

# STANDARDS OF MEASUREMENT

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REPRINTED FROM  
**SCIENTIFIC  
AMERICAN**

JUNE 1968

VOL. 218, NO. 6 PP. 50-62

# STANDARDS OF MEASUREMENT

The goal is to define standards of length, mass, time and temperature that are both precise and reproducible. Of the four only mass still lacks a referent in nature

by Allen V. Astin

The task of finding more accurate ways to measure length, mass, time and temperature never ends. These are the four master measures on which all others depend. They establish the fineness with which man can examine the physical universe and they provide the basis for all technology. The goal in devising standards of measurement is to provide a unit that can be reproduced anywhere with high fidelity by anyone with access to certain technical facilities. Thus the units of length, mass, time and temperature should be referred to basic constants of nature, preferably at the level of atomic behavior. Three of the four units—length, time and temperature—are now defined in terms of natural constants. This still remains to be done for mass.

When man first sought a unit of length, he adopted part of his body—his hand or foot—as a crude but convenient measure. In the 18th century French savants defined a new unit, the meter, as a particular fraction of the earth's dimension. In 1960 the 11th General Conference on Weights and Measures, meeting in Paris, redefined the meter in terms of a particular wavelength of the radiation from the isotope krypton 86 [see illustration on opposite page].

The unit of time, the second, was much earlier specified in terms of the relative positions of the earth and the sun. The second was defined as 1/86,400th part of a day, and more recently as 1/31,556,925.9747th part of the tropical year 1900. At the 13th General Conference on Weights and Measures, held in Paris last October, the second was redefined as 9,192,631,770 cycles of the frequency associated with the transition between two energy levels of the isotope cesium 133. The redefinition was needed because it was found that the rotation of

the earth is more erratic than had been thought. The irregularity is probably caused by tides, winds, earthquakes and magnetic fields. If a perfect clock had been running in 1900, it would now show that the rotation of the earth is half a minute behind schedule. With the best atomic clocks it is possible to measure time to about one part in  $10^{12}$ , an accuracy nearly 10,000 times greater than could be achieved by astronomical means.

A hundred and fifty years ago standards were important for only five different kinds of measuring unit: length, volume, weight, time and angle. Today we must have standards for the accurate measurement of temperature, light intensity, color, sound intensity, electric current, X-ray dosage, nuclear radiation and many other phenomena. The assembly of an automobile or a television receiver depends on scores of such measurements. A far greater number of standards is required for the much more complex and exacting task of constructing a space vehicle. If the vehicle is to operate successfully millions of miles from the earth, the physical, electrical and mechanical properties of thousands of individual parts and components must be carefully controlled by reference to accurate standards of measurement.

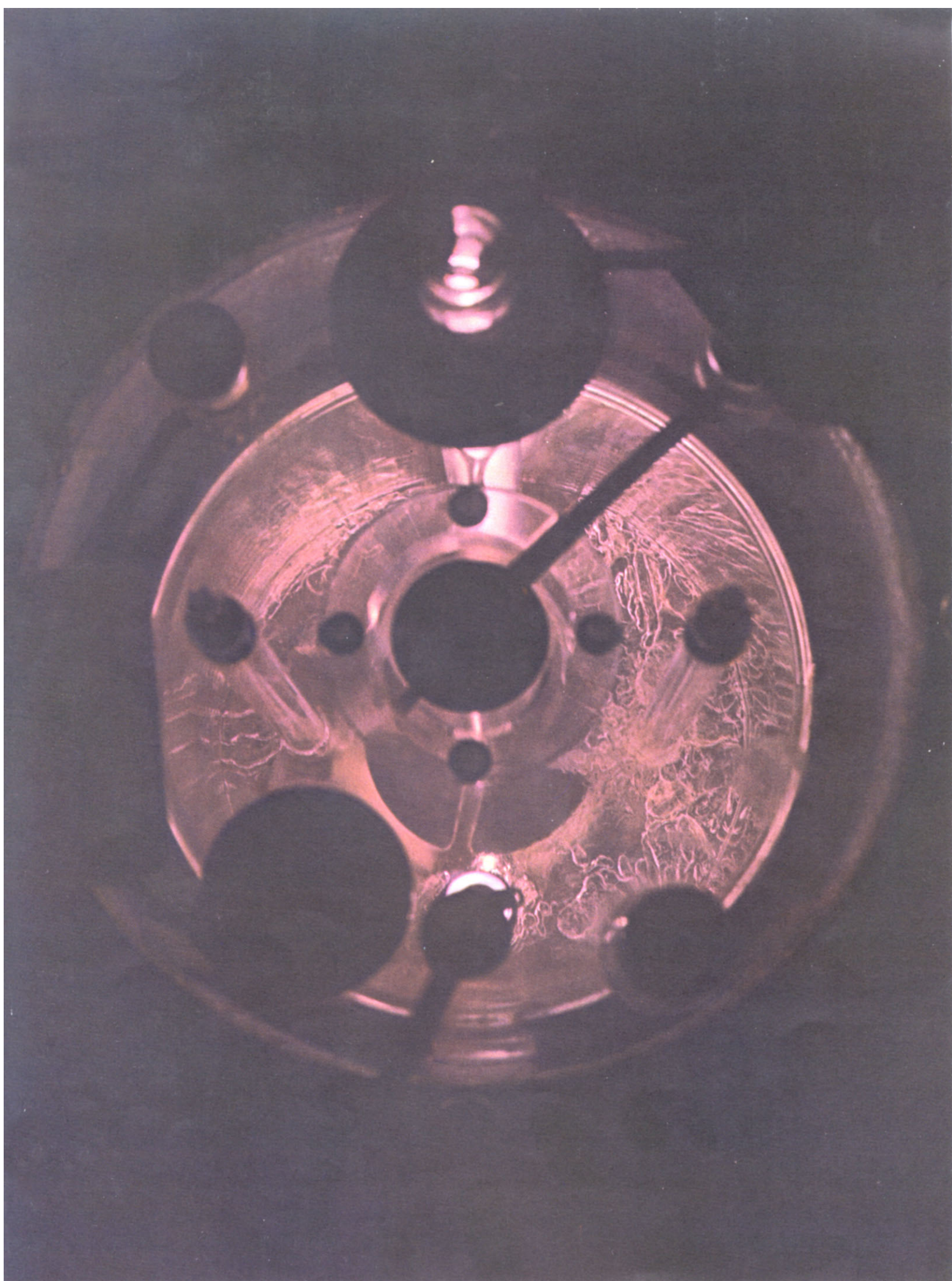
Although dozens of different units are now needed to express the magnitudes of the many properties routinely measured in science and technology, virtual-

ly all can be derived from four, and only four, independent units: the meter for length, the kilogram for mass, the second for time and the kelvin (formerly the degree Kelvin) for temperature. These four quantities, together with two derived quantities (the ampere and the candela) are the building blocks of the International System of Units, or *Système International*. Only a few important measurements do not depend on the four basic standards. These include angle measurements, which are basically ratios of two lengths and hence independent of particular units of length, and color measurements, which are really schemes of classification related primarily to the properties of the human eye.

By referring to a high school physics text one can usually see how secondary physical quantities can be related to the basic four [see illustration on page 14]. For example, the unit of force, the newton, is obtained from Newton's second law of motion, which states that force equals mass times acceleration ( $F = ma$ ). The newton is defined as the force that gives an acceleration of one meter per second per second to a mass of one kilogram. The ohm, a unit of electrical resistance, can be derived directly from standards of length and time. Most mechanical measurements—such as density, energy and pressure—involve combinations of units of mass, length and time. Thermodynamic measurements involve combinations of mechanical and tem-

UNIT OF LENGTH, the meter, was defined in 1960 as 1,650,763.73 wavelengths in vacuum of a particular emission line of krypton 86. Because the wavelength of the line varies with temperature, the discharge tube containing krypton 86 (opposite page) is held at the "triple point" of nitrogen,  $-210$  degrees Celsius (formerly centigrade). At the triple point, liquid, solid and vapor are in equilibrium. The photograph shows the nitrogen-containing vessel from above; bubbles of nitrogen are rising from a mixture of liquid and solid nitrogen. Excited atoms of krypton 86 produced pinkish light with which picture was taken. The length standard is a reddish-orange component whose wavelength is 6,057.8021 angstrom units.





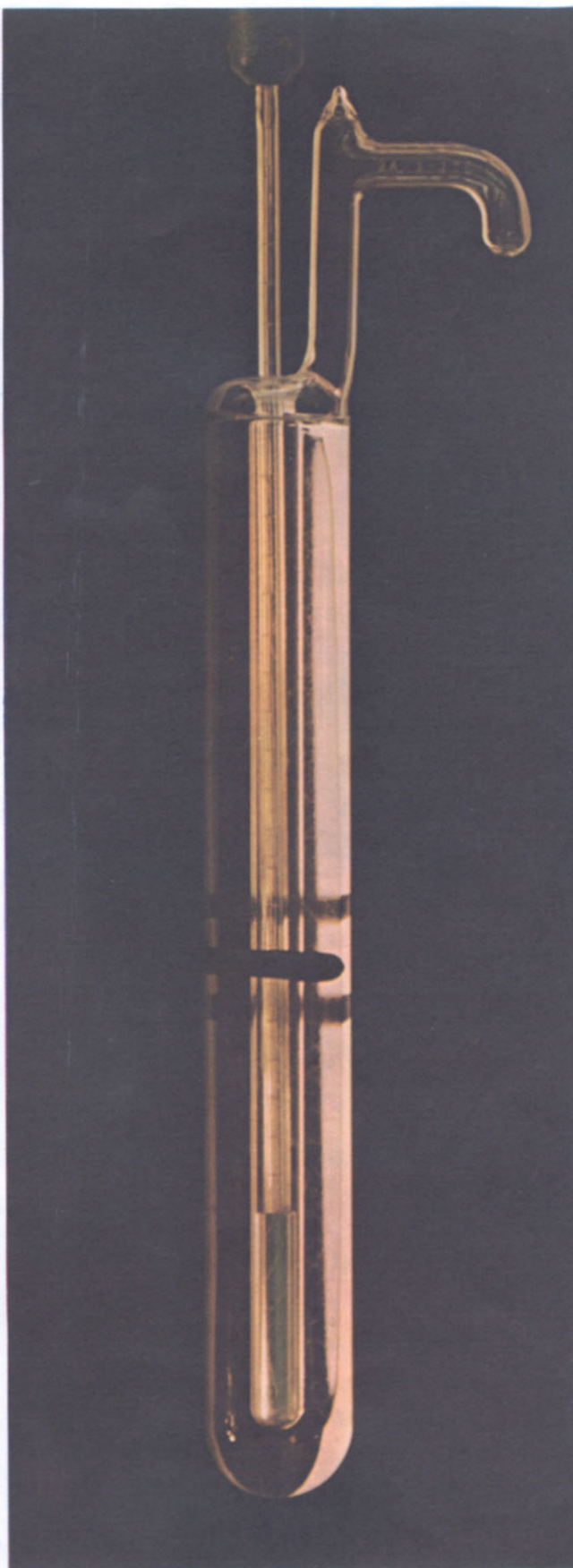




**FUTURE LENGTH STANDARD** may be provided by monochromatic light from a helium-neon laser, whose waves remain coherent, or in step, over long distances. Used in an interferometer it produces fringes such as these, which remain distinct over an optical path of 200 meters. The fringes produced by krypton 86 cannot be used to measure distances as long as a meter in a single step.



**STANDARD OF MASS** is the mass of a platinum-iridium cylinder, Prototype No. 1, kept at the International Bureau of Weights and Measures at Sèvres, near Paris. The kilogram shown here is one of several accurate copies kept at the National Bureau of Standards.



**TEMPERATURE UNIT**, the kelvin, or degree Celsius, is defined as  $1/273.16$  of the thermodynamic temperature of the triple point of water, which is .01 degree Celsius. It is measured in this apparatus, which brings pure water, ice and water vapor into contact.

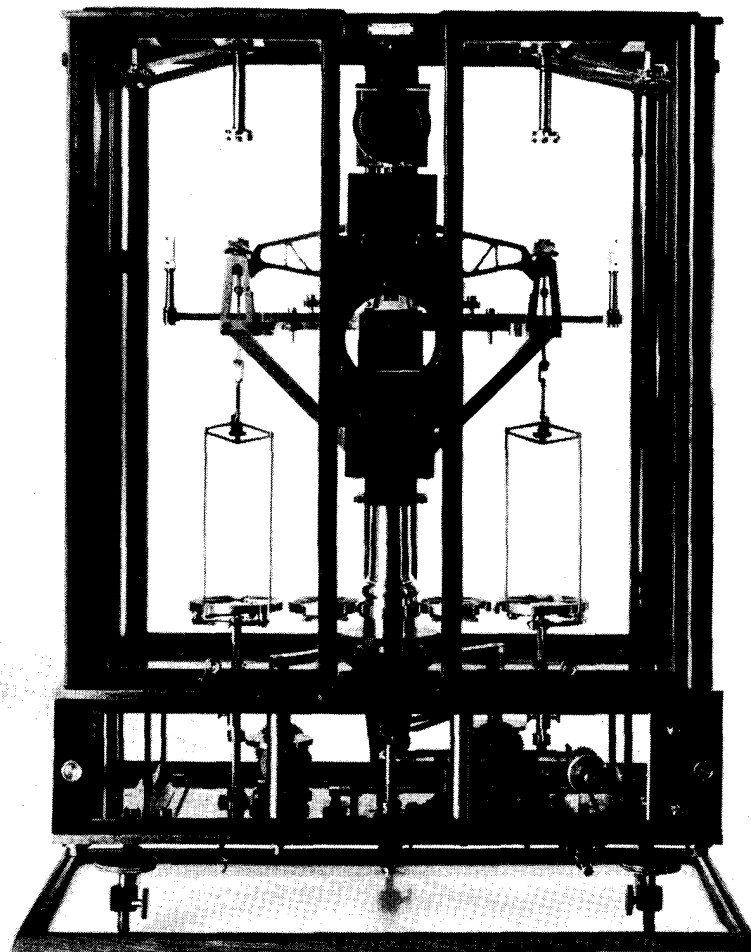
perature units. The roentgen, the unit of radiation exposure, is derived from electric-charge standards and mass standards.

Until the advent of experimental science at the time of Galileo in the 16th century only astronomers were much concerned with standards of measurement. At that time even in a single country there were usually a variety of units of different sizes for the same quantity, for example the grain, the ounce, the pound avoirdupois, the troy pound, the stone and the ton. Galileo's diverse inquiries made it clear that physical measurement was an integral part of studying natural phenomena. Natural philosophers began to realize that common, well-defined units of measurement were essential to the exchange and comparison of experimental results. By the second half of the 18th century a concerted drive had developed among the investigators of several nations to establish a truly international system of measurement resting on a sound scientific basis. The drive culminated at the time of the French Revolution, when the metric system was born.

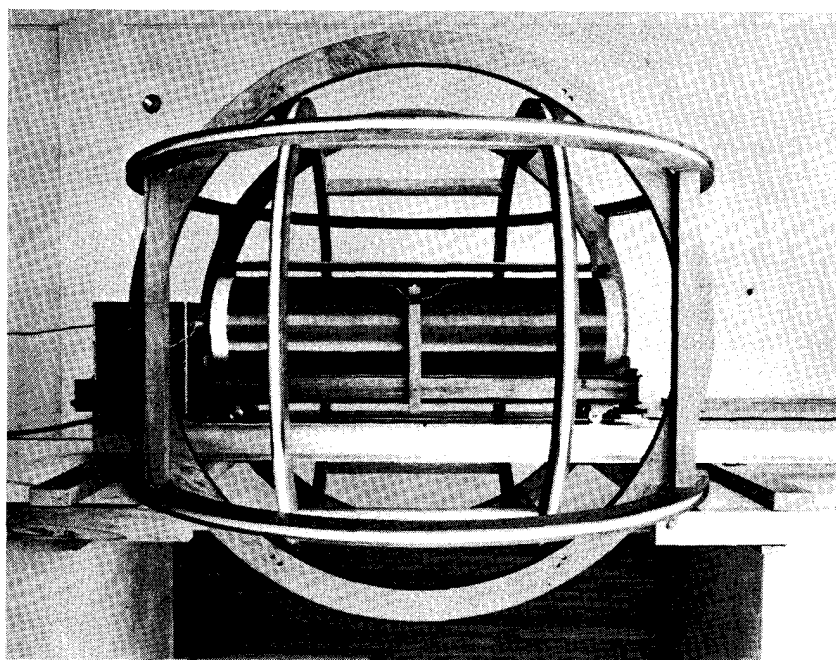
Various standards of length were proposed for the new measuring system. More than 100 years earlier the astronomer Jean Picard had suggested that the unit of length be defined as the length of a pendulum with a natural period of one second at sea level and a latitude of 45 degrees. The proposal had many adherents, including Thomas Jefferson. It was finally rejected as insufficiently precise by a committee appointed in 1790 by the French National Assembly. Another suggestion considered and rejected was to define the standard as some fraction of the Equator.

The winning proposal was to define a new unit of length, the meter, as one ten-millionth of a quadrant of the earth's meridian as carefully measured over that fraction of the quadrant lying between Dunkirk in France and a point close to Barcelona. The measurement was painstakingly carried out by a surveying party under the direction of the astronomer Jean Baptiste Delambre between 1792 and 1799. Astronomical measurements established that the distance between Dunkirk and Barcelona represented a little more than a tenth of the entire quadrant from the North Pole to the Equator. The measured distance from Dunkirk to Barcelona turned out to be 1,075,039 of the units subsequently defined as the meter.

The unit of mass, the kilogram, was taken as the mass of a cubic decimeter (a tenth of a meter) of water at the tem-



**SENSITIVE BALANCE** at the National Bureau of Standards can compare the Bureau's master kilogram, Prototype No. 20, with various copies with an accuracy of one part in  $10^8$ .



**POSSIBLE METHOD** of defining a substitute for the mass standard involves the gyromagnetic ratio of the proton: the ratio of the proton's angular momentum to its magnetic moment. Ratio has been measured by the Bureau with an accuracy of a few parts per million.

MEASURE	UNIT	DEFINITION
LENGTH	METER	<p><b>ORIGINAL:</b> 1/10,000,000th of quadrant of earth's meridian passing through Barcelona and Dunkirk</p> <p><b>PRESENT:</b> 1,650,763.73 wavelengths in vacuum of transition between energy levels <math>2p_{10}</math> and <math>5d_5</math> of krypton-86 atom, excited at triple point of nitrogen (<math>-210</math> degrees Celsius)</p>
MASS	KILOGRAM	<p><b>ORIGINAL:</b> Mass of one cubic decimeter (1,000 cubic centimeters) of water at its maximum density (4 degrees Celsius)</p> <p><b>PRESENT:</b> Mass of Prototype Kilogram No. 1 kept at International Bureau of Weights and Measures at Sèvres, France</p>
TIME	SECOND	<p><b>ORIGINAL:</b> 1/86,400th of mean solar day</p> <p><b>PRESENT:</b> 9,192,631,770 cycles of frequency associated with transition between two hyperfine levels of isotope cesium 133</p>
TEMPERATURE	DEGREE CELSIUS (KELVIN)	<p><b>ORIGINAL:</b> 1/100th interval between freezing point of water (0 degrees Celsius) and boiling point of water (100 degrees Celsius)</p> <p><b>PRESENT:</b> 1/273.16th of the thermodynamic temperature of the triple point of water (.01 degree Celsius)</p>

**REFINEMENT OF MEASURING STANDARDS** for length, mass, time and temperature is shown by this table. The original definitions of length and mass were those incorporated in the metric system, recommended by the Paris Academy of Sciences in 1791. The unit of time, the second, had been in use for so long and was con-

sidered so reproducible that it was not questioned by the founders of the metric system. The Celsius, or centigrade, scale for temperature had been proposed in 1742 by Anders Celsius of Sweden. It is often regarded as part of the metric system. The kelvin, named for Lord Kelvin, is now equivalent to the term "degree Celsius."

perature of its maximum density; this volume was to be called a liter. In this way the units of mass and volume were derived from the standard of length using the most available of all liquids as the medium for the conversion. Key figures in establishing the metric system in addition to Delambre were Charles Maurice de Talleyrand, the French diplomat, and Antoine Laurent Lavoisier, the discoverer of oxygen.

Progress in the adoption of the metric system was slow but steady. It was a major disappointment to its innovators that Jefferson failed to urge its adoption by the U.S. (partly, it seems, because the Dunkirk-Barcelona distance supposedly put France and Spain in a favored position). The metric system was accepted, however, in Italy, Belgium and the Netherlands in the first quarter of the 19th century. And in the mid-1860's it became legal to use metric measures in Great Britain and the U.S.

Meanwhile there had been growing dissatisfaction with the system as it was originally conceived. The whole reason for selecting the earth's meridian as a basis for a length standard had been that the meridian (or some specified fraction of it) would always be available for re-measurement. Experience showed, how-

ever, that two meter bars could be compared with each other with much greater accuracy than a meter bar could be related to the earth's meridian. In addition it was proving difficult to reproduce the kilogram in different countries simply by weighing the mass of a liter of water at maximum density.

In response to these concerns the French government arranged for a conference in 1870 to work out standards for a unified measurement system. These efforts led to the signing of the Treaty of the Meter in Paris in 1875. The treaty established an International Bureau of Weights and Measures, which was to be the custodian of the standards for an international system of measurement, and a General Conference on Weights and Measures. The Conference, meeting periodically, would handle problems and adopt new definitions as the need arose.

As provided by the treaty, special commissions began designing prototype standards of the meter and the kilogram so that this time the system could be based on two independent standards. After several years of work the meter was officially defined in 1889 as the distance between two engraved lines on a bar of platinum-iridium alloy at zero degrees centigrade (now Celsius). The

international meter bar was to be kept in a vault at Sèvres, near Paris, in the custody of the new International Bureau, and it was to be available for comparison with the length standards of all nations. Copies of the meter bar were furnished to the nations adhering to the treaty. Also in 1889 the kilogram was defined as the mass of a particular platinum-iridium cylinder, and copies of the cylinder were supplied to the treaty nations.

Soon after the new prototype copies were received in the U.S. the Office of Standard Weights and Measures in the Treasury Department, which was given custody of the standards, redefined the yard and the pound as appropriate fractions of the meter and the kilogram. Since that time yards, pounds and gallons in the U.S. have been based on metric standards. Formerly the U.S. standards for these units had been based on copies of English standards.

In the last half of the 19th century there were tremendous advances in the theories of heat, light, electricity and magnetism. Major industries came into being to exploit these developments. It became necessary to invent and build instruments that could measure a completely new set of properties. In addi-



tion standards had to be developed for many of the new units of measurement. These pressures led to the establishment in many countries of a central organization for setting and developing standards. Thus the National Physical Laboratory was created in England in 1889 and the National Bureau of Standards was established in Washington in 1901.

Over the past 75 years the General Conference on Weights and Measures has steadily extended and refined the metric system, so that it now goes far beyond the original standards of dimension and mass. In 1960 the Conference officially adopted the International System of Units, which rests on four independent base units for length, mass, time and temperature. The Conference also decided to include as base units the ampere for electric current and the candela for light intensity. These two, however, are not independent of the other four; they were given the status of base units for reasons of convenience.

### Patterns of Interference

As early as 1827 the French physicist Jacques Babinet had suggested that the wavelength of light had possibilities as a standard for length. The measurement of such a wavelength, however, was far beyond the simple resources of Babinet's day. His proposal could not be realized until much later, when the concept of interferometry had been developed. The idea is simple enough: when the crests of two waves coincide, they reinforce each other; when a crest coincides with a trough, the two waves cancel. In the first case the interference is constructive; in the second case it is destructive.

The interferometer makes it possible to see these interference patterns as a series of bright and dark lines. If two similar light beams from a single source travel over separate paths that differ in length by as little as a tenth of a wavelength and are then recombined, some destructive interference will occur and can be detected. The interferometer can be used either to measure wavelengths precisely or to measure distances or thicknesses in terms of known wavelengths.

A simple interferometer can be made by placing one optically flat glass plate on top of another [see illustration on next page]. The flats make contact at one edge and are separated at some other point by the object to be measured. Light of a single color, or wavelength, is directed at the upper surface. When this light reaches the lower surface of the

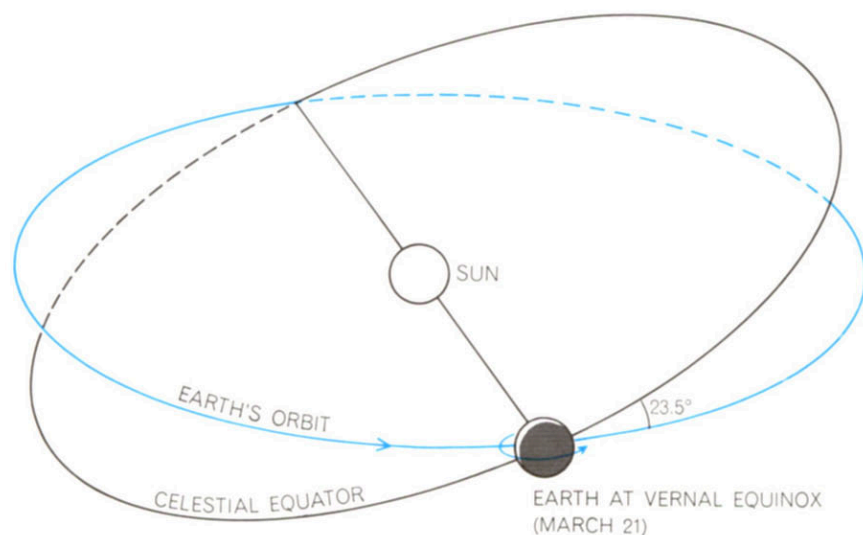
upper flat, it is divided into two portions. One portion is reflected upward by the lower surface and the other portion continues downward to be reflected from the upper surface of the lower flat. The two series of reflected rays recombine in the upper flat, where they in-

terfere to form alternate light and dark bands as seen from above.

Each fringe, or dark band, of this pattern represents a difference in optical path of the two rays equal to an odd number of half-wavelengths, or a separation of the two flats equal to an odd num-

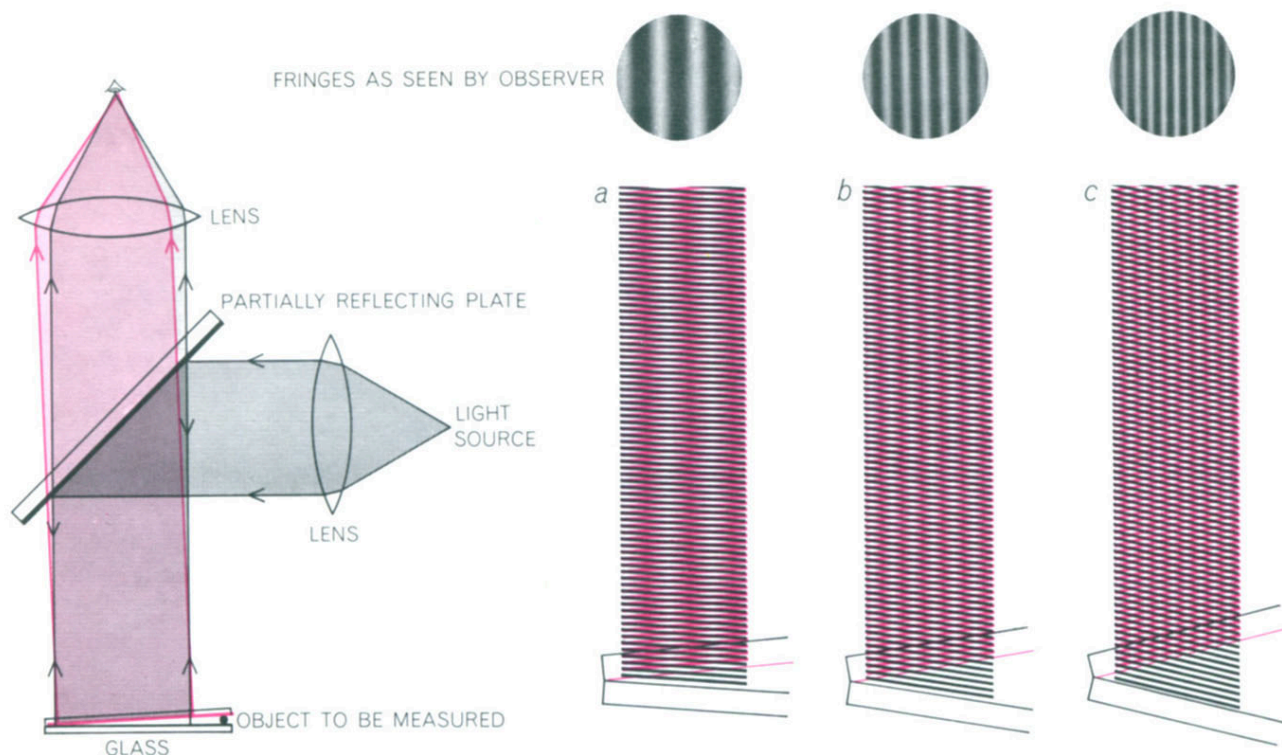


**BASIS OF METER** was the quadrant of the earth's meridian passing through Dunkirk, France, and Barcelona. The Dunkirk-Barcelona distance was measured by a French surveying team and extrapolated to the full quadrant using astronomical determinations of latitudes. The meter was defined as one-ten-millionth of the Equator-to-pole quadrant.



**BASIS OF SECOND**, generally accepted before adoption of the metric system, was the mean solar day, of which the second was  $1/86,400$ th part. The mean solar day, in turn, is  $1/365.2422$ th of the tropical year, measured from vernal equinox to vernal equinox.





**CONCEPT OF INTERFEROMETRY** for measuring length exploits the wave behavior of light. In the simple interferometer at the left a beam of parallel rays is directed at two optically flat plates of glass that are separated at one edge by the object to be measured. The rays (color) striking the bottom of the upper plate are reflected at an angle to the rays (gray) that are reflected from the upper surface of the lower plate. When these two families of rays interfere with each other (a, b, c), they produce a series of light and dark fringes whose spacing depends on the angle formed by the two flat plates, hence on the thickness of the object being measured. The

dark fringes represent "destructive" interference, where the crests of one wave coincide with the troughs of another. This is represented here by three moiré patterns formed when parallel lines intersect at different angles. Wavecrests are represented by colored lines, troughs by black lines. As the angle is doubled from a to b and tripled from a to c the number of intersections is similarly multiplied, corresponding to a similar multiplication in the number of fringes. The number of fringes is related to the wavelength of the light and to the size of the object. The photographs of the fringes (top right) were made at the National Bureau of Standards.

ber of quarter-wavelengths (since the path difference is twice the separation of the flats). Therefore by counting the number of fringes between the edge of the upper plate and its point of contact with the object to be measured, the object's length can be determined. It is equal to the wavelength of the light used multiplied by one-half the number of dark fringes to the point of contact.

Some 75 years ago A. A. Michelson revived Babinet's suggestion that an optical wavelength be considered for a length standard. He devised a type of interferometer, which bears his name, for comparing linear displacements with wavelengths of light.

At first Michelson thought that a brilliant green line in the spectrum of mercury would be satisfactory as the ultimate standard of length. Closer study showed, however, that the green line of mercury was too broad (that is, its wavelength was spread over too great a range) to provide adequate precision. Michelson then shifted his attention to a promi-

nent red line in the spectrum of cadmium. Even this line proved to be so broad that when the optical path difference was greater than a few centimeters the interference fringes became too blurred to be counted. This meant that a distance as long as a meter had to be measured in several steps, with a consequent loss in precision [see illustration on pages 10 and 11]. Nevertheless, Michelson did obtain by this method a value for the meter in terms of the red line of cadmium.

At the end of World War II William F. Meggers of the National Bureau of Standards returned to the problem of finding a wavelength standard for length, acting on a suggestion made in 1940 by Luis W. Alvarez. In 1950 Meggers demonstrated that a practical length standard could be provided by a mercury lamp containing mercury 198, an artificial isotope produced by the transmutation of gold in a nuclear reactor. A single isotope of mercury produces a much sharper green line than does natural mer-

cury, whose green line actually consists of 16 spectral components that are not quite coincident. The single emission line of mercury 198 provided such a substantial improvement in defining the meter in terms of wavelength that the National Bureau of Standards urged the 10th General Conference of Weights and Measures, held in 1954, to give fresh consideration to a wavelength definition. Meanwhile other nations reported results with krypton and cadmium isotopes. The Conference agreed that work should be pressed on various approaches with the goal of setting a wavelength standard in 1960.

After the comparisons had been carried out it was concluded that a lamp containing the isotope krypton 86, when excited at the temperature of the triple point of nitrogen ( $-210$  degrees Celsius) gave the highest precision. At the triple point the three phases of matter—solid, liquid and vapor—are in equilibrium. When a lamp is excited at a reduced temperature, it produces sharper spectral



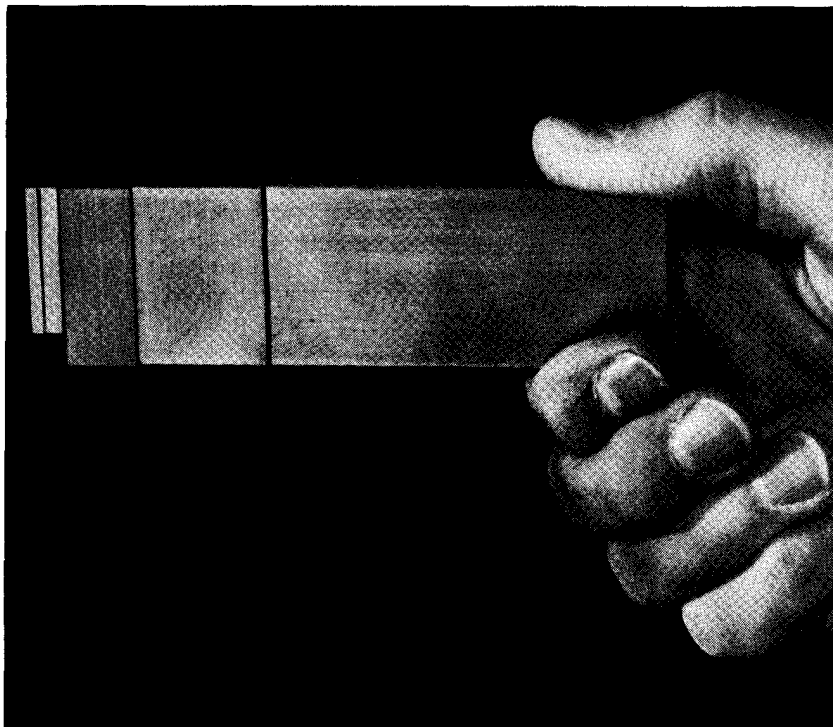
lines than it does at room temperature because of Doppler broadening. At room temperature the atoms in a lamp move with a wide range of speeds in all directions, and the wavelength of light they emit is shifted to values slightly higher and lower than the mean. By chilling the lamp the spread of values is much reduced. The krypton lamp was selected in part because of its superior operation at low temperatures.

In October, 1960, the 11th General Conference of Weights and Measures redefined the meter as 1,650,763.73 wavelengths in a vacuum of the reddish-orange radiation emitted by the transition between the energy levels  $2p_{10}$  and  $5d_5$  of the krypton-86 atom. The radiation is emitted when atoms excited to the  $5d_5$  level fall to the  $2p_{10}$  level. The accuracy of the old standard, in effect since 1889, was limited by the accuracy with which two meter bars could be compared: about one or two parts in 10 million. The krypton-86 standard improves on this accuracy by a factor of 10.

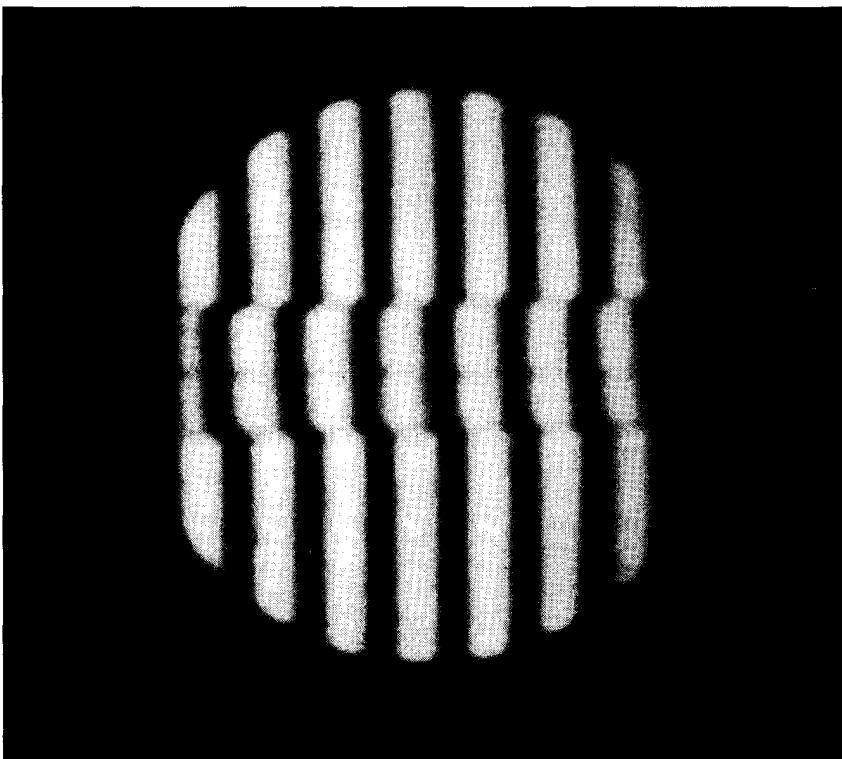
The chief defect of the krypton standard is that it still cannot be used to measure distances as long as a meter in a single step. Although the lamp's wavelength is very precise, the atoms in the lamp radiate more or less independently of one another. As a result the waves from the lamp are not in phase, or in step, and thus do not produce detectable fringes beyond a few tens of centimeters.

The development of the laser now provides a source of illumination that seems to meet all the requirements for measuring path differences of tens or hundreds of meters rather than centimeters. Because the light waves in a laser beam are all in step, they produce extremely sharp fringes. As early as 1963 workers at the National Bureau of Standards were able to obtain interference fringes over an optical path of 200 meters with a helium-neon laser. A year later they succeeded in measuring the length of a meter bar in a single step with an accuracy of seven parts in 100 million. More recently the Bureau has related one laser line—the neon line at a wavelength of 6,328 angstrom units—to the krypton standard with an accuracy of one part in 100 million, which is close to the limit of accuracy inherent in the krypton wavelength. Before a laser wavelength can be accepted as an international standard, however, it will have to be demonstrated that the laser wavelengths are sufficiently stable and reproducible.

Conceivably the laser could extend the limit of interferometric length measurement to hundreds or even thousands of



**PRACTICAL LENGTH MEASUREMENT** is performed with the aid of gage blocks, steel blocks with two highly polished opposite faces. The distances between the polished faces of the master blocks used by industry are calibrated by the National Bureau of Standards. There are usually 81 blocks of different sizes in the standard industrial set. By "wringing" the polished surfaces together, groups of the blocks can be assembled into measuring rods.



**CALIBRATION OF GAGE BLOCKS** is done by interferometry using two reference standards: light waves emitted by mercury 198 and by cadmium. In this picture light reflected from one surface of a gage block creates the offset pattern of fringes. The offset shows how much the gage block's dimension differs from an integral number of wavelengths.

kilometers. Such measurements, however, present the difficulty of counting several hundred million interference fringes, a task that could be accomplished only by automatic means.

### The Length Standards of Industry

A key link in the chain of measurement that leads from the krypton standard to the industrial production line is the precision gage block. In its simplest form the gage block is a rectangular piece of steel with a square or oblong cross section and two opposite faces that are ground and polished flat and parallel to each other. The length of the block is the perpendicular distance between these two faces, or, for highest precision, the distance between one of the faces and a specified point on the other.

A typical set of gage blocks consists of 81 blocks with sizes ranging from .05 inch to four inches. By carefully sliding the gaging surface of one block over the gaging surface of another, two blocks can be "wrung" together so tightly that they are difficult to separate [see top illustration on preceding page]. In this way one can use combinations of blocks to gage a large variety of distances. The dimensions of individual blocks are established by interferometric methods in which light beams are reflected from the gaging surfaces. Methods developed by the National Bureau of Standards make

it possible to calibrate industrial gage blocks routinely with an uncertainty as low as one part in a million, enabling industry in turn to calibrate other equipment with only slightly less accuracy.

In addition to gage blocks, which provide "end standards," industry also has need for "line standards." These are scales of graduated length that are used to define translation, or travel, distances in many types of precision machine tools and scientific instruments. Until recently the calibration of such scales was a laborious job involving visual microscope comparison with another standard. In 1966 the Bureau developed an automatic fringe-counting interferometer with a laser light source that measures line standards directly in lengths up to a meter with a precision of a few parts in 100 million. The new device has reduced the time needed for calibrating line standards by a factor of 10.

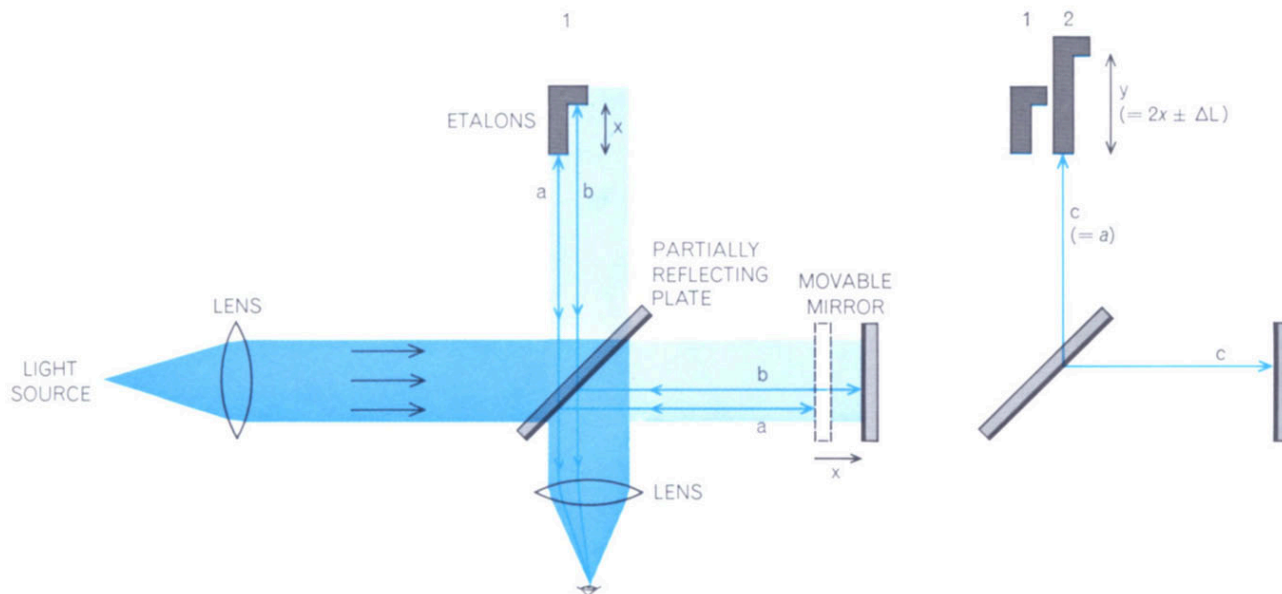
The U.S. copy of the international standard of mass, known as Prototype Kilogram No. 20, is housed in a vault at the Gaithersburg laboratory of the National Bureau of Standards. It is removed no oftener than once a year for checking the values of lesser standards. Since 1889 Prototype No. 20 has been taken to France twice for comparison with the master kilogram. The national standard is never touched by hands. When it is removed from the vault, two people are always present, one to carry the kilogram

in a pair of forceps, the second to catch the first if he should fall.

By means of a precision balance the national standard is compared with high-precision copies. The values obtained for the copies are accurate to one part in 100 million. In view of this high accuracy no great effort is currently being made to replace the prototype kilogram with a more permanent or independently reproducible standard. Corrosion or nicks in the platinum-iridium cylinder that would cause a mass change of as little as one part in a billion should be readily detectable by visual inspection.

It would, of course, be intellectually satisfying to have the mass standard defined in terms of a constant of nature, but no one has been able to propose a suitable constant or a way of measuring it that would come close to the precision desired. One constant that has been considered as a substitute for the mass standard is a property of the proton known as the gyromagnetic ratio, which depends on the precession frequency of the proton when spinning in a magnetic field of known strength. Although this ratio has been measured to within a few parts per million, it falls far short of the precision needed for a mass standard.

Recent work in crystallography at the Bureau has suggested another approach to a mass standard: actually counting the number of atoms in a precisely measured volume of a material. If the density of a



**MICHELSON INTERFEROMETER**, devised by A. A. Michelson in the 1880's, made it possible for the first time to define the meter in terms of the wavelength of monochromatic light. With the light sources then available Michelson could not measure the meter in a single step; therefore he built a series of "etalons," L-shapes with

two parallel reflecting surfaces (color). By adjusting the interferometer's movable mirror to match the two light paths *a* and *b* and counting fringes, Michelson could establish the precise value of *x* in the smallest etalon. He then introduced another etalon with a mirror separation *y* approximately equal to 2*x*. Again by counting



material is accurately known, the mass of an individual atom of the material could conceivably be computed and employed as an invariant standard of mass.

In order to realize such a standard it will first of all be necessary to have perfect crystals. In such a crystal the number of atoms in a unit volume is exactly equal to the cube of the number of crystal planes per unit length. The problem then becomes one of measuring the number of crystal planes in a particular length of the crystal. The Bureau is now working to adapt an X-ray interferometer to the making of such a measurement. An X-ray interferometer is similar in principle to an optical interferometer except that X rays are used instead of visible light rays, and crystals of silicon (or some other material) are used instead of glass plates or mirrors. Quite a few difficulties will have to be overcome before the method can challenge the precision attainable with the platinum-iridium prototype kilogram.

### Definitions of the Second

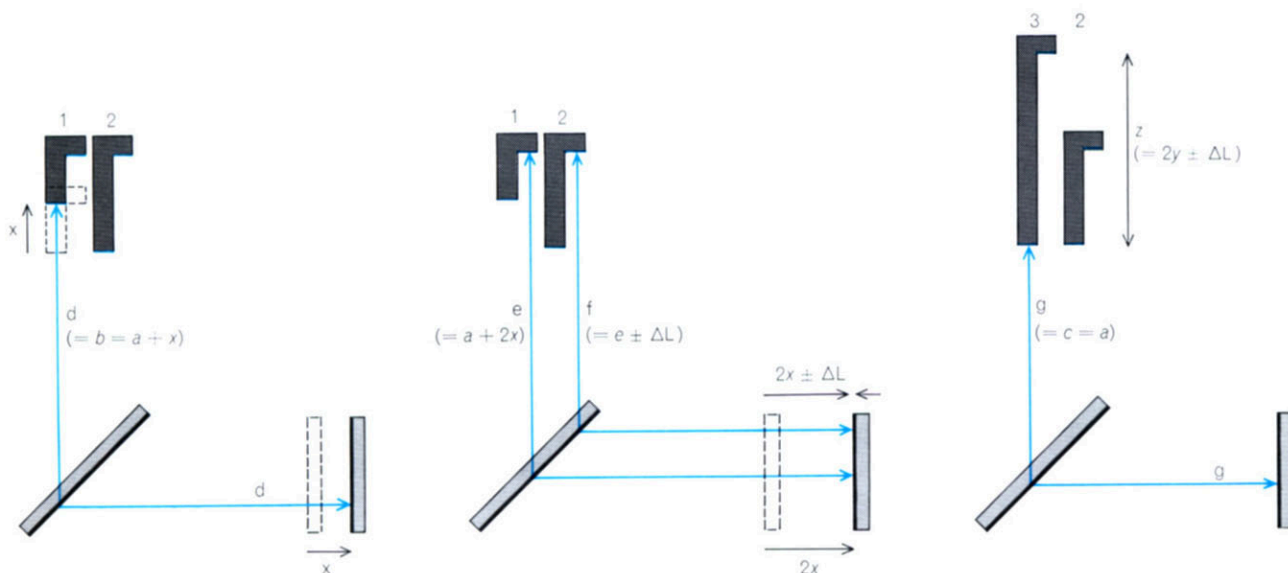
The measurement of time involves concepts and problems very different from those of the measurement of length and mass. We cannot choose a particular sample of time and keep it on hand for reference. Since ancient times the standard of time has been derived from some periodic event or motion.

It is curious that the originators of the metric system did not bother to define a unit of time. For centuries time had been measured in terms of the rotation of the earth, with the day divided into hours, minutes and seconds. The second had long been defined as  $1/86,400$ th of the mean solar day. This definition proved adequate until well into the 20th century, when clocks controlled by the resonance properties of quartz crystals made it clear that the second so defined was constantly changing by small amounts. In some years the length of the day was found to vary by as much as one part in 10 million, or three seconds in a year of 31.5 million seconds.

Meanwhile developments in physics and electrical engineering were making it possible to control clocks by using as a pendulum one or another of the natural frequencies associated with transitions between energy states in atoms and molecules. It had long been known, of course, that atoms and molecules, in going from one state to another, emit or absorb microwave energy at the sharply defined frequencies of spectral lines, but there seemed to be no way to use these extremely high frequencies in a clock. With the development of radar in the 1940's it became possible to measure transition frequencies in the microwave region by comparing them with electronic oscillators and so to use them for controlling highly accurate clocks.

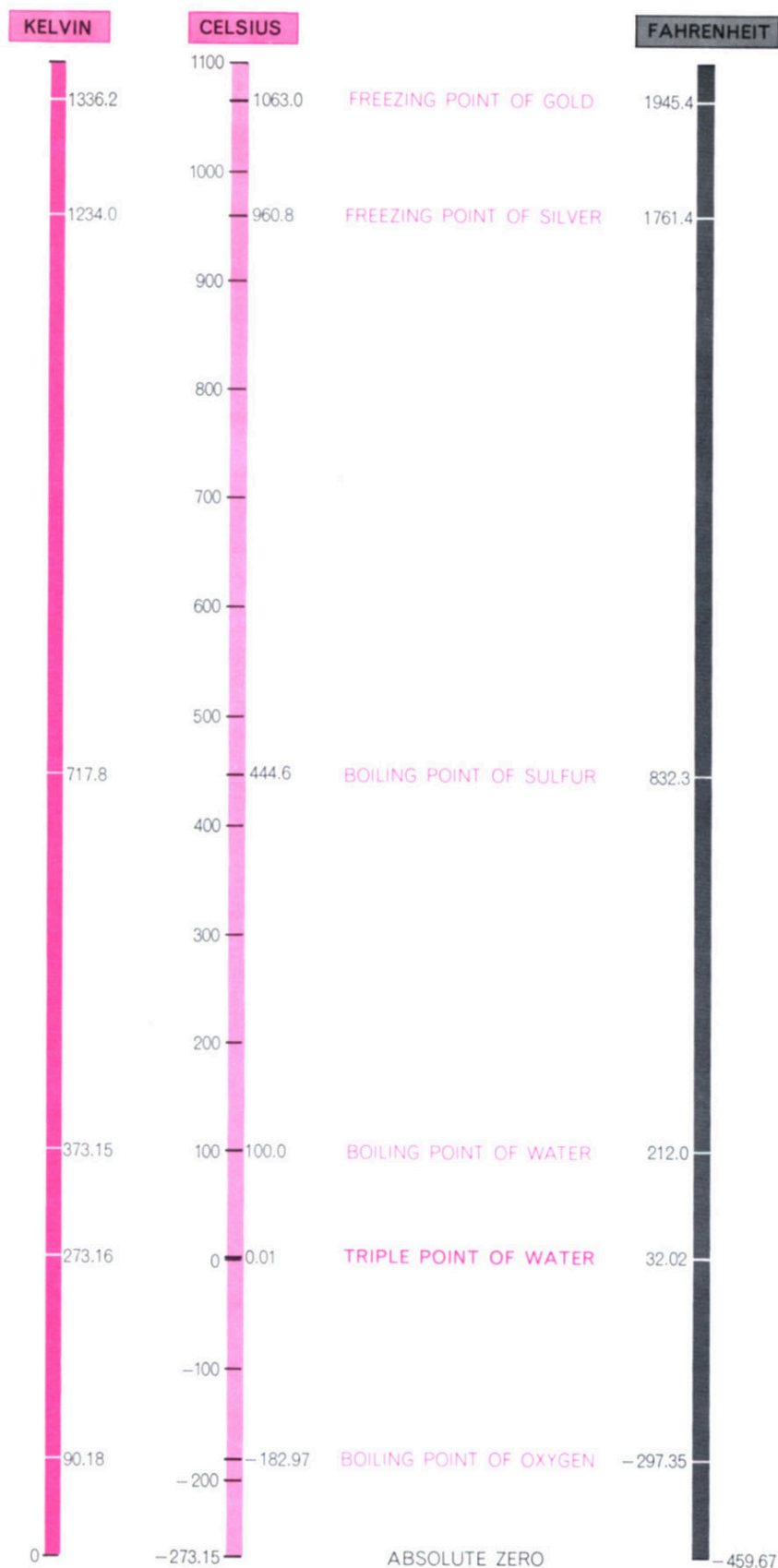
These developments suggested the possibility of defining the second once and for all in terms of the invariant frequency associated with an atom or a molecule. It was first necessary to resolve the discrepancy between the scale of time based on the irregularly rotating earth and the more reliable time scale used by astronomers: ephemeris time, based on the motion of the earth around the sun. Accordingly in 1956 the International Committee of Weights and Measures, acting on authority of the 10th (1954) General Conference of Weights and Measures and in cooperation with the International Astronomical Union, redefined the second as "the fraction  $1/31,556,925.9747$  of the tropical year 1900 January 0 at 12 hours ephemeris time." (The tropical year is the time between successive arrivals of the sun at the vernal equinox.) Four years of observations of the moon, completed in 1958, were needed to relate the solar second to the new second of ephemeris time, with an estimated uncertainty of a few parts in a billion—an uncertainty, incidentally, that far exceeded the exactness implied by the definition. The 11th General Conference ratified the new definition in 1960 and urged that work proceed on an atomic definition.

The first atomic clock built at the National Bureau of Standards in 1948 used a transition frequency of the ammonia molecule. Later good transitions



fringes he could accurately determine the value  $\Delta L$  by which  $y$  differs from  $2x$ . To do this he lined up the near face of the second etalon so that light path  $c$  equals light path  $a$ . He then moved the first etalon back by a distance equal to  $x$ , so that light path  $d$  equals light path  $b$ . Light path  $e$  then equals path  $a + 2x$  and can be com-

pared with light path  $f$ . The difference between  $e$  and  $f$ , determined by counting fringes, gives the value of  $\Delta L$ . The procedure is repeated using an etalon with a mirror spacing of  $z$ , about  $2y$ , and thereafter with longer and longer etalons. Michelson finally measured the meter with 10 successive shifts of an etalon 10 centimeters long.



**THREE TEMPERATURE SCALES** are in common use. Two of them employ the same unit, the degree Celsius, or kelvin, but differ in the location of their zero point. In the Fahrenheit scale one degree equals 5/9ths of a degree Celsius. The International Practical Temperature Scale defines six "fixed" points (*color*), including the triple point of water, .01 °C.

for timekeeping were found in the elements cesium, hydrogen and thallium. The isotope cesium 133 turned out to be the most suitable. The transition between two hyperfine energy levels of the fundamental state of the cesium-133 atom was adopted in 1967 by the 13th General Conference as the "pendulum" for defining the second. It was defined as 9,192,631,770 cycles of that particular transition in cesium 133.

The Bureau's standard of time is maintained by a cesium clock at its laboratories in Boulder, Colo. [see *illustration on opposite page*]. The clock's accuracy is about one part in  $10^{12}$ . This means that in 6,000 years it would not gain or lose more than a second. The Bureau is now working on still more accurate timepieces, for example the hydrogen maser, which promises to be 100 times more accurate than even the cesium clock.

The cesium clock at Boulder provides the basis for standards of time and radio frequency that are broadcast by four radio stations operated by the National Bureau of Standards. Two of the stations, WWV in Fort Collins, Colo., and WWVH in Maui, Hawaii, broadcast additional information such as standard audio frequencies (including the standard musical pitch, A above middle C), radio-propagation forecasts and geophysical alerts. The other two stations, WWVB and WWVL, both at Fort Collins, provide standards of higher accuracy for research laboratories, instrument makers and Government installations. By using communication satellites to relay time signals the international synchronization of time has been improved so that it is now accurate to within about a millionth of a second.

### Beyond the Triple Point of Water

Although temperature standards have long been based on highly reproducible constants of nature, such as the freezing and boiling points of very pure substances, their accuracy does not go beyond a few decimal places. The current international scale is based on a series of reference points known as fixed points.

The most familiar scale in the English-speaking world is of course the Fahrenheit scale, which was first crudely defined by taking the temperature of the human body as being 100 degrees Fahrenheit and the lowest temperature obtainable with a mixture of ice and salt as zero degrees. The scale is now based on the "ice point" (the temperature at which water and ice are in equilibrium at atmospheric pressure), 32 degrees Fahrenheit.



heit, and the temperature of boiling water, 212 degrees Fahrenheit. On the centigrade scale (the scale now called Celsius) as originally established, these two reference points were set at zero degrees and 100 degrees.

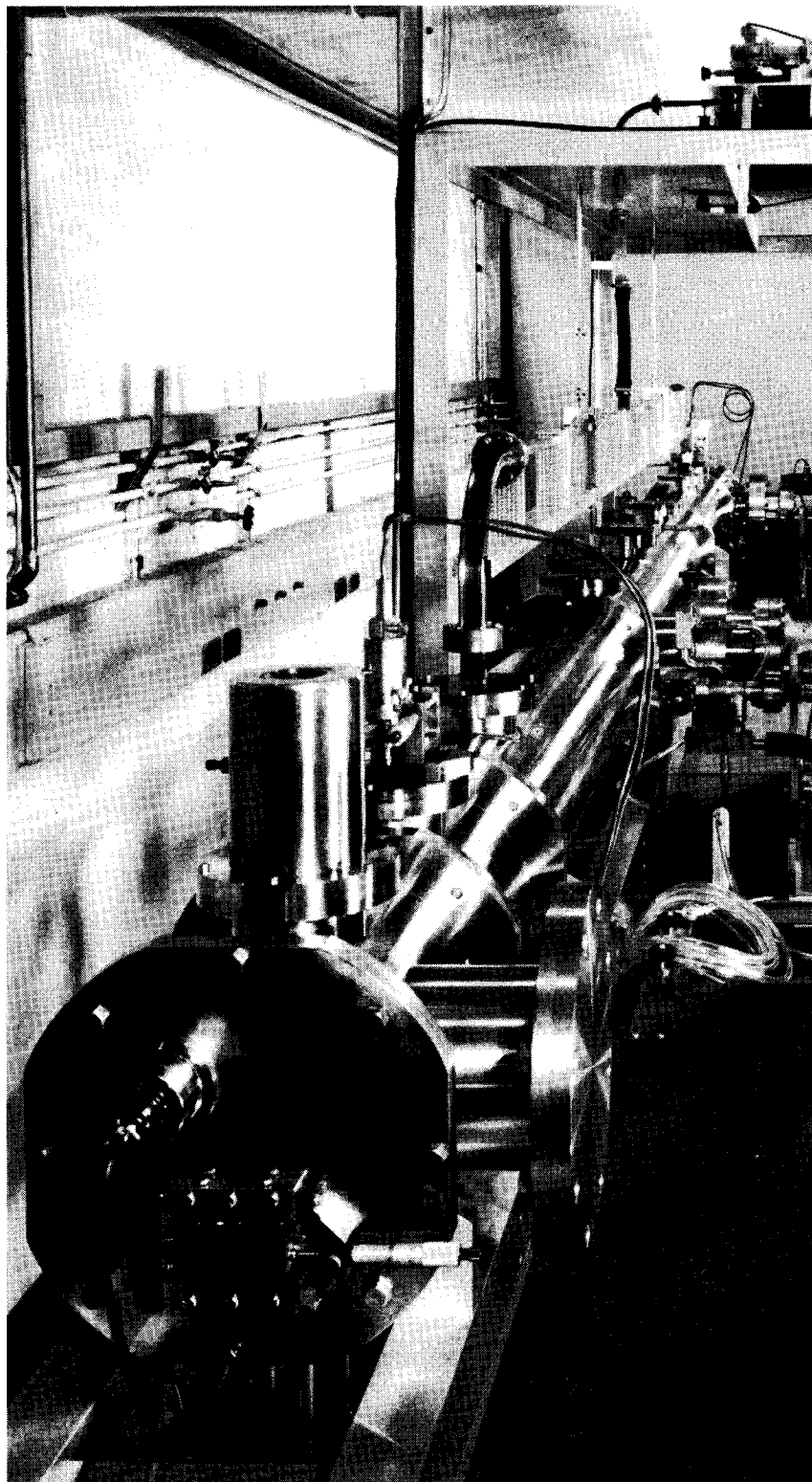
During the 19th century Lord Kelvin proposed a more fundamental scale in which the zero point was to be the point of zero thermal motion for an ideal gas:  $-273.15$  degrees Celsius, or  $-459.7$  degrees Fahrenheit. Each degree on this thermodynamic, or Kelvin, scale is equal to one degree on the Celsius scale. Because temperatures on the Kelvin scale can be determined only by complex experimental procedures, its use is limited to scientific work.

In the 1920's the International Committee of Weights and Measures sought to provide a practical scale compatible with the Kelvin scale by defining the temperature of a number of fixed points, based on the best experimental values available throughout the world. These values were expressed in terms of the Celsius (then centigrade) scale but were related to the Kelvin scale by a constant difference factor.

In 1954 the 10th General Conference redefined the thermodynamic temperature scale with a single fixed point, the triple point of water, and assigned to the temperature of this point the value  $273.16$  K. (Temperatures on the Kelvin scale now omit the word "degrees.") The triple point of water is the temperature at which the solid, liquid and vapor states of water exist together at equilibrium. It is  $.01$  degree Celsius above the ice point. This single fixed point can be reproduced with greater accuracy (about one part in a million) than either the ice point or the boiling point of water. In 1960 the International Temperature Scale was renamed the International Practical Temperature Scale at the same time that the ice point was replaced by the triple point as the fundamental reference.

The six defining fixed points on the International Practical Temperature Scale, all in degrees Celsius, are now the boiling point of oxygen ( $-182.97$ ), the triple point of water ( $.01$ ), the boiling point of water ( $100.0$ ), the boiling point of sulfur ( $444.6$ ), the freezing point of silver ( $960.8$ ) and the freezing point of gold ( $1,063.0$ ). It will be noted that none of these values is carried beyond the second decimal place, which is an indication of the comparatively low precision with which they can be reproduced.

Measurement of both extremely high and extremely low temperatures has be-



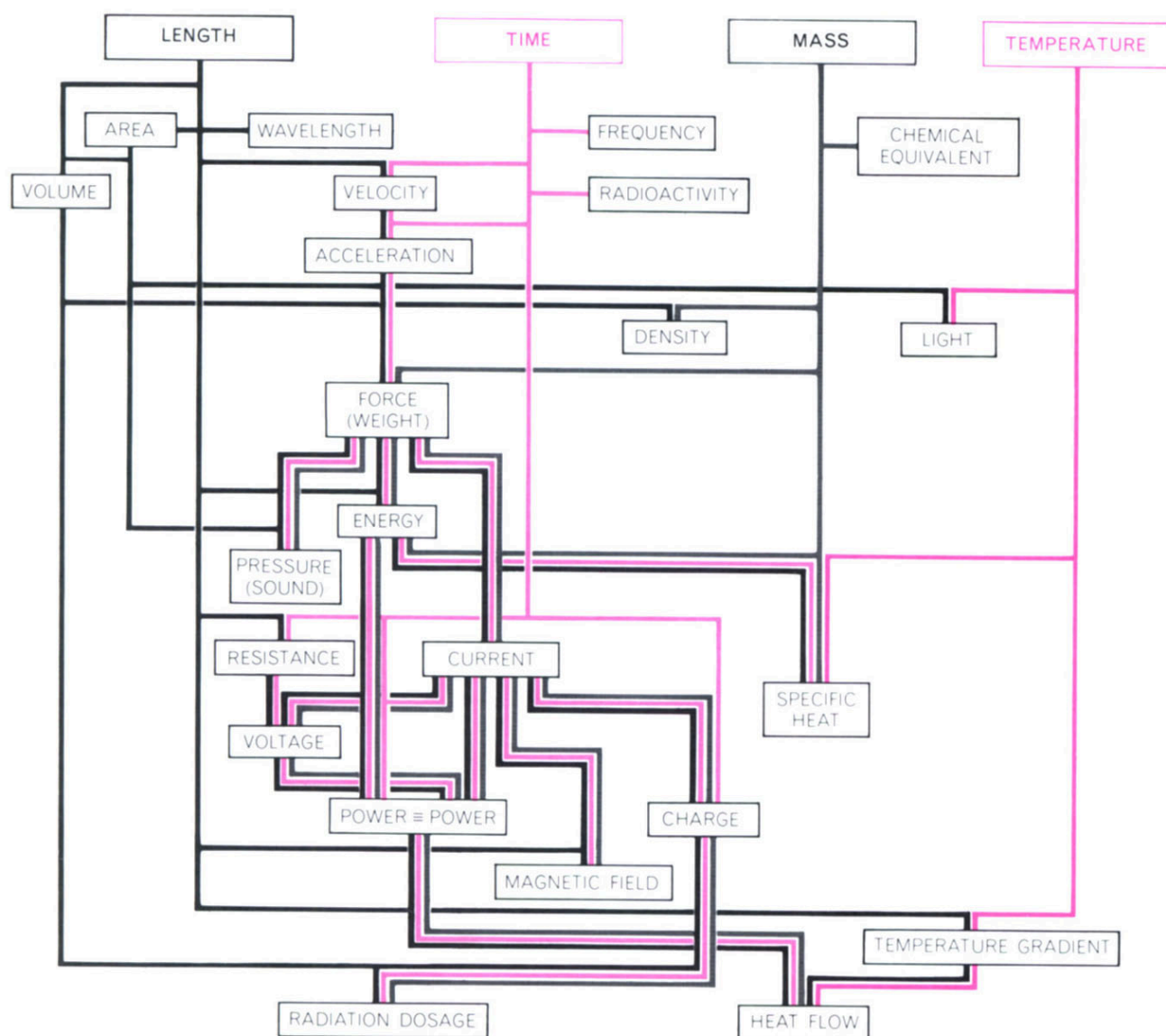
**CESIUM CLOCK** at the laboratories of the National Bureau of Standards in Boulder, Colo., provides the basis for the frequency and time signals broadcast by the Bureau. Atoms of cesium isotope 133 are boiled out of an oven located behind the end flange at which a micrometer is attached. As they leave the oven the atoms pass through a magnetic field that selects atoms in a certain energy state. The atoms then pass through a section where they are exposed to radio waves whose frequency is maintained at  $9,192,631,770$  hertz (cycles per second), which exactly matches a natural resonance frequency of the cesium atom. The frequency is maintained by feedback from a detector that records the arrival of cesium atoms at the far end of the clock. If the frequency drifts slightly away from the desired value, the number of cesium atoms reaching the detector falls off sharply, thus leading to a correction.

come increasingly important in many technologies. Extension of the temperature scale to these regions has proved to be most difficult. The National Bureau of Standards has established a scale known as the NBS Provisional Scale of 1955 for use in the range from 90 K down to 12 K. More recently two additional scales, the Helium-4 Vapor Pressure Scale and the Helium-3 Vapor Pressure Scale, have provided provisional scales below 5 K. These are based on the change in the vapor pressure of liquid helium with temperature. In 1965 the gap between 5 K and 12 K was closed by means of a scale based on an acoustic thermometer, developed by the National Bureau of Standards, that measures temperature in terms of the change

in the speed of sound in helium gas. Efforts are now being made to extend the International Practical Temperature Scale downward to about 14 K by use of resistance thermometers. International agreement on this extension is expected within the next year or two, leading to a new international practical scale.

Above the freezing point of gold the values on the International Practical Temperature Scale are obtained with optical pyrometers, whose readings can be converted to temperatures by extrapolation from the freezing point of gold on the basis of heat-radiation theory. A photoelectric pyrometer developed by the National Bureau of Standards provides readings up to 3,500 degrees Celsius with an uncertainty of two degrees at

the maximum reading. At higher temperatures, as in plasma arcs (10,000 to 15,000 degrees Celsius), spectroscopic methods must be employed. These are based on a theory that relates the temperature of an incandescent gas to certain characteristics of the resulting spectrum. At the extremely high temperatures associated with hydrogen fusion (10 million degrees Celsius and up) different temperature values are obtained depending on the spectroscopic method used to measure them. Apparently temperature as ordinarily defined has little meaning at the top of the scale. New concepts as well as new measuring methods will have to be developed in order to measure the properties that are relevant in these extreme regions.



**INTERRELATION OF MEASURING STANDARDS** provides a capsule course in elementary physics. Thus such quantities as velocity and acceleration are functions of distance and time. Force,

energy and pressure involve not only distance and time but also a third quantity: mass. Many important quantities such as inductance, capacity and viscosity have been omitted for simplicity.



## The Cover

The photograph on the cover shows the "face" of the atomic clock that provides the U.S. and much of the rest of the world with its standard of time. It was built by the National Bureau of Standards and is located at a Bureau laboratory in Boulder, Colo. Another photograph of the atomic clock and a short description of how it generates time signals can be found on page 13, in the article "Standards of Measurement." The clock exploits the natural precession frequency of the nucleus of the isotope cesium 133 when it is in a particular energy state. This frequency, 9,192,631,770 cycles per second, is now the official definition of the second. The margin of error of the atomic clock is plus or minus one second in a period of 6,000 years.

## The Author

ALLEN V. ASTIN is director of the National Bureau of Standards. He joined

the Bureau in 1932 as a research associate and became director in 1952. By training he is a physicist, and he has spent many years in physics work at the Bureau of Standards. In the 1930's he did work in dielectrics and electronic instrumentation. In dielectrics his contributions include the development of improved methods of measuring dielectric constants and the power factors of dielectric materials and a better understanding of the nature of energy losses in air capacitors. In electronic instrumentation he worked on the development of radio telemetering techniques and instruments and applied the results of the work to studies of meteorological problems in the earth's atmosphere and to studies of cosmic rays. During World War II he was closely involved with the development of the proximity fuze. Astin was graduated from the University of Utah in 1925 and obtained a Ph.D. at New York University in 1928. Before joining the Bureau he worked for four years as a research associate in

physics. Astin has been a member of the International Committee on Weights and Measures since 1954. He is also a member of the National Academy of Sciences.

## Bibliography

ATOMIC STANDARDS OF FREQUENCY AND TIME. John M. Richardson and James F. Brockman in *The Physics Teacher*, Vol. 4, No. 6, pages 247-256; September, 1966.

CONCEPT OF A NATIONAL MEASUREMENT SYSTEM. R. D. Huntoon in *Science*, Vol. 158, No. 3797, pages 67-71; October 6, 1967.

MEASURES FOR PROGRESS: A HISTORY OF THE NATIONAL BUREAU OF STANDARDS. Rexmond C. Cochrane. U.S. Department of Commerce, 1966.