks with a precision of a few parts in 10^{13}.
7. The development of refined techniques for the comparison of wavelengths of different optical sources through interferometric measurements.
8. The development of least-squares analysis for determining the best set of fundamental constants from the available measurements and identifying those measurements that may be incorrect.
9. The development of techniques for relating the wavelengths of optical, x-ray, and γ-ray transitions first by x-ray measurements with ruled gratings and crystals and subsequently by transfer using interferometers constructed from good silicon crystals and iodine-stabilized lasers.

10. The establishment of a frequency chain from the microwave region to the optical region so that the frequency of optical transitions can be directly related to the second as defined by the Cs clock.

11. The precision measurement of the velocity of light through the direct determination of the frequency and wavelength of an optical transition.

12. The development of techniques for making precision measurements of the fine structure of simple atoms. These measurements revealed a disagreement with the simple Dirac theory and were a major impetus for the development of renormalized quantum electrodynamics. Improved experimental precision and refined theoretical calculations continue to push tests of quantum electrodynamics to more refined levels.

13. The development of new calculational techniques that made it possible to determine the predictions of quantum electrodynamics with great accuracy--in particular the development of techniques for handling the enormous algebraic reductions and high-dimensional numerical integrals necessary for theoretical calculations.

14. The development of techniques for storing single electrons and ions and carrying out precision measurements of their properties.

15. The measurement of the properties of exotic atoms such as positronium and muonium and the improvement of related theories to provide tests of quantum electrodynamics and relativistic bound-state theory.

16. The development of the calculable capacitor for the maintenance of the electrical unit of resistance.

17. The development of portable devices for precise measurement of the acceleration of gravity for applications in geophysics and for navigation at sea.

18. The precise measurement of the Rydberg constant first using cooled light sources and subsequently using laser spectroscopy in a gas cell and an atomic beam.

19. The development of techniques for thermometry using thermal noise sources.

20. The measurement of the Faraday using several electrochemical techniques.

21. The development of a series of current balances for better realization of the electrical unit of current.

22. The development of more precise methods for measuring the density of matter as an ingredient for measuring the Avogadro constant.

23. The development of techniques for locking lasers to atomic and molecular lines and directly comparing the frequencies of lasers, thereby obtaining a short-term stability of a few parts in 10^{14}.

24. The investigation of the quantum "limits" of measurement and the development of methods for manipulation of these restrictions.

25. The establishment of limits on the variation of the fundamental constants with space and time.

26. The development of refined methods for measuring atomic masses.

27. The development of techniques for studying with great precision the energy levels of simple molecules.

28. The discovery of the quantized Hall resistance and its development as a standard for resistance measurements.

This is only a partial list. It does not, in particular, give proper credit to the value of good standards to industry and to the work that has been done to promulgate such standards. Mass production relies heavily on high-precision machinery for which parts are readily and easily replaceable. Commerce requires uniform measures of weight and fluid volume. The electrical industry requires uniform measures of voltage, current, resistances, electrical power, and microwave power. The electronics industry requires materials of high purity and precise control in the manufacturing of semiconductor devices. Medicine requires standardization of drugs and procedures for chemical diagnosis. A few of the applications of techniques developed for precision measurements are the following:

1. Use of lasers in surveying, microcircuit technology, computer storage, manufacturing control and supermarket sales and control.

2. Use of gravimeters for oil prospecting and detection of earthquakes.

3. Use of atomic clocks for navigation, long-baseline interferometry, television and radio-frequency standards, and narrow-band broadcasting systems.

4. Use of nuclear magnetic resonance (NMR) for magnetic-field measurements; whole-body scanners.

5. Use for inertial guidance of precise voltage and current measurements and ultra-precise ball bearings.

6. Use of gallium triple-point thermometry in studies of blood chemistry.

7. Use for sensors and control mechanisms for robotics.

5

SOME DIRECTIONS FOR FUTURE DEVELOPMENT

It is always difficult to predict the future of science. Important advances often result from unanticipated discoveries or realization of new avenues of approach. In this chapter, information will be used that is now available to suggest both experimental and theoretical areas in which there will be important advances in the next decade. A speculative point of view will be adopted.

Advances in the field of precision measurement and fundamental constants have often been associated with the introduction of new experimental techniques. The ripples are only now subsiding from the introduction over a decade ago of the Josephson-junction constant-voltage current steps and their subsequent use with a fixed microwave frequency to determine 2e/h. This has led to an independent determination of the value for the fine-structure constant, by using auxiliary constants such as the Rydberg, the magnetic moment of the proton in units of the Bohr magneton, the gyromagnetic ratio of the proton, and the speed of light. The recent discovery of the quantized Hall effect shows promise of producing an equally significant development in metrology.

For observation of the quantized Hall effect, a specially prepared semiconductor is placed in a high magnetic field at cryogenic temperatures and the relationship between the current and the Hall voltage is measured. The observed resistance is quantized, and its value can be calculated in terms of known fundamental constants. In particular, it depends on e^2/h rather than on the Josephson effect quantity 2e/h. With the aid of a value for the speed of light and knowledge of the SI value of the unit of resistance in terms of which the measurements are made, the quantized Hall resistance can be used to determine a value of $\alpha(=e^2/[4\pi\varepsilon_o\hbar c]$, which can be compared with that determined indirectly using the Josephson effect 2e/h and directly using measurements on simple atoms and quantum-electrodynamic (QED) calculations. Studies are now being carried out to see if the quantized Hall resistance is independent of the properties of the materials used in the samples and to improve the precision with which it can be measured. If the quantized Hall resistance turns out to depend in a calculable manner on the sample, it will provide an independent source of α and a check on the reliability of the Josephson effect α. Even if it proves to be material dependent, it will provide an easily maintained and transferrable standard for the ohm. It might even some day be used to define the standard ohm.

Another area in which major developments are taking place is the development of stable tunable lasers and the techniques for measuring their wavelengths and frequencies with great precision. It is anticipated that in the near future we will be able to use the techniques developed for radio and microwave frequencies over the last four decades in the optical region of the spectrum. The method of separated oscillatory fields has already been used to achieve line widths less than 1 kHz for the calcium intercombination transition at 657 nm. This development has great potential both for metrology and for tests of fundamental theories since many of the optical transitions are less limited by the natural or instrumental linewidth than are the accessible radio-frequency and microwave transitions. One can envision improvements by factors of 100 or more.

It has recently been demonstrated that a spectral source as variable and challenging to control as a jet-stream dye laser may be servo controlled to have a phase coherence time measured in a few tens of milliseconds. Since the dye-laser frequency of approximately 5×10^{14} Hz may be tuned anywhere in the visible and near ultraviolet regions of the spectrum by the use of appropriate dyes and/or frequency-doubling techniques, the sub-100-Hz linewidth implied by this coherence offers a spectacular measurement capability.

Techniques have been developed to establish a frequency chain based on the Cs-defined second all the way from the microwave region up to the visible spectrum. Techniques are being developed to beat the output of two visible lasers together and to measure directly the beat frequency between them. This will ultimately make feasible the direct measurement of the frequency of dye lasers in the visible part of the spectrum and render obsolete the tedious and difficult interferometric measurements of one wavelength in terms of another.

Another relatively new technique of great importance is the development of methods for working with trapped ions and trapped electrons. A trap containing a single electron has been used to measure g - 2 for the electron and the positron with a precision of 4 parts in 10^8. A similar trap has been used together with lasers to store and observe single barium ions. Radiation cooling techniques have been used to slow down the trapped ions and reduce the line width that is due to Doppler broadening. By bathing the trapped ions in light red-shifted from the natural frequency, one has a situation in which a photon is more likely to be absorbed during the time when the thermal velocity provides through the Doppler shift an approximate compensation of the detuning. On the average, however, the fluorescent radiation is emitted in all directions at the natural frequency. This cycle of absorbing quanta redder than the fluorescent quanta gives rise to cooling of the kinetic degrees of freedom. Final temperatures in the microkelvin range appear feasible. Not only will the lines be narrower, but the detectability of a small number of ions will be enhanced by their localization in micrometer-sized regions. These techniques are in their infancy, and work is now under way to improve the determination of g - 2 for the electron and to use trapped ions for frequency standards in both the microwave and optical regions. It appears certain that the synthesis of the new ultra-stable laser techniques with trapped-ion spectroscopy will result in dramatic advances in frequency standards. It is no longer science-fiction fantasy to contemplate clocks with a long-term stability and reproducibility of 1 part in 10^{15}.

Techniques have been proposed for direct multiplication from the microwave region to the optical region through the interaction of a focused laser and an electron in a circular orbit. This technique may not work, but one suspects that some such method will be made to work. The rewards are great and worth an intense effort.

A field that is certain to expand with the introduction of refined laser techniques is the precision spectroscopy of the simplest atoms, hydrogen and helium. Determination of the Rydberg constant by measurement of the wavelength of the radiation required to excite the 2s - 3p transition has reached a precision of 1 part in 10^9. Direct frequency measurement should make attainable a precision of 1 part in 10^{12}. Somewhat less precise results have been obtained for the 1s - 2s two-photon transition at 243 nm. Because the natural line width for this transition is 1 Hz, there are prospects for improvement by a factor of 10^6. Independent determination of the Lamb shift and the Rydberg can be made by measurement of the frequencies for the 1s - 2s two-photon transition and for the 2s to ns Rydberg transitions. Similar techniques can be used to study the Rydberg states of helium in both the singlet and triplet configurations.

Another domain for new precision measurements with lasers is transitions between long-lived Rydberg states in both hydrogen and helium. For high principal quantum numbers and especially for states with high angular momentum, the perturbations due to electromagnetic fields of thermal origin affect each state almost identically. Consequently, level shifts due to those fields will not prohibit precise measurements of the intervals. It has been suggested that the hydrogen spectrum might provide the ideal quantum-mechanical frequency multiplier. The connection between standards of frequency in the microwave and visible spectra would be made through the use of the Dirac energy formula and its QED corrections rather than a host of nonlinear mixers and auxiliary lasers spanning the spectral interval between these two interesting domains of the electromagnetic spectrum.

The availability of ultra-stable lasers will make possible improved tests of special relativity. A recent laser version of the Michelson-Morley experiment improved the limit on the effect of a residual preferred frame by a factor of 4000. In the simplest model, which expands special relativity to include such effects, one expects to see in the optical length of an étalon a term proportional to $P_2(\cos\theta)$, where θ is the angle between the direction of propagation of the light in the laboratory and the direction of the axis of spatial anisotropy. If the 3 millikelvin anisotropy in the direction toward the Virgo local supercluster of galaxies observed in microwave measurements of the spatial anisotropy of the cosmic blackbody radiation is attributed to a Doppler shift, it leads to a 400 km/s motion of the solar system in the direction of Virgo. If one takes this velocity as a scale for determining a small deviation from the predictions of special relativity, the experimental limit of $\pm 2.5 \times 10^{-15}$ for the fractional frequency shift of the rotated Fabry-Perot cavity translates into a variation that is less than 10^{-9} of the shift expected from classical mechanics (i.e., Galilean relativity).

A second test of relativity made possible by such lasers is a precise measurement of the second-order Doppler shift. At present the best experimental measurement of the relativistic time dilation is the ratio of the lifetime of the muon observed for muons at rest and in the CERN muon storage ring, with $\gamma = 29$ ($\beta = 0.9994$). These experiments confirm the theory to 1 part in 10^3. With the marriage of fast atomic-beam techniques and stable lasers it appears feasible to enhance the precision of measurement of the relativistic time dilation by several orders of magnitude. The fast beam-stable laser system can also be used to measure the first-order Doppler shift and to study its dependence on the orientation in space of the atomic beam.

Another area in which there will be important developments is the spectroscopy of leptonic atoms. The availability of meson factories with high-intensity beams of stopping muons has made possible greater precision in the measurement of the hyperfine splitting of muonium and the gyromagnetic ratio for the muon. The detection of the $n = 2$ state of muonium has been reported. New techniques for slowing down positrons have resulted in more intense sources of positronium. A radio-frequency measurement of the Lamb shift in the $n = 2$ state of positronium has been made. The two-photon transition from the $n = 1$ ground state to the $n = 2$ excited state of positronium has been observed and a preliminary measurement carried out. The next decade gives promise of important advances in this domain. These tests will require further refinements of the associated theory, probably requiring sophisticated applications of powerful computers. They will provide tests of relativistic bound-state theory, which, if successful, will give us confidence in applying such theories to the quark model of hadrons.

Throughout the last decade, there has been a large effort to establish a more precise relationship between wavelength measurements in the microwave and optical domain and wavelength measurements in the x-ray and gamma-ray domain. This link is crucial for relating tests of QED using x rays and tests at lower energy. Throughout the first part of this century, this has been a source of confusion and uncertainty in the determination of the atomic constants. In the next decade, this link, currently at about 1 part in 10^6 accuracy level using combined x-ray optical interferometry, will be improved one to two orders of mangitude. This will make possible more precise tests of theory over a wider range in energy and more precise determinations of conversion factors such as the Avogadro constant. This will also make interpretable measurements of the Lamb shift in high-Z one-electron atoms such as Kr XXXVI.

The next decade may also see the development of a standard of mass based on an atomic quantity rather than the prototype platinum-iridium block at Sèvres. Although this would require two to three orders of magnitude improvement in existing density and isotopic abundance ratio measurements, it would make possible a redefinition of all the units in terms of atomic or molecular systems readily transferable from one place to another.

Another area in which there should be great advances in the next decade is the study of the gravitational interaction. Because of the weakness of the gravitational interaction, 10^{-40} of the electromagnetic interaction, it is difficult to study its fundamental properties with precision. G is known absolutely with a precision 100 to 1000 times less than most of the fundamental constants. Techniques are now being developed for measuring G with greater precision. A more important question is whether the force law for gravitation varies as $1/r^2$ over the complete range from nuclear dimensions to galactic dimensions. Experiments are now under way to detect any small deviation from a $1/r^2$ force law.

An exciting prospect for stabilized laser techniques is the construction of a new generation of gravitational-wave detectors based on long, high-finesse interferometers. It is proposed to use an interferometer with two arms at right angles to one another each with a length of a kilometer to detect gravitational waves. (See diagram on frontispiece.) The laser is frequency locked to one of the arms, and the other arm is locked to the laser. The correction in the second lock is then used as a signal for detecting gravitational waves. Similar detectors have been proposed for construction in space with a much longer baseline. This may be the way gravitational waves are first detected on the Earth.

The high sensitivity required to measure the small strains that would be produced by a gravitational wave has resulted in a series of efforts to understand the "quantum limits" of measurement and to devise methods to manipulate these restrictions to their best advantage. Experiments are just now being undertaken. This is an important area in which activity will increase and that should result in a new understanding of the ultimate limit to which we can make measurements.

Tests of the equivalence principle were extended to massive bodies in the solar system in 1976 through the lunar laser-ranging experiment. In this case the gravitational self-energy of the test body is a significant fraction of the total mass, so a fundamental property of gravitation is tested accurately. Tests of the equivalence principle for laboratory-sized bodies are being improved by using liquid flotation instead of thin fiber suspensions in constructing torsion balances. Both the laboratory and space experiments are likely to give better accuracy in the future.

A third line of experimentation uses high-precision rotators to look for deviations from general relativity. With careful attention to detail it appears feasible to construct in the laboratory a rotor with a decay time longer than 50 billion years. This rotor can be used to look for the spontaneous creation of matter suggested by some theories and to compare the gravitationally modified rates of clocks based on different electromagnetic principles, e.g., electrostatic versus magnetic interactions.

Two additional tests of general relativity made possible by the availability of atomic clocks are the precise measurement of the gravitational red shift and the measurement of the round-trip time delay for radio signals passing very close to the Sun. The gravitational red shift was measured by comparing the continuous-wave microwave signal generated from hydrogen masers located in space and at an Earth station. The result of this experiment agreed with the relativistic frequency shift predicted by general relativity at the 70×10^{-6} level. The Viking Lander on Mars was used as the transponder to measure the round-trip time delay of radio signals passing very close to the Sun. These measurements agreed with the predictions of general relativity to 1 in 10^3. The latter measurement could be improved by using spaceborne clocks to reduce disturbances due to near-Earth propagation. Both these measurements have the potential for providing more precise tests of general relativity.

6

CONCLUSION

Accurate knowledge of the fundamental constants is essential to the development of many branches of science. Fundamental constants can provide a unifying basis to apparently diverse fields. This report has attempted to demonstrate their importance to the sciences and the need to know their values accurately.

Determination of the fundamental constants requires continual development of advanced techniques for making precision measurements and for creating reliable standards. The last three decades have witnessed the creation of atomic standards for length, time, and voltage. The increased reliability and reproducibility of these standards have made possible more critical tests of fundamental theories. Practical spin-off from these developments has led to significant technological advances, which have had a profound effect on society, both socially and economically.

Because of the vital role played by the field of precision measurements and fundamental constants in basic and applied science and in industry, it is essential that the agencies responsible for funding scientific and engineering research recognize the contributions of the field and be sensitive to its needs.

The testing of fundamental theories to ever greater accuracy and the development of new methods for precision measuremnts should always be given serious consideration whenever an appropriate opportunity presents itself.

APPENDIX

ORIGINS AND HISTORY OF COMMITTEES AND COUNCILS FOR CONSTANTS

Standards for measurement of time, length, and mass have been needed ever since the existence of modern man in order to record observations of celestial and other natural phenomena, to guide his agricultural activities and to quantify transactions in trade. In view of humanity's basic needs, it is not surprising that many different measurement systems evolved. Coordination and uniformity of standards for measurement became a necessity when intercomparisons of measurements as performed by different parties became essential.

By 1875, the Convention du Mètre was adopted by 28 nations. This resulted in the establishment of the International Bureau of Weights and Measures (designated BIPM, the initials of its name in French). The BIPM is the executive body and is assigned the responsibility for maintaining the international primary standards. An International Committee of Weights and Measures is given responsibility for technical activities of the organization; each of its 18 members, of different nationality, is empowered by the assembly of government representatives but is free from any instructions of his own government. The International Committee also has the power to create and to decide on the membership of small, scientific advisory bodies called Consultative Committees.

The Consultative Committee for Electricity was created in 1927 to prepare a changeover from the so-called international electrical standards then legally in force (the ampere defined by $AgNO_3$ electrolysis, the ohm by a mercury column, the volt by a voltaic cell) to the absolute standards that are decimal multiples of cgs units. The date initially decided by the International Committee was January 1, 1940; it was postponed to 1948 on account of World War II. The definitions of the units newton, joule, watt, ampere, volt, ohm, coulomb, farad, henry, and weber were drafted by the Consultative Committee.

A second Consultative Committee, for photometry, was created in 1929 and instructed to establish an international system of units and standards for the measurement of luminous intensity and luminous flux to replace the so-called international candle and the Hefner Kerze, which were different by 10 percent.

The third Consultative Committee, created in 1937 for thermometry, established the thermodynamical temperature as defined by a single point definition, the triple point of water, instead of the previously adopted definition, which used the ice point and the steam point separated by an interval of 100 degrees.

The fourth Consultative Committee was created in 1952 to prepare a redefinition of the meter based on the wavelength of atomic radiation. The scope of this Committee now covers secondary wavelength standards, length measurement techniques, gas-laser radiations, the stabilization of their frequency, and the speed of light.

The fifth Consultative Committee was created in 1956 to study the definition of time and frequency units at the time when the International Committee adopted the definition of the second in terms of the tropical year to replace the century-old definition based on the mean solar day, which had proved to be of variable duration. In 1967 the second was redefined in terms of the atomic frequency of ^{133}Cs.

The sixth Consultative Committee was created in 1958 to deal with ionizing radiation. The seventh Committee, which was created in 1964, deals with units, their definition, their logical arrangement in a system, their symbols, and the instructions for their use. The eighth and most recent Consultative Committee was formed in 1979 to deal with questions relating to mass and the related quantities force and pressure.

Attempts to base the primary standards for measurement on accurately reproducible physical phenomena involving constants of nature started well before the Treaty of 1875, although this idea was not then used in the establishment of these early standards. A review by Huntoon and McNish[1] summarizes some of the early work attempting to base standards for measurement on physical constants of nature or fundamental properties of matter:

> Definition of the primary standards of measurement in terms of physical constants has been the hope of many physicists for years. The proposal by Jacques Babinet (1829), Clerk Maxwell (1870) and others to adopt the wavelength of light as the primary standard of length was probably the first step in this direction. As early as 1887, Michelson and Morley proposed a "method of making sodium light the actual and practical standard of length." In 1892-93 Michelson and Benoît accurately measured the wavelength of the cadmium red line in terms of the metre. Maxwell (1870) also suggested taking the periodic vibration of light as a standard of time and the masses of molecules as the standard of mass.[2-5]

Because selected fundamental properties of matter can be determined quite accurately and always have the same value, they form a reliable and transferable basis for universal measurement standards. In fact all units for physical measurement, except the unit of mass, are now linked to atomic properties. An atomic basis for the standard for mass is being developed. Much remains to be done, however, to disseminate this technology beyond the confines of the standards laboratories.

By their very nature, fundamental constants have a single "true" value. When, however, measurements are made in the laboratory, the values obtained differ from measurement to measurement even if the two measurements were made under seemingly identical conditions. Furthermore, the same fundamental constant can often be measured in rather different types of experiments, which give apparently different results. As a result, until the early 1920s, a consistent set of fundamental constants was not available. This caused confusion and was due in part to apparent inconsistencies and nonuniformity in the published literature. The realization of the magnitude and scope of the problem led to the establishment of the International Critical Tables by the International Union of Pure and Applied Chemistry (IUPAC) in 1919. The executive, financial, and editorial responsibilities for this project were given to the United States National Research Council of the National Academy of Sciences. The International Research Council (which later became the International Council of Scientific Unions (ISCU)) gave its endorsement to this project. Editors were chosen from various countries. The Editor-in-Chief was Edward W. Washburn from the U.S. National Bureau of Standards (NBS).

The first item of business to be completed prior to embarking on critical evaluation of the data was the adoption of a consistent set of most probable values for fundamental constants and conversion factors. Consequently, the editors compiled and accepted a set of nine fundamental constants, and evaluators were instructed to base all their data on these values. In this task, the editors obtained advice from scientists at NBS, the National Physical Laboratory (U.K.), and the Société Française de Physique, after an initial list of fundamental constants was prepared by F. E. Fowle of the U.S. Smithsonian Institution. The list appears in Volume I of the *International Critical Tables*, which was published in 1926.

As this history is being written in 1983, the Academy is still receiving requests regarding availability of the *International Critical Tables*--testimony to the obvious success it had in fulfilling a need for such authoritative compilation and to the confusion that exists today. The *International Critical Tables*, were published for the National Research Council by McGraw-Hill, New York; Vol. 1, 1926; Vol. II, 1927; Vol. III, 1928; Vol. IV, 1928; Vol. V, 1929; Vol. VI; 1929; Vol. VII, 1930; Index 1933.

In 1929, on the first page of the first issue of the *Reviews of Modern Physics* (then called *Physical Review Supplement*), Raymond T. Birge[6] published the first extensive treatise on, and documentation of, critical values for the fundamental constants. In addition, the author describes the motivation for the work as well as the multiplicity of inputs required to achieve the desired result:

> The need is continuous since the most probable value of to-day is not that of to-morrow, because of the never-ending progress of scientific research. These remarks appear to the writer so self-evident that the mere statement of them may be deemed superfluous. However, in spite of these facts, an investigation of the values of general constants in current use in the literature reveals a surprising lack of consistency, both in regard to the actually adopted values and to the origin of such values . . . .
>
> . . . In attempting to respond to this need, the writer has become only too well aware of the intrinsic difficulties involved, but at the same time he has become increasingly convinced of the existence of the need itself. The present investigation was undertaken

> only at the express request of others, and the results given here should be considered more as a presentation of the situation than as a final solution of the problem. To obtain a satisfactory and thoroughly reliable judgement in such matters, there is required the unbiased cooperation of many persons situated in scientific laboratories throughout the world. In the preparation of this paper, I have endeavored to obtain such cooperation by means of an extensive correspondence, but because of a necessary limitation of time, such correspondence has been confined almost entirely to this country. In addition I have received valuable advice and suggestions from various persons on the campus of this University [University of California, Berkeley] . . . .

Although the editors of the International Critical Tables (ICT), as well as individual scientists, at that time recognized the need for periodically reassessing the numerical values assigned to the fundamental constants, surprisingly, they established no structured, continuing effort to implement such reassessment. The work of the ICT itself having been terminated, a large portion of the revenues from their royalties were transferred to the Annual Tables of Constants and Numerical Data in Chemistry, Physics, Biology,and Technology, located in Paris, an entity that had been functional ever since 1912 under joint auspices of ICSU and the International Union of Chemistry, (which later on became IUPAC). The U.S. contribution to the Annual Tables organization was provided by the National Academy of Sciences/National Research Council (NAS/NRC) Division of Chemistry and Chemical Technology, which, on the whole, recorded concerns about standards, symbols, and other related matters. The idea was that this would represent an annual update of the ICT. It appears, however, that the Annual Tables did not address evaluated fundamental constants, as such. Meanwhile, a separate group in the Division of Physical Sciences at the NRC undertook from 1934 to 1936 a large effort to compile a Glossary of Physical Terms, which is on record as including "a number of standard tables with physical constants." There appears to be no single published result of this effort, though the Glossary may well have been published by members in an appropriate journal, as was common practice at that time.

In 1940, a joint committee representing the interests of both physics and chemistry divisions of the NRC was established (with Lyman Briggs, Jr., Director of the National Bureau of Standards, chairman; members were Edward U. Condon, who succeeded Briggs as NBS director, Karl K. Darrow, Jesse W. M. DuMond, Frederick G. Keyes and F. G. Brickewedde, secretary). The committee's responsibilities included atomic constants, nuclear masses, isotope ratios, thermodynamic data, and other miscellaneous groups of constants. During World War II, the collection of data continued in spite of the demands of war-related work on most of the committee members.

It is clear that the establishment of this committee did not alleviate ambiguities and duplication of efforts. In 1941, Birge independently published an authoritative and well-documented update of his 1929 table of fundamental constants.[7] Birge insisted on remaining independent and pointedly refused to become a member of any committee. Furthermore, as the NRC committee geared up for postwar increased efforts, a Subcommittee on Fundamental Constants of the NRC Committee on Physical Chemistry was formed (with F. Rossini, chairman; members were H. L. Johnston, L. Pauling, G. W. Vinal, and later also F. T. Gucker and J. O. Hirschfelder). By 1949-1950, this subcommittee saw a need to re-evaluate the Faraday, as a result of which a new list of fundamental constants was to be prepared.

The next attempt to unify the efforts occurred in 1953-1954, bringing both NRC efforts under the Subcommittee on Fundamental Constants (F. Rossini, chairman; members were J. A. Bearden, E. R. Cohen, J. W. M. DuMond, F. T. Gucker, Jr., J. O. Hirschfelder, L. Pauling, and G. W. Vinal). This grouping brought together not only the two NRC activities but also the work of Bearden and Watts, which, up to then, had been independent.

In 1961, as a result of correspondence between the then Director of the National Bureau of Standards, A. V. Astin, and NRC representatives, a Standing Committee on Fundamental Constants was established under the administration of the Office of Critical Tables (now the Numerical Data Advisory Board). The members of this committee were A. G. McNish, National Bureau of Standards, Chairman; J. A. Bearden, E. R. Cohen, J. W. M. DuMond, J. P. McCullough, N. F. Ramsey, F. D. Rossini, J. S. Thompson, and G. Waddington.

All this seemingly abundant organizational activity should not be assumed to have eliminated the confusion that existed ever since the ICT values for fundamental constants became obsolete owing to substantial leaps in laboratory sophistication. Only the ICT values of 1923 were recognized and adopted by ICSU. Subsequent tables were published by individual authors in a variety of journals such as Reports on Progress in Physics.[7] Reviews of Modern Physics,[8] and the IRE Transactions on Instrumentation and Measurement.[9] It was the practice of committees to report their recommendations as journal publications (e.g., the summary report by the NRC Subcommittee on Fundamental Constants was published in the Journal of the American Chemical Society.[10]) Only in 1963 was a second list of fundamental constants[11] accepted by IUPAC. The 1963 list was specifically not endorsed by the International Union of Pure and Applied Physics (IUPAP) or by the IUPAP Commission on Nuclidic Masses, with whose "encouragement" it was carried out. The reasons for this action are explained in the following quotation from the minutes:

> The role of the Commission in "recommending" the use of sets of values was discussed at length. It was recalled that, at the time of our formation, we were instructed to "encourage the compilation and tabulation of data". It was agreed that our encouragement should only be extended to persons of undoubted competence . . . but that such persons should then publish the results of their work on their own responsibility. In keeping with this point of view, it was agreed to inform the General Assembly of IUPAP of Cohen and DuMond's important work in the following words:
>
> > The Commission on Nuclidic and Related Atomic Constants has encouraged two of its members, J. W. M. DuMond and E. R. Cohen, to prepare a self-consistent list of the most probable values of the fundamental constants. This list was presented to the Second International Conference on Nuclidic Masses held in Vienna, July 15 - 19, 1963. The Commission expects that these values will be widely used and will help to remove many of the confusions that have arisen from the use of differing sets of constants. In addition, it is expected that the appearance of this list will encourage further experimental work aimed at improving our knowledge of these values.

In 1966, the Committee on Data for Science and Technology (CODATA) was established as an ICSU committee. One of its functions was, and still is, specifically to deal with the maintenance and updating of the constants through its Task Group on Fundamental Constants. (The current chairman is E. R. Cohen; members are B. A. Bamyrin, B. N. Oleinik, B. W. Petley, H. Preston - Thomas, T. J. Quinn, B. N. Taylor, B. Kramer, and M. Morimura). This Task Group has reviewed and accepted the current list and recommended it for ICSU adoption. In 1973, it was adopted and recommended for general international use.[12] In view of improved measurements since that time, the values are being re-evaluated, and it is anticipated that the Task Group will recommend a new set to CODATA and to ICSU for formal international acceptance in 1983. Both the 1973 and 1983 adjustments are two-man collaborations (E. R. Cohen and B. N. Taylor) and not the product of a committee. The Task Group's purpose is to improve information flow and to facilitate cooperation and acceptance by the national laboratories.

The principal lesson learned from this history is that fundamental constants must be treated as a field in itself. In the early days of ICSU, the total field of science was relatively small and the fundamental constants used were manageable by small voluntary efforts. The first list of accepted values was the result. As science grew and the number of individuals in different areas requiring reliable values for the fundamental constants increased, their measurement, compilation, and uniform utilization became increasingly complex. Attempts to bring the efforts together failed until the degree of diversification was recognized and the subject was treated as a single field.

The committee publications, which present the "recommended" values and only a summary of the full analysis, are important in that they provide the basis for the international adoption of a consistent set of numbers for general use. There should be no implication that the "recommended" values are the correct ones. They should be used only to the extent that they are useful in providing consistency with other data. For those working in the field of precision measurements the importance of the analysis is not the recommended set of consistent values but the space orthogonal--the residuals in the least-squares adjustment and the inconsistencies of the input data. These are what have to be corrected or explained, and this is where the important new discoveries and understanding reside.

REFERENCES

1. R. D. Huntoon and A. G. McNish, Nuovo Cimento, Suppl. Ser. X, 146 (1957).
2. J. Babinet, Ann. Chem. Phys. 40, 177 (1829).
3. J. C. Maxwell, Rep. Brit. Assoc. Not. Abstr. 7 (1870).
4. A. A. Michelson and E. W. Morley, Am. J. Sci. 38, 181 (1889).
5. A. A. Michelson, Trav. Mem. Bur. Internat. Poids Mesures 11, (1893); J. R. Benoît et E. Guillame, Annexe 1 (1893).
6. R. T. Birge, Rev. Mod, Phys. 1, 1 (1929).
7. R. T.Birge, Rep. Prog. Phys. VIII, 90 (1941).
8. J. W. M. DuMond and E. R. Cohen, Rev. Mod. Phys. 20, 82 (1948) [Erratum 21, 651 (1949)]; J. W. M. DuMond and E. R. Coheen, Rev. Mod. Phys. 25, 691 (1953); E. R. Cohen, J. W. M. DuMond, T. W. Layton, and J. S. Rollett, Rev. Mod. Phys. 27, 363(1955).
9. J. W. M. DuMond, IRE Trans. Instrum. Meas. IM-1-8, 136 (1958).
10. F. D. Rossini, F. T. Gucker, Jr., H. L. Johnston, L. Pauling, and G. W. Vinal, J. Am. Chem. Soc. 74, 2699 (1952).
11. E. R. Cohen and J. W. M. DuMond, Proc. 2nd Int'l Conf. on Nuclidic Masses; W. H. Johnson, ed. (Springer-Verlag, Vienna, 1964), p. 152; Rev. Mod. Phys. 37, 537(1965); A. G. McNish, J. A. Bearden, E. R. Cohen, J. W. M. DuMond, L. P. McCollough, N. F. Ramsey, F. D. Rossini, J. S. Thomsen, and G. Waddington, Chem. Eng. News 41, 42 (1963); F. D. Rossini, Pure Appl. Chem. 9(3), 453 (1964).
12. "Recommended Consistent Values of the Fundamental Physical Constants, 1973," Report of the CODATA Task Group on Fundamental Constants, August 1973, CODATA Bulletin No. 11. International Council of Scientific Unions, Committee on Data for Science and Technology, December 1973; E. R. Cohen and B. N. Taylor, J. Phys. Chem. Ref. Data 2, 663 (1973).