MEASUREMENT STANDARDS

by A. G. McNish

The kilogram, made by man, still serves us well as the standard for mass. But the new standards for length, time, temperature—nature's standards—are more accurate than any man could devise

IN BRIEF: *All units of measurement, including the ampere of current and candela of light intensity—two base units included in the new International System of Units, are ultimately derived from four original prototype units—the meter of length, kilogram of mass, degree Kelvin of temperature, and second of time. To make all measurement units more effective tools, the standards that physically embody or define three of the prototypes—length, time, and temperature—have been changed in recent years. In the case of length, the change has replaced the man-made meter bar with a more accurate and more easily reproducible natural constant, the wavelength of an energy transition in krypton-86, and before the decade is out this in turn may be replaced by a length standard based on the laser. This rapid overthrow of long-established standards is not without precedent; the second of time has been redefined twice in the last ten years and it soon may be again. Temperature scales seem to have achieved a stability of sorts, however, with the partial success of attempts to relate the International Practical Temperature Scale to the Thermodynamic Scale.—S.T.*

■ What is a good strategy for a measuring system? A measuring system is like a language. Units—meters, kilograms, and so on—are the words of that language. Standards—the International Meter Bar, the International Kilogram, and so on—are the definitions of the words, the physical realization and embodiments of the units. As with a language, we could have independent units for every quantity we need to measure, and an independent definition for each. Convenience—and an ever-present sense of parsimony—call for using only a few base units. Countless others are derivable from these through defining physical equations. With our units and their definitions (standards) in hand, we can define measurement itself as the comparison of a quantity of unknown magnitude with a standard for that quantity.

This definition places us under no serious constraints in attempting to answer the question with which I began this article. We could select any units and define them in any arbitrary way; just so long as these units and standards were physically realizable and reproducible with satisfactory precision they would suffice for all measurements germane to our workaday world. And they also would serve as an unambiguous language for technical and scientific communication.

It is only when we attempt, by means of this language, to read the cryptic "literature" which nature has already written for us—the law of conservation of momentum, for example, is not Newton's but nature's—that we are best advised to adapt our measuring system to nature; to select units so that its laws will become most evident when expressed in terms of our chosen units, and with which calculations can be carried out most easily. This strategy was attempted but unrealized by the founders of the original metric system. It lies within our grasp today.

There are several added advantages in pursuing this course. Natural standards can be regarded as unchangeable in contrast to artificial ones. They may be independently reproduced in any suitably equipped laboratory and, therefore, in principle, they do not require tedious intercomparison from laboratory to laboratory and they do not invite accrual of the inevitable errors inherent in a chain of intercomparisons. Thus they are more exact than any man-made standards.

But which of nature's many constants are most suitable? The most intellectually satisfying measuring system, for example, might be based on such natural constants as the speed of light, Planck's constant, Boltzmann's constant, and the gravitational constant. We could assign the value of unity to these and on this basis one meter would turn out to be approximately 2×10^{34} length units, for example, and one second would be 8×10^{42} time units, and so on.

What would this buy us? Could we, then, measure length, mass, force, and so on, more accurately? Would this improve our ability to fit parts together in a machine shop or to exchange technical information more readily with our colleagues? No; the uncertainty involved at the present time in experimentally relating the gravitational constant to other quantities of physics would create an uncertainty in the practical realization of these other quantities of about 1 part in 1000, far greater than the uncertainties achieved with the less elegant system which we now use.

Our present system uses four, and only four,

HOW ACCURATELY CAN WE MEASURE? A Gallery of NBS Capabilities

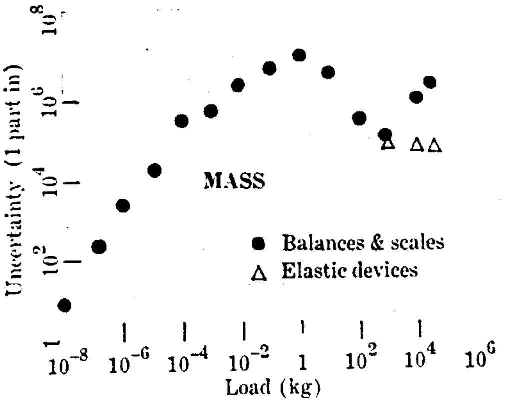
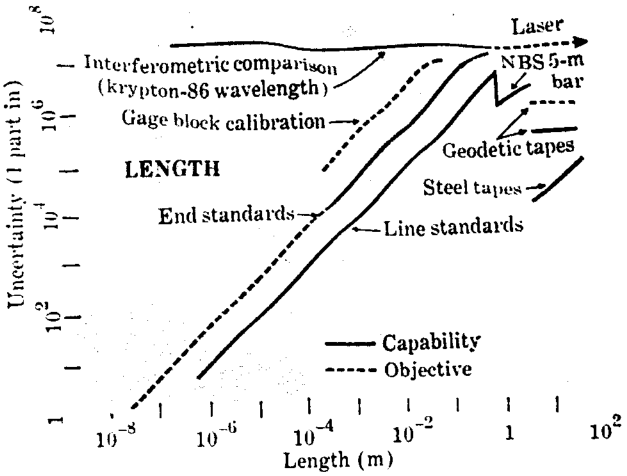
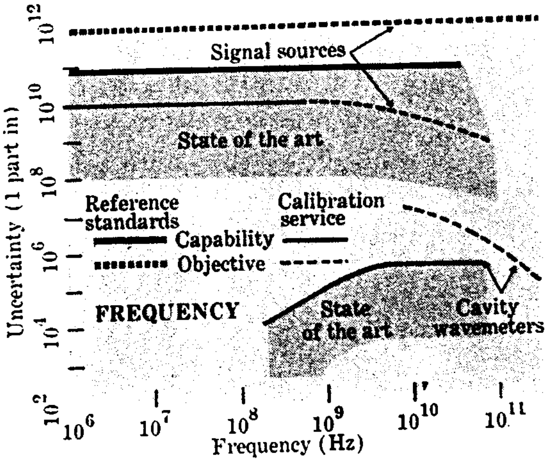


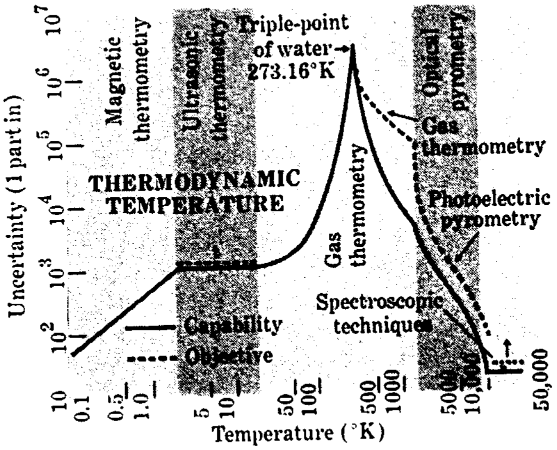
Chart showing precisions achievable in single weighing of mass is based, as are other charts on this page, on equipment and environments used at the National Bureau of Standards. Accuracy attainable at factory is inevitably less than at calibration point.



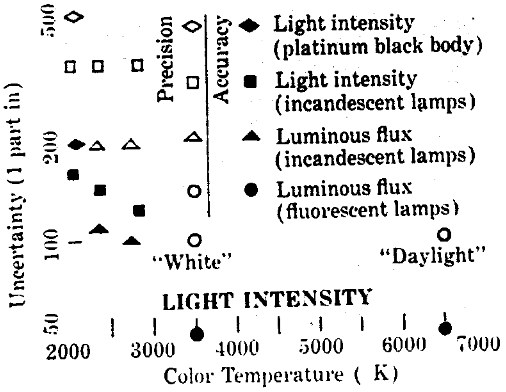
Uncertain refractive index in air of krypton-86 wavelength, used to measure meter, sets limit on accuracy with which interferometry can measure other lengths.



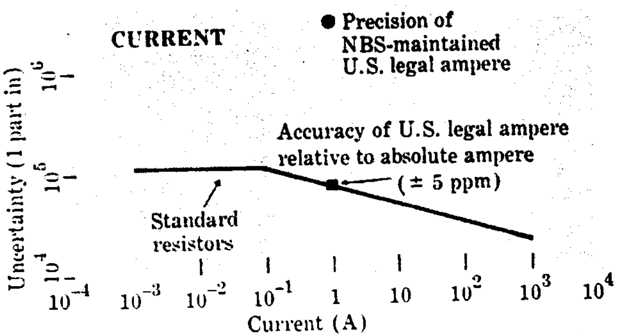
Existing capabilities shown for signal sources are based on new cesium standard for reciprocal frequency (time) which, with ideal, unperturbed Cs atom, would be accurate to 6 parts in 10ⁿ.



The thermodynamic (Kelvin) scale is completely defined by value assigned to triple point of water, but techniques indicated must be used in practice, using phase transitions in other substances, to calibrate thermometers at other temperatures.



Photometric standards are based on the candela—the light intensity of 1/60 cm² of a black body at temperature of freezing platinum. Uncertainties in flux and intensity shown are therefore plotted against color temperatures of a fictitious black body.



The absolute value of the ampere is realized to a few ppm by a current balance "weighing." The NBS (legal) ampere is about 12 ppm above the absolute value and held to within ± 0.3 ppm by use of the proton's gyromagnetic ratio and calibrated coil. Other dc values than 1 A are obtained with standard resistors and dc potentiometer. The ac values are based on dc standards.

independent units—the meter for length, the kilogram for mass, the second for time, and the degree Kelvin for temperature. These we designate prototype units; they are units for quantities which can be measured very accurately and standards for them can be preserved or reproduced with fidelity. Furthermore, standards for other quantities of every conceivable kind can be constructed from these, with adequate accuracy, in accordance with the defining physical equations. The International System of Units, today's version of the metric system, recognizes the ampere of electric current and the candela of light intensity as additional base units, but their definitions depend in part on the four prototypes.

The long and the short of it

Measurement of length is the easiest to comprehend and the simplest to perform of all the measuring processes, because the demarcations of length are visually discernible in many cases. Jacques Babinet, a French physicist, suggested in 1827 that if we wished to define our unit of length in terms of a natural constant we should select a wavelength of light for the purpose. This is what we finally did. Two-thirds of a century elapsed, however, before an optical-interference method was developed (by Michelson and Benoit in 1892) for relating the wavelength of the red cadmium line to the length defined by the International Meter Bar. Another two-thirds of a century passed before the proposal was put into effect. Only in 1960, was the meter redefined as the length equal to 1,650,763.73 vacuum wavelengths of a specified line in the spectrum, not of cadmium, but of the isotope krypton-86, abrogating the 200-year old definition based on the platinum-iridium bar.

The krypton-86 lamp, developed by Engelhard of the (German) Physikalisch-Technische Bundesanstalt, was chosen as the source of the new wavelength standard because its light was more coherent than the light from the cadmium lamp used by Michelson, permitting interferometer measurements to be made over a distance of several decimeters, or several hundred thousand wavelengths, instead of the few millimeters attainable previously.

The adoption of this new standard for the meter has no effect on the use of meter bars, gage blocks, and so on. They continue as standards for the everyday measurements for which they are suited. In the very important field of spectroscopy, however, new measurements were required before the krypton standards could be adopted, because through the years spectroscopists had been expressing their results in terms of Michelson's value. Extensive tables of spectral wavelengths had been compiled on this basis, and it is on these that our knowledge of atomic structure is founded.

Thoughtful men do not toy capriciously with a measuring system upon which so much science and technology depends. The 1960 conference that abrogated a definition of the meter which had stood for 200 years acted with due caution and after due deliberation. Yet the pace of technical progress today is such that before the printed report of this well-considered decision had even reached the conferees, another scientific breakthrough was achieved. Continuous maser action in the optical region of the electromagnetic spectrum had been dem-

16th-century woodcut shows how standards were set for the German rute, a variant of the old English rod. Sixteen men, selected at random as they came from church, were lined up heel to toe. The over-all length became the rute, and a foot—surely to no one's surprise—1/16 part of it.

1,650,763.73 wavelengths in vacuo of a specified transition in the isotope krypton-86 now define the meter. The lamp used to produce these wavelengths is shown being placed in a dewar flask. U-shaped tube contains krypton gas in which continuous electric discharge is maintained.

onstrated. Here was the possibility for a new, still better standard of length!

The importance of the optical maser (or laser) as a measuring device is clear when it is compared with the krypton standard. Length measurements with krypton light cannot be made in a single step for distances as great as one meter because the light waves from a krypton lamp are themselves not sufficiently coherent. By virtue of its greater coherence, and intensity, as a source, the laser conceivably could extend the limit of length measurement by interferometric techniques to hundreds or even hundreds of thousands of kilometers. But its practical usefulness for measuring distances greater than a few meters seems limited. We are currently using a laser for our automatic fringe-counting interferometer at the Bureau of Standards, for example, and the difficulty of counting the several hundred million interference fringes involved in measuring distances beyond a few meters is formidable.

In applying the laser to interferometer-based measurement of greater lengths, such as 50-m geodetic tapes, it may prove more practical to determine the total number of fringes representing length in the optical path by another means, and then use the precision capabilities of the laser only to get the exact distance.

Lasers as standards of length?

Can the laser itself be used to establish an independent standard of length? The Bureau has already related one laser line—the 632.8 $\times 10^9$ m wavelength of neon—to the krypton standard with an accuracy of 1 part in 10^8, which is close to the accuracy inherent in the krypton standard. Can we look forward to changing the definition of the meter once more, so that we can say the meter is equal to x wavelengths of a certain laser line?

The question was seriously discussed at the last meeting of the International Consultative Committee for the Definition of the Meter. To obtain an affirmative answer to this question experimental demonstrations will be required that the energy states from which laser lines can be generated are adequately reproducible under specified conditions. If the more enthusiastic hopes of laser workers can be fulfilled soon, it is likely that in the present decade the science of precise length-metrology will have been advanced more than it has been in the nearly two centuries which have elapsed since the meter was first defined, incorrectly as it turned out, as 1/10,000,000 part of the length, from the equator to the pole, of the meridian of longitude passing through Paris.

What's new among the masses?

Mass has long been the most precisely and accurately measurable of all physical quantities, although during the past decade it has yielded this distinction to time. It retains the distinction of being the only one of our four prototype units that is not firmly tied to a constant of nature. The international standard for mass is still a certain cylinder of platinum-iridium, called the International Kilogram, kept in the vault at Sevres, France. Its mass is compared with various national standards (also mainly platinum-iridium) by the weighing process.

While two masses of about one kilogram may be compared with each other with a precision of a few parts in 10^9 under favorable conditions, we still cannot measure the mass of a single atomic nucleus in terms of the International Kilogram with any satisfying accuracy. But we can compare the masses of the thousand-and-odd known nuclei with each other with great precision, by mass spectrometry—illustrating a principle which is axiomatic in measurement, that the more alike two things are, the more precisely some property of theirs can be compared.

In measuring gross masses by weighing, we use the earth's gravitational attraction as the base against which the masses are compared. In mass spectroscopy, on the other hand, we employ directly the inertial properties of mass itself in our measurement. Among nuclear masses, fortunately, a large number of close-to-equal and thus precisely comparable, mass doublets are available, most of them involving the carbon atom. For this reason the new scale of nuclidic and atomic masses, recently adopted internationally by the Union of Pure and Applied Chemistry and by the Union of Pure and Applied Physics, was based on the mass of the carbon-12 atom, even though this made all tables of atomic masses based on oxygen-16 obsolete. But only those research workers requiring the most exact values were affected by the change. On the new scale some nuclidic masses are known in atomic mass units, as defined by carbon-12, with a standard error of only a few parts in 10^8, nearly the same precision which is attainable in comparing two standard kilograms. However, the size of the atomic mass unit still cannot be related to the kilogram with a standard error smaller than a few parts in 10^5.

Why strive for greater precision than this in measuring nuclidic masses when the atomic mass unit itself is so inaccurately known? One reason is that the small difference between the masses of individual nuclides and the sums of the masses of the neutrons and protons of which each nuclide is composed, the "mass defects," indicate the amounts of energy available in various nuclear reactions, in accordance with the familiar Einstein equation relating mass to energy. Since these mass defects are very small—they never exceed about 1% of the mass of the nuclides involved in such work—the relative masses must be known with great precision to calculate the energies available. As our measurement capabilities now stand, it is fortunate that these theoretical mass-energy relations are so well known that the masses of many nuclides can be calculated from the energy relationships more precisely than they can be measured by mass spectrometry.

Suggestions are frequently made that the kilogram be defined in terms of the atomic mass unit instead of in terms of a cylinder of platinum-iridium. While this would offer the attractive possibility of establishing an immutable physical constant as the standard for mass, it would greatly degrade the accuracy achievable in measurement of all masses except atomic particles.

Of time, stars, and atoms

The spectacular success of recent attempts to improve time and frequency measurements may seem a futile quest to some, a desire for precision for precision's own sake, a pointless pushing of the decimal point. This is a naive view. These attempts to refine standards are aimed precisely at learning what physics lies beyond the decimal point. For such discoveries Nobel Prizes have been awarded. And now we can ask, do time scales based on astronomic, atomic, and molecular processes change with respect to each other, as some think they might?

The unit of time itself was not defined by the founders of the metric system. But, by convention among scientists, time has long been measured in terms of the rotation of the earth, the scientific unit of time—the second—having once been defined as 1/86400 of a mean solar day. But the rotation of the earth has proved to be too erratic a timekeeper to meet modern scientific needs—it is subject to periodic fluctuations within a year and to unpredictable fluctuations from year to year—and, therefore, the mean solar second is continually changing. The inconsistencies created by this are small—of the order of a part in 10^8—yet enough so that the time scale kept by the rotation of the earth on its axis now lags behind that kept by the revolution of the earth about the sun by about 30 sec, reckoning from the year 1900.

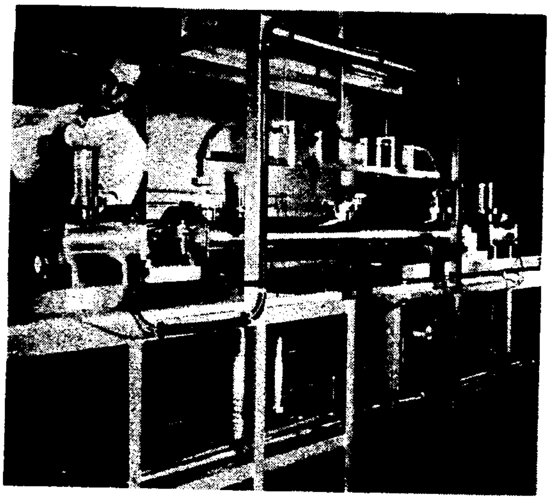
A partial remedy was achieved in 1956 when the International Committee on Weights and Measures redefined the second for scientific use as 1/31,556,925.9747 of the tropical year at 1200 hours, ephemeris time, 0 January 1900. This imposing number was obtained from Simon Newcomb's equation for the apparent motion of the sun across the celestial sphere. This so-called ephemeris second is made available in practice with the aid of atomic clocks, but only retrospectively, as an average value over several years, by means of continual observations of the position of the moon. It can be determined experimentally with an uncertainty of a few parts in 10^9, a large uncertainty compared with the exactness implied by the multidigitality of the definition itself.

This 1956 definition of the second—though a great improvement for astronomers—still had one serious fault. No one else could measure an unknown interval of time with it by direct comparison. But even as this redefinition of the second was being formulated, a spectacular revolution in the measurement of time was taking place in the laboratory, where experimental techniques in molecular and atomic physics had been advancing rapidly.

Physicists had been able to excite some of the lower energy states of atoms and molecules, associated frequencies of which, in accordance with Planck's equation $e = h\nu$ fall within the microwave part of the spectrum. These frequencies could be measured by comparison with laboratory oscillators and expressed in terms of the germane time-inverse unit of frequency, the cycle-per-second (now called the hertz—Hz—incidentally). Even in the early experiments, the better ones at any rate, frequencies could be compared repeatedly with an agreement to within parts in 10^8 or 10^9. Subsequently, atomic beams, masers, and absorption cells were developed which also proved to be very stable standards for frequency and time; not only could they be compared with each other with a precision of 1 part in 10^{10} or better, during an observing time of an hour or so, but cesium-beam resonators, independently constructed in different laboratories, agreed in frequency to a few parts in 10^{11} (equivalent to a sec of cumulative error in 3000 years). It was apparent that if the second were defined as the interval of time corresponding to x cycles of a suitably selected atomic resonant frequency, the second could be defined more easily and more exactly than by the ephemeris second.

This redefinition of the second, the second one in the past ten years, was accomplished by the Twelfth General Conference on Weights and Measures in 1964. It designated the frequency associated with the transition between two hyperfine energy levels of the fundamental state of the isotope cesium-133 to serve as a temporary time standard, and assigned to this frequency a value of 9,192,631,770 hertz. A little over a decade after a realistic method for defining the unit of time by an atomic constant was conceived, a new standard was born! The fact that the standard designated in 1964 was a temporary one did not imply any misgivings about an atomic standard for time, only a reluctance to arrive at any final abiding decision when the chances were quite good, as they are, that an even better atomic standard—based on the hydrogen atom or possibly the thallium atom—might be developed soon.

The new standard lays at least the preliminary groundwork for an eventual experimental assault on the question I mentioned earlier: Are time scales based variously on gravita-



NBS cesium-beam apparatus shown became national frequency standard in 1964, when astronomers' unit of time—the ephemeris second—was supplementarily defined in terms of it, as the inverse of the frequency 9,192,631,770 cps of a specified hyperfine energy transition in Cs atom.

Better accuracy and reproducibility of the ampere, unit of current, may come from work shown, which seeks better value for gyromagnetic ratio of the proton. The large coil is a precision solenoid for producing a reference magnetic field. Within it is the detector of proton precession.

tional, electric, and nuclear forces compatible and consonant with each other? And if they are not, why not?

Empirical progress in electromagnetism

Measurement of electrical and magnetic quantities directly in terms of length, mass, and time is difficult, and unless performed with great care, very inaccurate. By any of several well-known procedures, however, the resistance of a length of wire, in ohms, can be determined to within a few parts in a million in terms of the base units of length and time. Such a piece of wire may then be regarded, with the dignity that is its due, as a standard for resistance. If the quality of wire has been wisely selected, and if the resistors are preserved with care, their resistances are not likely to change appreciably through time, and by constant intercomparison each serves as a witness to the fidelity of the others. From time to time the average resistance of the group may also be checked by repeated absolute determinations. Such a group then can serve as a satisfactory, if inelegant, standard, and long experience has led us to view that the average resistance of the set is indeed constant to within much closer limits than its absolute accuracy is known.

In a similar way, a current flowing in a wire can be determined in absolute units through weighing the magnetic force it exerts on an identical current. But, since we cannot preserve a standard of current as we can preserve a standard of resistance, we must compare the voltage drop which that current produces, when flowing through a standard resistor, with the electromotive force of an electrochemical system, such as a standard cell. A group of such cells then serves as a standard of voltage, just as a bank of resistors serves as a standard of resistance.

These empirical standards of resistance and voltage furnish the basis for establishing standards for other electrical and magnetic quantities through the physical equations which define them. By accepting the established standards for resistance and dc voltage as correct, such dc quantities as current, charge, power, and energy can be realized in terms of them by the defining equations, and by dc techniques, to better than 1 part in 10^6. However, the consistency of these measurements with respect to the standards for length, mass, and time is not nearly so good. The electromagnetic system of units is like an isolated continent in the world of measurement; the relations between points on it are closely tied together, in an empirical way, but the distances to other continents are not nearly so well established. Another troublesome thing is that the corresponding ac electrical quantities cannot be realized within the same limits, and the difficulties become still greater at higher frequencies, such as those which characterize microwave work. The uncertainty in relating microwave power around 10-cm to dc power, for instance, is estimated at fully 1 part in 10^3, even when great pains are taken in experimental procedures.

The improvement of standards in the electromagnetic field may be helped considerably by the results of work in progress, based on two recent discoveries, nuclear magnetic resonance and a new theorem in electrostatics, known as the Lampard-Thompson theorem.

Nuclear magnetic resonance depends on the fact that a proton spinning in a magnetic field, if disturbed in its orientation, will precess about the field lines like a gyroscope. The precession frequency, easily measured by electronic techniques, is proportional to the strength of the magnetic field, thus providing a sensitive new means for measuring magnetic fields, great and small.

NMR and new progress in an old field

NMR studies also have strengthened our confidence in the electrical units, isolated though they are from the prototype units of our measurement system. Applying NMR to the measurement of strong magnetic fields, which cannot be calculated accurately, a value for the charge-to-mass ratio of the proton can be obtained. This quantity, when multiplied by the mass of the proton in atomic mass units, in turn yields the value of the important physical constant, the faraday, which is the charge associated with one gram-atomic mass of a monovalent element. The faraday can be determined also by the methods of electrodeposition or electro-erosion. The highly comforting thing is that its determination by each of these two different methods agrees, to within about 4 parts in 10^6.

The discovery of the Lampard-Thompson theorem in electrostatics, the oldest branch of electric science, is also encouraging. The theorem relates capacitance to the dimensions and geometry of the capacitor. Its details are unimportant here, but their significance is not. A capacitor constructed to satisfy the conditions of this theorem now enables us to establish the magnitude of the ohm, unit of electrical resistance, more accurately than ever before. Indeed, applying the experimental techniques engendered by this new theorem leaves the uncertainty in the true value of the ohm limited as much by our uncertainty about the true value for the speed of light as by all other limitations of the determination.

Closing on a hot note and a cold one

Although we are reviewing temperature last, it has the distinction of having been the first physical quantity to have had its standards established by physical constants—the familiar ice-water and boiling water reference points—which early thermometer makers seized upon to establish their temperature scales. But they failed to prescribe an adequate method for interpolating between these fixed points or for measuring temperatures much hotter or colder than these. The concepts of heat and temperature remained poorly understood until the young engineer, N.L.S. Carnot, analyzing the practical performance characteristics of steam engines, developed the basic thermodynamic concept which came to be called the Carnot cycle and which now forms the conceptual foundation for our definition of temperature. Kelvin seized the inspired concepts of Carnot and proposed the first formal definition: If there are two heat reservoirs of infinite capacity, and if a perfect heat engine (one operating in accordance with the Carnot cycle) transfers heat from one reservoir to the other, then the temperatures of the two reservoirs are to each other, inversely, as the heat energy taken from the first reservoir is to the heat energy delivered to the second reservoir. This definition requires that only one fixed point be chosen and a value other than zero be assigned to its temperature; then all temperatures are uniquely defined. It is nature's own temperature scale—the same which appears in the gas law and in the thermal radiation law. Man's contribution consists only of selecting the fixed point and assigning a number to it.

Defining a temperature scale in terms of a perfect heat engine is an intellectual achievement but it does not constitute a practical means of measuring temperature. The gas law affords a more vulnerable front for attack, although it applies only to a "perfect" gas. There are two key steps in establishing a temperature scale by use of the gas law. The first is to calibrate a platinum resistance thermometer by placing it in thermal contact with a gas whose temperature is varied. The temperature of the gas is calculated from variations in its pressure in accordance with the gas law $pv = RT$. The second step is to place the thermometer in contact with some substance undergoing a phase transition, such as melting ice. Then all we need do is assign an arbitrary value to the temperature of that transition. We now have a thermometer calibrated to read temperatures on nature's own (though it's called Kelvin's) thermodynamic scale.

The phase transition to which this scale is anchored is the triple point of water, at which solid, liquid, and vapor phases coexist. It is slightly warmer—by about 0.01°K—than the ice point, but is more readily reproduced. The precise value assigned to it is 273.16°K so that temperatures expressed in this scale will agree closely with those expressed on the long-used Celsius scale by merely adding 273.15° to the Celsius temperature.

Calibrating a thermometer by this means, however, is long, tedious and laborious, taking years to perform with the desired accuracy. Some other means had to be devised to make the results readily available to people other than metrologists who also had to measure temperature precisely. For this end the International Practical Scale of Temperature was agreed on. Thermometers calibrated the tedious way are used to measure the temperatures of several other phase transitions—the boiling points of oxygen and water, and the freezing points of zinc, silver, gold, etc. These fixed points now serve as the functional standards for temperature, standards which can be reproduced readily.

The strategy and tactics of measurement can be pursued in the references on p. 73.