# The Basis of Our Measuring System*

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*Summary*—The measuring system used for scientific work affords a means of making physical measurements with great precision and accuracy. The best measurements can be made of the quantities taken for the basis of the system. A decrease in both accuracy and precision arises in measuring quantities which are related to them in a complicated way. The standards which fix the magnitudes of the units on which the system is based appear to be very constant. Some improvement in the system may be obtained by substituting physical constants for these standards. This has already been done for the standard of temperature, and it can be done advantageously for the standards of length and time; but there seems to be no way to replace advantageously the standard for mass.

## Introduction

THE most satisfactory kind of information that we can secure about phenomena is developed through measurement. If the phenomena are not susceptible to measurement, the information we can obtain of them is rather unsatisfactory and incomplete. It is the high measurability of the phenomena involved which sets the physical sciences apart from the others and causes them to be called the exact sciences.

Corollary to this, the more accurate the measurements, the better is the information which we obtain. To a considerable extent, the spectacular advances we have achieved in the physical sciences during the past few decades are the results of more accurate measurements. Rough descriptions of phenomena are no longer satisfactory. A few centuries ago, it was adequate to know that the rate of free fall for a body is independent of its mass. Later, the knowledge that the path of a freely falling body with some initial motion describes an approximate parabola sufficed. Today we recognize that the ideal path is actually an ellipse; and, if the gravitational field is not completely specified by the inverse square law, perturbations of the elliptical path must be allowed for, as in the case of an artificial satellite.

In order to carry out accurate measurements, we have established a system of units and a system of standards to fix and preserve the sizes of the units. What are the requirements of such a system? How many units and how many standards do we need? And how many of them are what we call "basic"?

Let us consider several possible systems. For example, we might take for the unit of length, the length of some arbitrarily selected bar; for the unit of mass, the mass of some specified object; the unit of electromotive force, the open circuit EMF of a particular Clark cell; the unit of current, the short-circuit current of a particular gravity cell; the unit of resistance, the resistance of a particular piece of wire, etc. For each quantity in physics, we would have an independent unit for measuring that quantity and the magnitude of each unit would be fixed by the standard embodying it.

What are the faults of such a system? One of its disagreeable aspects is that, with units so chosen, it would be a rare case of good fortune if we found that the equation $E=IR$ holds. We would find, of course, $E \propto IR$. Each physical law expressed in the form of an equation would require a different factor of proportionality to relate the sizes of the units involved. However, if we have selected our standards for such a system with good judgment, we would have an excellent set of standards and we could measure physical quantities with great accuracy in terms of the unit embodied by the standards. Also, we could select the standards so that all units would be of convenient size for practical use.

We can exercise a little parsimony in our choice of independent standards by selecting only a few to fix the units of several quantities and have the units for other quantities fixed by physical equations. Thus, for example, having independent units for electromotive force and resistance, we can write $I=kE/R$ to define the unit of current. We can simplify things by setting $k$ equal to unity. How far can we go in our parsimony? What is the smallest number of arbitrary, independent units and standards which are required for a measuring system?

The founders of the metric system sought to reduce the number of independent standards by defining the gram as the mass of one cubic centimeter of water, leaving the meter as the one independent unit and adopting a constant of nature, the density of water, to fix the unit of mass. For reasons to be discussed later, they found this unsatisfactory. Had it worked we would have found it convenient for it would be necessary for measuring laboratories to compare only meter bars. Each could then set up consistent units of area, volume, and mass, depending only on the meter bar.

We can see that with a system such as this an entire system of measuring units can be built up based upon a single arbitrary, independent standard. The unit of time could be the time of swing for a one-meter pendulum, or the time light takes to travel one meter. Other units could be defined by various equations as we did before for the unit of electric current.

If we set all of the constants in our defining equations equal to unity, we will find this system very convenient for theoretical work, for most equations are in their simplest form. But we will not find the system good for experimental work because many of the quantities most frequently measured in physics would not be measurable

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with sufficient accuracy in terms of the units prescribed for them.

Thus we see that we can have a multi-unit multi-standard system in which all units and standards must be regarded as "basic." Also, we have seen that we can have a single-standard system in which only one quantity is taken as basic. Is this the limit to which our parsimony can go? Can we have a consistent system of measurement with *no standard at all*? The answer to this is, yes, and a moment's reflection will show that it can be done in a number of ways.

To illustrate one of the many ways this can be done, suppose, we rewrite the electromagnetic wave equation $\partial^2\phi/\partial t^2 = \partial^2\phi/\partial x^2$ instead of $\partial^2\varphi/\partial t^2 = c^2\partial^2\varphi/\partial x^2$, the quantum equation $E=\nu$ instead of $E=h\nu$, the gravity equation $F=m_1m_2/r^2$ instead of $F=Gm_1m_2/r^2$, and the molecular energy equation $E=(3/2)T$ instead of $E=(3/2)kT$. Now with provisional measuring units of arbitrary size we can perform various experiments involving these equations, assuming that other equations of physics are written in their conventional forms. We then solve the results obtained and find what values we must assign to our provisional units. If these sets of experiments are performed by different people, they will be in agreement on the sizes of their units.

The necessary experiments already have been performed, using our conventional units of measurement, so that we can write down the equivalence of these in our new units as shown in Table I. To put it another

TABLE I

Approximate Values of Conventional Units in Terms of Units Derived by Setting $c$, $G$, $h$, $k$ and $\epsilon_0$ Equal to Unity

| | |
|---|---|
| One meter | $2\times10^{34}$ length units |
| One second | $8\times10^{42}$ time units |
| One kilogram | $2\times10^{7}$ mass units |
| One degree Kelvin | $2\times10^{-33}$ temperature unit |
| One watt | $2\times10^{-53}$ power unit |
| One coulomb | $2\times10^{17}$ charge units |

way, what we have done is to assign the value unity to the speed of light $c$, Planck's constant $h$, the universal gravity constant, $G$, and Boltzmann's constant $k$. If we also set $\mu_0$ and $\epsilon_0$, which we call the permeability and permittivity of space equal to unity, as we may do consistently since $c$ is unity, further interesting results are obtained. We now find that the units of the electrostatic system and the electromagnetic system as defined by Coulomb's equations are of identical magnitude; the unit of electric charge is about $4.8\times10^{-18}$ coulombs, which is approximately equal to the nuclear charge for the elements where the percentage mass defect is a maximum; the electronic charge is given exactly by $e=\sqrt{\alpha/2\pi}$, where $\alpha$ is the well-known Sommerfield fine-structure constant, approximately equal to 1/137, Eddington's magic number! Also the unit of energy is exactly the energy released when one unit of mass is annihilated in accordance with Einstein's equation $E=mc^2$.

In spite of a number of appealing features of this system we cannot recommend it for practical use. Because of the uncertainty involved at the present time in relating experimentally the gravitational constant to other quantities of physics, the magnitudes of the units so defined would have an uncertainty in their practical realization of about 1 part in 1000. We can, of course, use some other constant instead of $G$ and thus reduce the uncertainties, but they would still be much greater than we can afford to have them.

We now ask ourselves if we have really eliminated standards from our system by this procedure. Have we not made $c$, $h$, $G$, $k$, and $\epsilon_0$ our new standards? Are these not our new "basic" quantities of physics? This is all a matter of point of view.

Some of these concepts may seem heterodox to those who have been indoctrinated in the trinity of mass, length, and time as fundamental units. They have been touched on here because some smattering of them is necessary to understand the system of units and standards currently used by physical scientists of all nations of the world. They serve to illustrate the requirements of a system of units and standards for an adequate measuring system, requirements which are very well met by our present system.

## Our Present Units and Standards

The authors of the metric system intended that the meter should be one ten-millionth of the length of the north polar quadrant of the Paris meridian, demonstrating a desire that a measuring system be based on some natural magnitude which would remain constant, a desire which still exists with metrologists. But they soon found that they could compare two meter bars with each other with greater precision than they could relate them to the earth's quadrant.

Similarly, they found that the masses of two metal cylinders weighing about one kilogram each could be compared with each other more precisely than either could be related to the mass of 1000 cubic centimeters of water which was supposed to define them. Thus, the pioneers in precise metrology found that greater precision in measurement could be achieved if they adopted some readily measurable artificial things for standards than if they adopted less readily measurable things of nature.

Accordingly, the International Commission of the Meter, meeting in 1872, resolved to take the meter in the Archives of Paris "as is" (*dans l'état où il se trouve*) for the standard of length. Similarly, they adopted the platinum-iridium kilogram of the Archives as the standard of mass, "considering that the simple relationship, established by the authors of the metric system between the unit of weight and unit of volume, is represented by the actual kilogram in a sufficiently exact manner for the ordinary uses of industry and science . . . and that the exact sciences do not have the self-same need of a simple numerical relationship, but only of a determination as perfect as possible of this relationship." Three years later many of the leading nations of the world signed the treaty of the meter which created a procedure for coordinating the standards of measurement for the scientific world through an International Bureau of Weights and Measures and a General Conference of Weights and Measures.

For many years no new standard for time was adopted, the ancient definition of the second as 1/86,400 part of a mean solar day being retained. A separate and independent standard for temperature measurements was adopted and changed a number of times until, in 1954, the thermodynamic temperature scale was based on the triple-point temperature of water as 273.16°K. Other units were defined in terms of the units embodied by these standards by agreed-on equations of physics.

Thus, our system of units and standards does not follow either of the extreme types of systems described in our introduction. Four, and four only, independent standards have been adopted to which we attach the name prototypes. The reasons for this are clear. They are standards for quantities which can be measured very accurately and they are standards which we believe can be preserved or *re*-produced, as in the case for the standard of temperature, very accurately. Furthermore, standards for other quantities can be constructed from them with adequate accuracy in accordance with the defining physical equations.

### From Prototypes to Electricity Standards

As pointed out before, we could establish our standards of electricity and magnetism with the same degree of arbitrariness that we used for the prototypes. However, it is not desirable that we do this, for then the units of electrical and mechanical power would not be the same unless we cluttered up the equations of electricity and magnetism with an unnecessary number of numerical constants. Furthermore, standards for the more useful electric quantities may be established in terms of the prototype standards with great accuracy, as shown by Silsbee.[1]

In the early days of research in electricity and magnetism, there was no way to measure these phenomena accurately. The strength of a current was measured by the deflection of a compass needle which the current produced, but, since the deflection depended on the strength of the earth's magnetic field, two observers in different places could not compare their results. Variations in the strength of the geomagnetic field from place were measured by timing the oscillations of a "permanent" magnet which, even in those days, was known to be far from permanent.

C. F. Gauss first showed how magnetic and electric quantities could be measured accurately in terms of the units used for mechanical quantities which are embodied in relatively invariant standards. This is the well-known magnetometer experiment which every student of physics and electrical engineering must have performed. That Guass thoroughly understood what he was doing we must presume. That he anticipated the reverence and mysticism with which future generations of scientists would regard the units of mass, length, and time is not likely. It is clear from the writings of those who followed him that they recognized a duplicity in electric units (esu) and magnetic units (emu) and that they could not simultaneously set $\epsilon_0$ and $\mu_0$ in these systems equal to a dimensionless unity and still retain the generally agreed-on unit of time as well as the metric units of length and of mass.

Thus, in the early days of electromagnetic science, the systems of units were not on a satisfactory basis since electric and magnetic units were conflictingly defined. Nor was the situation remedied by combining the esu and emu systems into that bifurcated system which falsely is called Gaussian. A further disagreeable feature is that some of the units in both systems are of inconvenient size, and are not even approximately equal to the units for voltage, current, and resistance which had been adopted by the communications engineers of that day.

To resolve these difficulties, Giorgi proposed that one more arbitrary unit and a standard for it, this time for an electric quantity, be added to the system. By suitably choosing this new unit we can make the MKS units and the practical electrical units form a consistent system. What we mean by this is that equations of the type $W=I^2R$ would be valid if $I$ and $R$ were expressed in the electrical units and $W$ is expressed in MKS units. Of course, Coulomb's equations for the force between unit electric charges and between "unit magnetic poles" would contain constants of proportionality other than unity just as does the equation for the gravitational attraction between two unit masses, as it is ordinarily written.

Giorgi's proposal found such increasing favor among scientists that in 1946 the International Commission on Weights and Measures adopted it in principle. But instead of adopting a new independent unit and a standard for it, they redefined the ampere[1] in accordance with another suggestion of Giorgi in such a way as was equivalent to rewriting the equation for the force between two infinitely long current-carrying conductors. The old emu equation for force per unit length for unit separation of the conductors was $F=2I^2$, where $F$ is in dynes and $I$ in abamperes. The new form of the equation became $F=2\mu_0I^2/4\pi$, where $F$ is in newtons, $I$ in amperes, and $\mu_0$ has the value $4\pi\times10^{-7}$, if rationalized equations are used. It follows from this that the equation for the force between two charges is $F=Q_1Q_2/4\pi\epsilon_0R^2$ and, if $F$ is in newtons, $Q_1$ and $Q_2$ in coulombs, and $R$ in meters, the equation is correct if $\epsilon_0$ is given by $1/\mu_0c^2$, where $c$ is the speed of light in meters per second.

The present-day system of electric units is known as the MKSA system. It is important to recognize that the unit for electric current, the ampere, does not oc-

[1] F. B. Silsbee, "The ampere," this issue.

cupy quite the same position in it as the meter, kilogram, and second, for they are prototype units and their values are fixed by their independent, proper standards. On the other hand, the value of the ampere is fixed in terms of them as given by an equation involving an arbitrarily adopted constant of proportionality. Thus the position of the ampere today is somewhat like that of the kilogram in the scheme proposed by the founders of the metric system.

We can measure all physical quantities directly in terms of the prototype standards, but following this procedure in all measurements is inconvenient, inaccurate, and imprecise. For this reason we construct standards for various derived physical quantities and assign values to them in terms of the corresponding unit as derived by experiment from defining equations involved and the units fixed by the prototype standards. It is clear that, however carefully we perform the experiments in deriving these standards, they can never have the exactness inherent in the prototype standards. How these errors enter our derived standards is discussed in detail by Silsbee[1] and Engen.[2]

Among the most accurate of the derived standards are those for some of the electric quantities. Because of this high accuracy and the convenience of making electric measurements, these standards are often used for measuring other quantities. We measure the heat of combustion of fuels, for example, by comparing the heat evolved when they are burned in a calorimeter with the known heat evolved by the passage of an electric current through a resistor. The results are given directly in joules, the internationally agreed-on unit for heat, but many chemists foolishly divide the results by 4.1840 to convert them to calories.

We can see how well our measuring system works in practice by examining how well various physical quantities can be measured in terms of the prototype standards. Several typical quantities are listed in Table II with estimates of the uncertainties involved in the best measurements of standards for these quantities at the National Bureau of Standards. The uncertainties are expressed in two ways, those of accuracy and those of precision. Under precision are placed the uncertainties in comparing two nominally identical standards for the quantity involved. Under accuracy are placed estimates of the uncertainties in relating the derived standards to the prototype standards. The uncertainties correspond approximately to "probable errors." No entries under accuracy are given for the meter, the kilogram, or the triple-point temperature of water since they are "accurate" by definition. The quantity, time, is not included in the table because it involves some considerations which will be treated at length later.

The table illustrates a number of interesting characteristics of our measuring system. The greatest precision is attained in measuring the quantities which have been selected as the basis of our system. In all cases illustrated except one, maximum precision is achieved when the magnitude of the quantity is the unit for the quantity. In all cases there is a decrease in accuracy for standards which embody a multiple or submultiple of the selected unit. Derived standards are subject to considerable inaccuracy, and this inaccuracy increases with the experimental complexity involved in relating them to the prototype standards. However, derived standards may be compared with similar ones with a precision far greater than the accuracy of the particular standard involved.

TABLE II
ESTIMATES OF ACCURACY AND PRECISION IN MEASURING PHYSICAL QUANTITIES

| Physical quantity | Device | Magnitude | Uncertainty in parts per Million | |
|---|---|---|---|---|
| | | | Accuracy | Precision |
| Length | Meter bar | 1 meter | — | 0.03 |
| | Gage block | 0.1 meter | 0.1 | 0.01 |
| | Geodetic tape | 50 meters | 0.3 | 0.10 |
| Mass | Cylinder | 1 kilogram | — | 0.005 |
| | Cylinder | 1 gram | 1 | .03 |
| | Cylinder | 20 kilogram | 0.5 | 0.1 |
| Temperature | Triple-point cell | 273.16°K | — | 0.3 |
| | Gas thermometer | 90.18°K | 100 | 20 |
| | Optical pyrometer | 3000°K | 1300 | 300 |
| Resistance | Resistor | 1 ohm | 5 | 0.1 |
| | Resistor | 1000 ohms | 7 | 1 |
| | Resistor | 0.001 ohm | 7 | 1 |
| Voltage | Standard cell | 1 volt | 7 | 0.1 |
| | Volt box-standard cell | 1000 volts | 25 | 10 |
| Power DC | Standard cell-resistor | 1 watt | 11 | 1.5 |
| 60 cycle | Wattmeter | 10–1000 watts | 100 | 50 |
| *X*-band | Microcalorimeter | 0.01 watt | 1000 | 100 |

The maintenance and establishment of standards for all kinds of physical measurements is the basic responsibility of National Bureau of Standards. Fulfillment of this task requires development of precise measurement techniques and prosecution of basic research in most fields of the physical sciences. For a standards program is not a static program. Growing technology requires more and more standards, extension of the range of existing standards, and improvement in accuracy. For example, the rather poor accuracy associated with measurement of microwave power is not due to difficulties in the experiment alone, but partly to the fact that accurate measurement of microwave power is a recent requirement of our technology. It is interesting to note that the old "International" Ohm as embodied in the standard specified for it by the International Conference on Electrical Units and Standards in 1908, and used until 1948, differed from its theoretical value by about 500 parts in 1,000,000.

[2] G. F. Engen, "A refined X-band microwave microcalorimeter," to be published.

## Physical Constants as Standards

The desire of metrologists to have their units of measurement embodied in indestructible, immutable standards was evidenced by the founders of the metric system. There are good practical reasons for this desire apart from its aesthetic appeal. If realized, we would be assured that measurements made at one time would be strictly comparable with those made at another, unless the substances and the laws of physics are themselves changing with time. But most important is the circumstance that each adequately equipped laboratory could have its own set of standards known to be identical with those of a similar laboratory without the need for regular intercomparisons.

We have seen how, in the early days of the metric system, it was necessary to abandon this desire in order to achieve the greatest precision in measurements. To what extent are we now able to substitute physical constants for the artificial standards of our measuring system without impairing accuracy? We should like, of course, to adopt physical constants of the most basic nature to set the scale of our measuring system, such as $G$, $h$, $c$, and $k$, but, as we saw, precise measurements cannot be made in terms of them. Improvement can be obtained by abandoning $G$ and using another constant instead of it, but the improvement is not enough.

We can gain considerable improvement in precision, though with a sacrifice of elegance, by selecting less general physical constants as the standards for our measuring system. In fact, this already has been done for one physical quantity, temperature, since the number 273.16 is assigned to the triple-point temperature of water on the thermodynamic Kelvin scale. We can see what an advantage this is, because anyone versed in the art of temperature measurements can construct his own triple-point cell and establish the standard of temperature which can be realized with a precision of two or three ten-thousandths of a degree. Furthermore, this standard can be re-produced at any time in the future with complete confidence that the standard will be the same. (The definition is still deficient in that the isotopic composition of the water is not specified, but this fault will probably be corrected in the near future.) Pleasing to think about, although of no immediate advantage, is that a man on Mars, or even in some other solar system or galaxy, could establish the same standard for temperature measurement as we use on the earth.

If establishment of a standard for the temperature scale were all there were to temperature measurements, our task would be simple and dull. We must make temperature measurements over a wide range, and we must be able to express our measurements over this range with as great an accuracy as possible in terms of our standard. This led to extensive research in the Bureau on phenomena involving temperature and the atomic constants which are needed for measurement of temperatures by Planck's radiation law. Outgrowth of this work involved some of the pioneer precise measurements of the energy levels of excited atoms in the days when Bohr's theory was still an hypothesis.[3]

By taking a physical constant to define our temperature scale we have gained a great deal and lost nothing in precision of temperature measurements. There does not appear to be any better way to establish a standard for temperature. This is not true for all the other prototype standards.

Can we replace the standard for length by a natural standard, say, the wavelength of some chosen spectral line? Babinet proposed this in 1827, but 65 years passed before the first measurements were made to reduce this to practice by Michelson and Benoît in 1892–93. However, the use of a wavelength for a standard of length instead of the meter bar is not without fault.

By precise spectroscopy we can compare wavelengths of two highly monochromatic spectral lines with a *precision* of a few parts in $10^9$. Thus, if a suitable spectral line is accepted as a standard of length, this would also be the approximate *accuracy* with which good spectral lines can be measured. But the task of measuring a material standard in terms of a wavelength standard is more difficult. Since the pioneer measurements of Michelson and Benoît, eight determinations of the relationship between the wavelength of the red line of cadmium and the length of the meter have been performed. From concurrence of the results, the probable error of the precision of a single determination is calculated to be 1 part in $10^7$. This is somewhat inferior to the precision with which two meter bars can be compared. Also the wavelength measurements may be subject to systematic errors affecting all determinations alike. The Bureau has graduated a meter bar directly using the accepted value for the wavelength of the cadmium line as a standard. Subsequent comparison of this meter bar with others indicates a discrepancy in the graduation consistent with the above results.

The cadmium red line originally used by Michelson is not the best line for precision spectroscopy. To obtain a better line, Meggers, Chief of the Bureau's Spectrographic Section, developed a new lamp.[4] Earlier, Michelson had suggested the use of the mercury green line as a wavelength standard, but this was found to have too much fine structure because mercury in nature consists of seven isotopes, two of which have nonzero spin. To cure this fault Meggers used mercury 198, which has zero spin. This was produced in pure form by bombarding gold, which has only one staple isotope, 197, with neutrons. This lamp gives much clearer interference patterns, but, to excite the radiation, it is necessary to have some argon in the lamp. The wavelength of the mercury radiation depends on the argon pressure, so that leakage of argon will affect the standard.

[3] P. D. Foote and F. R. Mohler, "Determination of Planck's constant $h$ by electronic atomic impact in metallic vapors," *J. Opt. Soc. Am.*, vol. 2–3, pp. 96–99; 1919.

[4] W. F. Meggers, "A light wave of artificial mercury as the ultimate standard of length," *J. Opt. Soc. Am.*, vol. 38, pp. 7–14; 1948.

Since wavelengths emitted depend on conditions of excitation, experiments have been conducted with lamps containing krypton 86 held at constant pressure by immersion in liquid nitrogen at its triple point. Various national laboratories have found this wavelength standard so satisfactory that the International Committee on Weights and Measures in October last year recommended that the General Conference, which meets in 1960, redefine the meter in terms of wavelength of a specified krypton line, and suggested a number for this equivalence based on the measurements of the cadmium wavelengths and comparisons of the wavelengths of the cadmium and krypton lines.

The effect of this redefinition, if it is adopted by the General Conference, will not be marked. The meter has never been related directly to the chosen krypton line, but the interrelations are sufficiently well known that any differences will probably be within the uncertainties of measurement now existing. It will have the effect of embodying the unit of length in what we believe to be an immutable standard and thus fulfilling an old aspiration. Meter bars, gage blocks, etc., will continue to be used as standards for the kinds of measurements for which they are suited. Every once in a while the length of meter bars will be redetermined in terms of the wavelength of light, instead of determining the wavelength of light in terms of the international meter bar.

The possibility of embodying our unit for time in a physical constant is even more attractive. We can measure time, and its reciprocal, frequency, with the greatest precision of any physical quantity. For example, we may compare the ratio of the average frequencies of two oscillators over concurrent time intervals with as great a precision as we choose. The limit is set by how long the oscillators will operate and how many cycles we wish to count, but such comparisons are pointless if the frequencies of the oscillators are not relatively stable over the interval involved. Conversely, we may measure time with equal precision by counting cycles of a particular oscillator, assuming its frequency is constant.

There is a serious problem in measuring time accurately. We can lay two meter bars side-by-side and compare their lengths. If, by subsequent comparisons, we find that their lengths have not changed relatively we have confidence that our length standards have not changed. But there is no way to lay two time intervals side-by-side; we must rely on the stability of an oscillator to compare time intervals. Man-made oscillators show drifts in frequency with respect to each other, and since oscillators are not passive things like meter bars and kilogram weights, we expect them to drift.

To obtain a good standard for time and frequency we adopted first an astronomical constant, the rotational frequency of the earth which had been regarded as constant since the days of Joshua. Man-made oscillators were used to interpolate for shorter intervals of time and the second was defined as 1/86400 of a mean solar day. Since the apparent solar day varies throughout the year due to eccentricity of the earth's orbit, astronomers kept track of time by observing star transits, in relation to which earth's rotation is much more uniform.

Precise astronomical observations revealed that this standard was not good enough. The frequency of rotation of the earth is changing with respect to the revolutions of the moon about the earth and the earth about the sun, when allowance is made for perturbations of the revolution time. All planetary motions are in substantial accord. In addition to a gradual slowing down, which is to be expected from tidal friction, there are erratic fluctuations in rotational speed. For this reason astronomers carry out their more precise calculations in ephemeris time, which is based on planetary motions.

With the improvement of quartz-crystal oscillators, seasonal fluctuations in the earth's rotation with respect to the stars have appeared. Though the oscillator frequencies drift, they drift monotonically, allowing us to measure these seasonal fluctuations which amount to 1 part in $10^8$. Correcting for this seasonal fluctuation, astronomers[5] have established a more uniform time scale, called UT2, good to 1 part in $10^9$, tied in with the earth's rotation, and hence subject to effects of long term changes.

So we see that even the smoothed rotation frequency of the earth is not good enough for a standard. Accordingly the second was redefined in 1956 by the International Committee on Weights and Measures as 1/31556925.9747 of the tropical year 1900 at 12 hours ephemeris time. Why this strange definition? Why not take the sidereal year or the anomalistic year? The lengths of all these years change in known, highly regular ways, so that specification of any epoch was necessary. We chose the tropical year, which is the time between two successive passages of the center of the sun across the celestial equator in the same sense, because accurate tables were already available for its variation, based on the epoch 1900.

The need for a better standard of time became urgent during the past decade with the improvement in microwave techniques. Microwave terms in the spectra of molecules and atoms were being measured with increased precision. The Bureau began to explore these phenomena as the basis for constructing more stable oscillators.[6] Before 1952 Lyons and his co-workers at the Bureau[7] had measured the microwave resonance in the ground state of the cesium atom with a precision of 1 part in $10^7$. Essen and his co-workers[8] at the National Physical Laboratory a few years later increased this precision to a few parts in $10^{10}$. It is likely that greater

[5] U. S. Naval Observatory, "The Naval Observatory Time Service," Circular No. 49; 1954.

[6] B. F. Husten and H. Lyons, "Microwave frequency measurements and standards," *Trans. AIEE*, vol. 67, pp. 321–328; 1948.

[7] J. E. Sherwood, H. Lyons, R. H. McCracken, and P. Kusch, "High frequency lines in the hfs spectrum of cesium," *Phys. Rev.*, vol. 86, p. 618; 1952.

[8] L. Essen and J. V. L. Parry, "The caesium resonator as a standard of frequency and time," *Phil. Trans. R. Soc., London*, vol. 250, pp. 45–69; 1957.

precision can be attained in measuring the cesium frequency and also other atomic frequencies such as those of rubidium, as was indicated by recent work of Bender and Beaty of the Bureau and Chi of the Naval Research Laboratory.[9] Since the frequencies of these resonances depend on energy levels of the atoms involved, and since, in the case of the cesium, independent experiments have agreed to within the limits of precision, we may presume that they can serve well as standards for time and frequency.

How can we relate these resonance frequencies to the defined unit of time, the ephemeris second? Since the second is defined by an event which occurred over 50 years ago we must measure the resonance frequencies in terms of current values of the UT2 second, and then, through observations on the moon, relate the UT2 second to the ephemeris second. This was done[10] recently, based on four years of observation of the moon, showing that the ephemeris second corresponds to $9{,}192{,}632{,}770 \pm 20$ cycles of the cesium frequency. This is much less precise than the defined value of the second or the precision with which the cesium resonance can be observed.

We have no hope of relating the atomic resonances to the ephemeris second with much greater precision in the near future. We thus are faced with the fact that atomic constants are much better standards for time and frequency than astronomical constants. Furthermore, as standards they are much more accessible than the astronomical constants which require long years of observation to compare them precisely with other quantities. Clearly, we are able today to improve our standard for time by selecting one of the atomic resonances and defining the second in terms of it, making the definition such that the new definition will agree as closely as feasible with the present one.

The frequencies broadcast by the Bureau's stations WWV and WWVH are now monitored and kept as constant as possible by reference to the cesium resonance. The intervals between the seconds pulses are maintained in the same way. Therefore the seconds pulses gradually get out of step with mean solar time. When the difference becomes great enough the pulses are shifted by exactly 20 milliseconds to bring them back in. Thus we are already using two kinds of time, atomic time—that's for the scientists—and mean solar time—that's for the birds and other diurnal creatures.

These attempts to improve time and frequency measurement may seem a quest for precision for precision's own sake, a futile pushing of the decimal point. But this is not correct. It is an attempt to establish standards so that we may learn what physics lies beyond the decimal point. For such things have Nobel Prizes been awarded.

[9] P. L. Bender, E. C. Beaty, and A. R. Chi, "Optical detection of narrow $Rb^{87}$ hyperfine absorption lines," *Phys. Rev.* (*letter*), vol. 1, pp. 311–313; 1958.

[10] W. Markowitz, R. G. Hall, L. Essen, and J. V. L. Parry, "Frequency of cesium in terms of ephemeris time," *Phys. Rev.* (*letter*), vol. 1, pp. 105–107; 1958.

We have already learned that the earth turns irregularly on its axis. Now we ask, do time scales based on astronomic, atomic, and molecular processes change with respect to each other as some think they might? (The ammonia maser depends on molecular processes for its frequency stability.) Perhaps from these newly achieved precisions and those soon to be achieved we may even be able to resolve experimentally the famous clock paradox of relativity!

We see that, of the four prototype standards, one is already embodied in a physical constant. Another seems about to be, and a third one is ready to be. What about the standard of mass? We can see no way of embodying that in a physical constant at present without detracting from the accuracy of our system. We seem to be "struck" with the platinum-iridium kilogram. And is that bad?

Table II showed that the kilogram is the most precisely measurable of our prototype standards, that uncertainty in comparing it with other masses is about as small as the uncertainty in comparing the cesium second with the ephemeris second. What could cause the kilogram to change? Any damage to it which would remove 1 in $10^9$ of its mass by a scratch or nick would be perceived readily by the naked eye. The oxidation of platinum at normal temperatures is so slow it has never been measured and no sign of an oxide coating on the metal has ever been noticed. We know of one calculable change which will take place in it. One of the isotopes of platinum, Pt 190, is radioactive. It undergoes $\alpha$-decay with a half-life of about $10^{12}$ years. Since the abundance of this isotope is only 0.012 per cent it will take about $10^8$ years for it to produce a change as great as the imprecision of measurement. We do know that the Arago kilogram, produced during the first half of the last century, has exhibited a loss of mass of the order of a few milligrams. This kilogram was forged from sponge platinum and must have had inclusions of gas which escaped. The kilograms of today are of fused metal and free from changes of this nature. There appears to be no good practical reason for replacing the kilogram with a physical constant.

Physical constants are extensively used for derived standards and for standards embodying magnitudes differing greatly from the defined unit. The International Temperature Scale, which is an approximation to the Thermodynamic Scale, is based on the equilibrium temperatures of various substances. Higher temperatures are measured in terms of the constants in Planck's radiation law. The speed of light is employed in the measurement of large distances in optical and radio surveying. The gyromagnetic precession frequency of the proton,[1] which has been measured with great accuracy at the Bureau, affords a means of comparing two different magnetic fields with high precision. Many other physical constants, too numerous to mention, find employment in extending the range of physical measurement. The determination of the values of these many constants with the greatest possible accuracy in terms of our prototype standards is one of the main tasks of the Bureau.

## Conclusion

Our measuring system has developed over the years in such a way as to provide the maximum of precision and accuracy in measuring the many quantities of physics. The standards chosen from time to time to preserve the magnitudes of the units were sufficiently measurable and durable to meet the needs of their days. As scientific advancement required better standards, the persons responsible for preservation of the system have been ready to adopt new standards for the old ones. Thus we see a transition taking place now from a system based on man-made standards to a system based mainly on physical constants, as far as this is possible.

The prototype standards seem to need little improvement. The advances which we must make in our metrology are in extension of the range over which accurate measurements can be accomplished. Particularly, we need to develop techniques to measure accurately new quantities and new aspects of old quantities to meet the requirements of our expanding technology.

# The Ampere*

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*Summary*—**The purpose of this paper is to supplement the preceding paper[1] by describing in some detail the various measuring procedures and supporting research which must be carried on by a national standardizing laboratory to meet its responsibilities related to a single one of the many units of measurement on which modern science, engineering and industry are based. The example chosen is the ampere, the unit of electric current in the MKSA system. The tasks involved naturally fall into five successive stages, namely; the definition, establishment, maintenance, extension and dissemination of the unit.[2,3]**

## Definition of the Ampere

ALMOST a century ago, a committee of the British Association for the Advancement of Science, under the chairmanship of Clerk Maxwell and guided by the ideas of Weber and Gauss, defined an electrostatic and an electromagnetic system of electric and magnetic units based upon the centimeter, the gram, and the second, as the fundamental mechanical units. For the electromagnetic system, the further assumption was made that the permeability of empty space was to be regarded as a dimensionless quantity numerically equal to unity. (In the electrostatic system, the permittivity of empty space was regarded as a dimensionless quantity numerically equal to unity.) The resulting electromagnetic units of voltage and resistance were found to be inconvenient in magnitude; and in the 1890's, units larger by factors of $10^8$ and $10^9$ and named the volt and the ohm, respectively, came into use as the basis for the so-called "practical" electrical units. To retain the coefficient in Ohm's Law at the convenient value of unity required that the practical unit of current, the ampere, should be 1/10 of the cgs electromagnetic unit.

At that time it was considered important that the electrical units be so defined that they could be reproduced in any laboratory with a minimum of inconvenience. In the case of electric current, there was wide use of the coulometer, in which the amount of metal deposited from an electrolytic solution in a measured time is taken as the measure of the average current. In 1908, an international electrical congress was held in London, at which the "International Ampere" was defined as the unvarying current which would deposit silver at the rate of 0.00111800 gram per second from an aqueous solution of silver nitrate.

With the establishment of national standardizing laboratories in the industrial nations, the need for ready reproducibility of the ampere became much less important. The succession of studies at the National Bureau of Standards of the silver coulometer and of the iodine coulometer, which had been suggested as an alternative basis for the definition of the ampere, had shown disconcerting discrepancies and sources of error: there were, in particular, errors from the inclusion of solution in cavities in the deposited silver, the presence of complex ions, and later the recognition of the isotopic complexity of silver. Other studies at the national laboratories showed that methods of measuring the ampere in terms of length, mass, and time, while still difficult

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[1] A. G. McNish, "The basis of our measuring system," Proc. IRE, this issue, p. 636.

[2] F. B. Silsbee, "Establishment and Maintenance of the Electrical Units," NBS Circular 475; June, 1949.

[3] F. B. Silsbee, "Extension and Dissemination of the Electrical and Magnetic Units by the National Bureau of Standards," NBS Circular 531; July, 1952.