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Status of the National Standards for Physical Measurement

Progress in science and technology requires a highly developed measurement system of national scope.

R. D. Huntoon

The Institute for Basic Standards (IBS), one of four institutes which comprise the National Bureau of Standards, has the responsibility within the federal government of providing "the central national basis for a complete, consistent system of physical measurement properly coordinated with those of other nations."

Implicit in the assignment of this responsibility is recognition that there exists in fact a national system of measurement and that this system is a centralized one, with a central laboratory which develops and maintains the national standards (*1*) for physical measurement and provides the starting point for a chain of measurement leading from these standards to the ultimate users of the system. This chain must provide for measurements of all necessary magnitudes, from the properties of atoms to those of the universe.

From the point of view of the ultimate user who faces a measurement problem, such as finding the diameter of a ball bearing or the melting point of a metal, the measurement chain can operate in two different ways. (i) It can provide the user with a calibrated instrument, traceable back to the national standards, with which he can measure the diameter or the melting temperature. (ii) In the case of the melting temperature or other, similar properties, it can provide him with an immediately available answer in the form of critically evaluated data which previous investigators have obtained in measurements based on the national standards, so that he does not need to make the measurement himself.

As the nation's central measurement laboratory, the National Bureau of Standards exercises leadership in both these measurement areas. In the Bureau's laboratories the acquisition of standard reference data by precise measurement goes on side by side with research to develop and improve the national standards and associated measurement methods.

The strength and utility of the measurement system depend fundamentally upon the existence of a complete, consistent system of units and standards around which the system can develop. In IBS we are concerned with the establishment of these units by international agreement, the realization of the standards which represent them, and the development of a chain of measurement from these standards to the multiples and submultiples needed by our technologically based society. These activities, we find, offer an exciting field of technical endeavor which reaches to the frontiers of science and technology. Indeed, the state of sophistication of our measurement system is an important gage of the scope and utility of our science and technology. Let us look more closely at this system and at the units upon which it is based.

Our national measurement system is part of an international system used by all leading nations of the world, and is the result of a worldwide progression toward increasing sophistication of measurement, both in concepts and in application. This international system has its basis in the metric system of weights and measures, originally devised by a committee of the French Academy in 1791. An Act of Congress in 1866 made the metric system legal, though not mandatory, in the United States. In 1875 the United States joined with 16 other principal nations of the world in signing the Treaty of the Meter. This treaty provided for the establishment of an International Bureau of Weights and Measures to be situated near Paris, and an International Conference of Weights and

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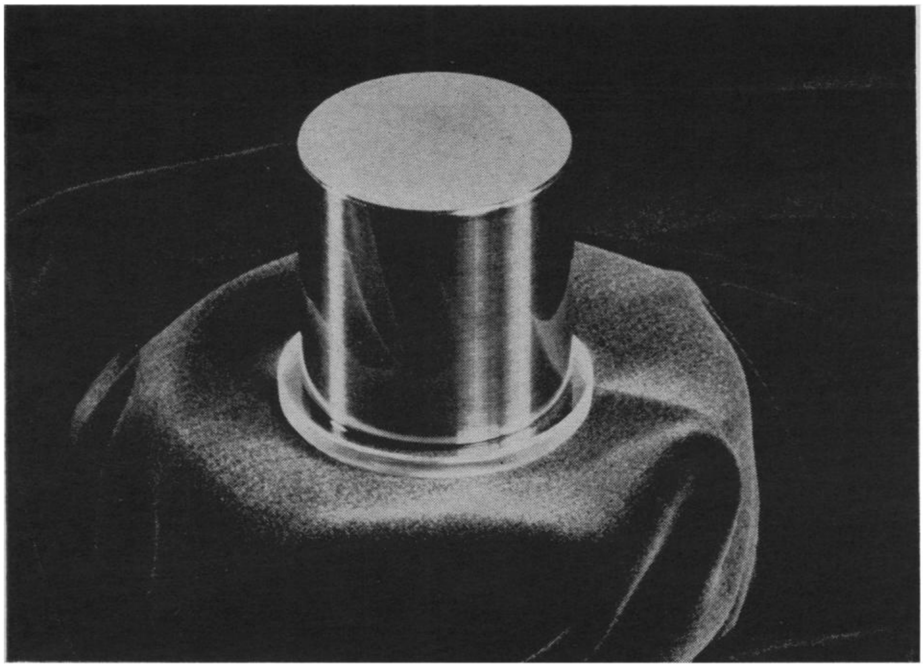

Fig. 1. The national standard of mass, known as Prototype Kilogram No. 20—a platinum-iridium cylinder 39 millimeters in diameter and 39 millimeters high. It is an accurate copy of the international standard kept at the International Bureau of Weights and Measures at Sèvres, France.

Measures to meet at stated intervals and to consist of official delegates designated by the signatory powers. In 1960 this Conference adopted an International System of Units (abbreviated SI for Système International (*2*). The SI is a metric system based on six fundamental physical quantities in terms of which all others are to be defined so as to be consistent with the generally accepted equations of physics. These quantities and their units are mass (kilogram), length (meter), time (second), temperature (degree Kelvin), current (ampere), and luminous intensity (candela).

The new International System supplants the older centimeter-gram-second system. Within the United States, by virtue of our adherence to the Treaty of the Meter, the basic SI units and the units derived from them now form a legal, though not mandatory (except for the units for current and luminous intensity), basis of measure. Our U.S. "customary system" of units is defined in terms of the SI units by simple numerical ratios, such as "1 inch equals 2.54 centimeters." The customary system, although based on the metric system and widely used throughout the United States in industry and commerce, is not a consistent system and is thus little used for scientific measurements. Most of the world has now gone directly to the metric system, rather than a system derived from it, and if we are to maintain our place in world markets, we may ultimately be forced to adopt the metric system for commerce and industry as well as for science—and very likely within the next two decades. A proper understanding of the importance of the International System and its potentialities for the future requires a brief examination of the way in which such systems develop.

Evolution of a Measurement System

A measurement system begins with recognition of the existence of a set of physical quantities which can be defined and given names. For like quantities, a scale of "greater than" or "less than" can be established, and comparisons can be made. The next step is to select a convenient well-defined sample of each quantity, to be used as a unit of measure for that quantity. Then we can compare the values of other samples with the reference sample (the standard) to find how many of the reference sample it takes to equal the unknown sample. This determination of "how many" is the process of measurement.

This elementary stage of measurement sophistication is called a "unit-standard" system, since the unit for any particular quantity is defined in terms of a preexisting standard, which then provides a unique realization of the unit. In principle, we could develop a complete measurement system of the unit-standard type, in which there are a unit and a standard for each different physical quantity. In some cases the standard might be a physical object (such as a yardstick); in others, a physical process (such as we observe in an ammeter or clock). Such were the beginnings of our measurement system, and the new International System retains vestiges of this beginning.

With the development of greater measurement sophistication, certain general principles have evolved which now guide the development of any measurement system. The important ones are as follows:

1) There should be only one unit for each physical quantity. This avoids confusion and ambiguity in dealing with such quantities as energy, which can exist in several forms—electrical energy, kinetic energy, thermal energy, and so on.

2) All users should use the same unit for the same quantity. Data can then be used directly, without translation from one measurement language to another.

3) The unit selected should be of a size to admit of the most precise comparisons possible at the time. History shows that the unit which provides the greatest precision wins greatest acceptance.

4) When older units are replaced by improved ones the new units should be defined within the zone of confusion of the old. That is, any change in the size of the unit should be less than the uncertainty in measurements with respect to the old one. This insures that all values obtained by previous measurements will remain valid.

5) The standard should be invariant in time. Otherwise measurements of the same thing would not always give the same value.

Although these general principles have never been officially adopted, they have grown up through tradition and have exerted a powerful influence on the development of the present measurement system.

In ancient times the development of our measurement system reached a second stage of sophistication—that of a conceptually defined unit, independently reproducible without access to an original sample, but tied to some body or phenomenon of nature. Thus, loss of the standard would not mean loss of the basis for the system, as it would in the unit-standard system. The definition of a unit of time as a fraction of a solar day is an example of an independently reproducible conceptual unit that has survived until recent times, when the need for greater accuracy brought about a new definition.

An important characteristic of a measurement system based on either the unit-standard or the conceptual definition of units is that for each unit the basis for definition and realization is arbitrary—the unit is chosen without regard for the other units. Complete systems could, in principle, be constructed on either the unit-standard or the conceptual basis; however, in recent times the confusing deficiencies of such arbitrary systems became apparent as Western society began to undertake the serious study of science.

When such an arbitrary measurement system was used, it was found, the equations of physics which expressed relations between the various physical quantities involved proportionality constants. Each of these constants required determination by experiment. However, it was soon recognized that the values of the constants depended upon the units of measurement and that an appropriate choice of unit sizes could reduce the proportionality constants to unity in most cases. The units so selected would no longer be arbitrary; they would be consistent—that is, of a size consistent with the set of equations of physics used to define them. For each physical quantity there would be one degree of freedom in the system. Thus, each time a constant of proportionality was adjusted to have a certain assigned value, one degree of freedom would be used up and the size of one of the units would have to be correspondingly adjusted.

Conceivably we could have carried this process to its ultimate conclusion, assigning values not only to dimensional constants but to natural physical constants such as the speed of light, until all the units had been uniquely determined. We have not gone this far, however, because as yet we cannot measure the physical constants with the precision we can attain when we refer our standards back to their conceptual units. Such a procedure does not remove the measurement problem, it merely makes the problem one of determining the unit sizes that make the constants unity (or some other convenient number). It makes the measurement system much simpler to work with and to understand, but at the same time it complicates the problem of arriving at standards for the units themselves.

The International System of Units is a consistent system in which the "basic units" for length, mass, time, and temperature (the meter, kilogram, second, and degree Kelvin) are established independently on an arbitrary basis and the units for all other physical quantities are defined in terms of these basic units in accordance with the equations of physics. As an aid to dimensional analysis, the ampere has also been given the status of a basic unit in the International System, although it is defined in terms of length, mass, time, and a particular value of the magnetic constant which is taken as $4\pi \times 10^{-7}$ (*3*). The sixth basic unit, the candela (*4*), which is used for measurements of visual light, is in a class by itself; it is not purely physical nor uniquely defined, as it involves an assumed average human observer (*5*).

As time goes on we may expect a decrease in the number of independent, arbitrarily defined units. Of the four independent units that now remain in the International System, three —the meter, second, and degree Kelvin—have been defined on an independently reproducible basis. Thus, the meter is defined in terms of the wavelength of the red radiation from krypton-86; the second is defined in terms of a particular average of annual trips of the earth around the sun (tropical year 1900), and provisionally in terms of an invariant transition of the cesium-133 atom; and the degree Kelvin is defined in terms of the triple point of pure water. Each of these three basic units is tied to some constant of nature which, as far as we know, is invariant in time (principle No. 5). In principle, any nation can reproduce the standards for these quantities in its own laboratories.

Mass remains the only unit-standard quantity in our system. Its unit, the kilogram, is defined as the mass of Prototype Kilogram No. 1 at the International Bureau of Weights and Measures at Sèvres, France (see Fig. 1).

To a great extent, the strength of our entire measurement system depends on the status of the six base units, particularly the four—meter, kilogram, second, and degree Kelvin —that are arbitrarily defined. Thus, an examination of the present status of these four units may provide considerable insight into the nature of the system and the present trends in its development.

The Meter

When the metric system was first established, the meter was conceptually defined as one ten-millionth of the north polar quadrant of the earth on the meridian through Paris. The meter so defined was independently reproducible, but metrologists soon found that they could not realize this definition in the form of a meter bar with sufficient accuracy. So the meter was redefined in terms of a platinum-iridium meter bar then located in the Archives of Paris. The meter thus reverted to the simpler unit-standard stage, and it remained in that stage for many years.

Finally, on 14 October 1960, by action of the 11th General Conference of Weights and Measures, the meter was redefined in such a way as to be independently reproducible (*2*). According to the 1960 definition, the international standard meter is now equal to 1,650,763.73 wavelengths, in vacuum, of the red radiation from krypton-86 (Fig. 2) corresponding to the unperturbed transition between the energy levels $2p_{10}$ and $5d_5$. Spectral lines of this type can be intercompared with an overall limit of uncertainty of about 2 parts in 10^9 (equivalent to 1 cm relative to the distance across the United States), but the translation of these measurements to material standards such as the meter cannot be accomplished so precisely, today's limit being somewhat better than 1 part in 10^7.

For spectral measurements the new unit is already becoming obsolescent. New wavelength sources of greater purity have been developed by means of an atomic beam method, and lasers now show coherence properties indicating wavelength purity approaching 1 part in 10^{12} or 10^{14}. Phase coherence over paths of more than 100 meters has already been demonstrated for laser beams in air (*6*), and it would be much better in a vacuum. An effort is being made to stabilize the radiations from lasers so as to make them consistently reproducible. Thus we may confidently expect that still another definition of the meter will be available in the near future which will push the precision forward by several orders of magnitude.

Today the limits upon our ability to measure length with the precision afforded by the new standard are proving to be the limiting factor in measurement of the velocity of light, a constant needed in the space program and in geodesic measurements. Thus it becomes possible to consider assigning a value to the velocity of light and thereby establishing a new unit of length consistent with it. Any such assignment, if made, should be such that the new unit lies within the zone of confusion of the old (principle No. 4).

The Kilogram

The founders of the metric system attempted to make the unit of mass dependent on the unit of length by defining the kilogram as the mass of a cubic decimeter of pure water at its temperature of maximum density. But, in the interest of accurate measurement, it was found necessary, at the time of the Treaty of the Meter, to give the kilogram its present unit-standard definition. So far it has not been possible to discover any physical basis for the definition of an independently reproducible unit of mass that would lead to greater precision than the present unit-standard definition provides. Thus, the problem of putting this standard on an independently reproducible basis remains a challenge to metrologists, though the need is not urgent at this time. The various standard kilograms in existence can be intercompared within a few parts in 10^9 (equivalent to the mass of ink in one punctuation period as compared to the mass of a whole book). However, as one moves from the 1-kilogram mass of the prototype standard, the precision of measurement becomes degraded by errors in the chain of measurement.

In some fields of science special units that are not consistent can be, and have been, devised which permit greater precision of measurement than can be achieved through the chain of measurements leading from the prototype standard itself. Such units are quite useful because they lead to a greater uniformity of measurement within a special field of science. The measurement of atomic masses is a notable example. For many years the chemists used an atomic mass scale in which the atomic weight of natural oxygen was arbitrarily set at 16. Then, when the physicists discovered isotopes they established a scale in which the isotope oxygen-16 was given the arbitrary value 16. Thus, for a time we had both a chemical and a physical atomic mass unit (in violation of principle No. 1), each arbitrarily set and independently reproducible, and each different from the metric unit, the kilogram. This led to confusion, as the units were almost the same.

After extensive work by Mattauch, Olander, Wichers, and others, it was agreed in 1960 (by the International Union of Pure and Applied Physics) and in 1961 (by the International Union of Pure and Applied Chemistry) that the dominant isotope of carbon—carbon-12—with the exact number 12 as its assigned atomic (nuclidic) mass, would be the defining standard for the scale of atomic weights (*7*). The change in the chemical scale was 43 parts per million; that in the physical scale, 318 parts per million. Thus, for the chemists, the change was small enough to lie within the errors of most of their extensive tables of chemical data. The physicists had to make significant changes, but the mass spectrometrists, who were most concerned, found the carbon-12 scale so convenient that they were willing to make the changes. The relation between the atomic mass unit and the kilogram is known to about 25 parts in a million but is seldom used. We may expect

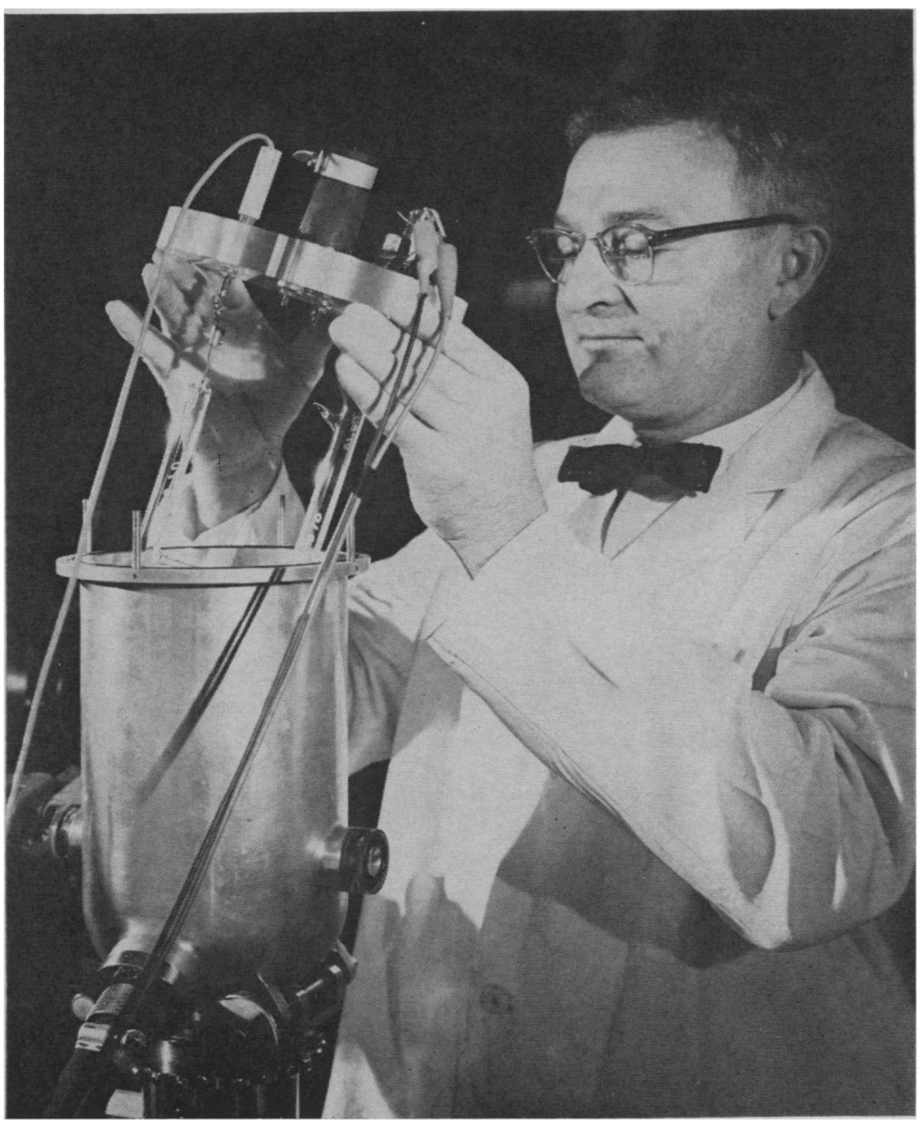

Fig. 2. A National Bureau of Standards scientist inserts a krypton-86 lamp into its liquid-nitrogen bath. The wavelength of the orange-red light emitted by the lamp has been adopted as the international standard of length. The lamp is operated at liquid-nitrogen temperatures to increase the stability of the standard wavelength.

the special atomic mass unit to be with us for some time, inasmuch as atomic mass measurements can be made relative to carbon-12 with a standard error of 1 part in 10 million.

Over the years, comparisons of the kilogram mass standards of the various nations have shown them to be surprisingly stable; unless all are drifting identically together, they are properly invariant. Drifts as large as 1 part in 10^6 would have been detected in the measurements of physical constants. Today the great need in mass measurement is not for a better basic standard but, rather, for better techniques of measuring both very large and very small masses.

The Second

The second is more difficult to define than the meter or the kilogram; one cannot keep a sample on the shelf as a standard, and so one resorts to operational definitions. Nonetheless, by use of frequency measurements, time interval can be measured more precisely (by three orders of magnitude) than any other physical quantity can be measured. Proper specification of time requires the definition of both an interval (second) and a starting point (epoch) for reference.

The second was, for centuries, defined arbitrarily in an independently reproducible way as 1/86,400 of a mean solar day. The second thus defined, known as the second of Universal Time (U.T.), could be realized in many ways—by astronomical measurements, mechanical clocks, molecular clocks, oscillating crystals, or atomic clocks. However, determination of time by direct observation of the daily rotation of the earth has been found to be inadequate for high-precision work because of small but perceptible changes in the earth's speed of rotation.

Various smoothed time scales have been used to remedy this difficulty. The latest of these, a smoothed version called UT2 and accurate to 1 part in 10^9, was used for a while, until the second was redefined, in 1956, by the International Committee on Weights and Measures as 1/31,556,925.9747 of the tropical year 1900 at 12 hours ephemeris time (a time scale based on planetary motions). This particular mode of definition was selected because accurate tables for predicting the variation in the length of the tropical year were already available, based upon the epoch (starting point) 1900. As the defined interval is thus tied to a specific period of time in the past, it cannot vary. Four years of observations of the moon, completed in 1958, were necessary to relate the second of UT2 then in use to this new second of ephemeris time, with an estimated standard error of 2 parts in 10^9. At the same time, the frequency of cesium-beam-controlled clocks was determined to be 9,192,631,770 ±20 hertz (cycles per second) in terms of the ephemeris second. That is to say, this frequency was also determined to about 2 parts in 10^9. But such clocks can today be compared with an accuracy of the order of 1 part in 10^{12} (equivalent to 1 second in 30,000 years or to the blink of an eye in all time since the dawn of history). So here again, as in the case of the meter, we have an instance in which a standard can be realized in a form admitting a precision of measurement higher than the precision with which it can be related to the defined unit.

Since there appears to be little hope that the relation of atomic-clock frequencies to the ephemeris second can be significantly improved in the near future, a new definition of the second on an atomic basis has been proposed. On 8 October 1964, the 12th General Conference of Weights and Measures authorized such an atomic definition (*9*). The International Committee on Weights and Measures, acting for the Conference, temporarily based the definition on an invariant transition of the cesium-133 atom, in expectation of a more exact definition in the future, assigning a value of 9,192,631,770 hertz to the cesium transition selected. Meanwhile, the various national laboratories are being encouraged by the Committee to continue their efforts to isolate the best possible atomic transition for use as a permanent standard. Until such a standard is adopted, both the ephemeris second and the atomic second will be used. This will not lead to confusion until the means for comparing the two are considerably improved, and even then the uncertainty should not exceed 2 parts in 10^9. Eventually, when a permanent atomic standard is adopted, a zero point or origin will be chosen for the resulting time scale, and time will subsequently be carried forward by an atomic clock.

Precision time measurement is moving forward at a rapid pace. Precision to increasingly high orders of magnitude may soon be attainable from optical pumping devices such as the rubidium vapor standard, or from the hydrogen maser. Meanwhile, the NBS standard broadcasts of frequencies and time intervals are controlled on an atomic basis (*10*).

Figure 3 shows how rapidly the ability to make precise time measurements has increased in the last decade. Extrapolation of the curve indicates that within the next few years we can expect to have clocks of such stability that they will keep time with an accuracy of 1 microsecond over the lifetime of an average scientist. Figure 4 shows present accuracies in measuring frequencies from 10^4 to 10^{11} hertz. For the microwave region, the curve at lower right shows accuracies now achieved in the calibration of cavity wavemeters by resonance frequency measurements.

The reader may well ask whether the accuracy of present time measurement has not already far outstripped the need. Actually the need for timing accuracy in such fields as satellite tracking, rocket control, and astronomical observations is far from met. We must remember that there are almost 100,000 seconds in one day, that light moves 300 meters in a microsecond, that we use light waves to measure distances, that satellites move at the rate of 9000 meters per second (32,400 kilometers per hour), that we need clocks which agree with each other to within 100 (some say 10) microseconds to make range and orbit measurements. All this means that clocks accurate to 1 part in 10^{11} (1 second in 3000 years) would have to be reset every 100 days to hold 100-microsecond accuracy, or every 10 days to hold 10-microsecond accuracy. To measure distances between aircraft with an accuracy of 30 meters by means of airborne clocks would require an accuracy of 1/10 microsecond in one day, or 1 part in 10^{12}. However, if clocks can be achieved that are accurate to 1 part in 10^{14}, they will keep in step to within 1 microsecond in 3 years. Thus the need for continual reference to a central master clock will disappear.

With the timing accuracies now available, clocks must be kept in agreement by radio broadcasts of standard frequencies. It takes several days

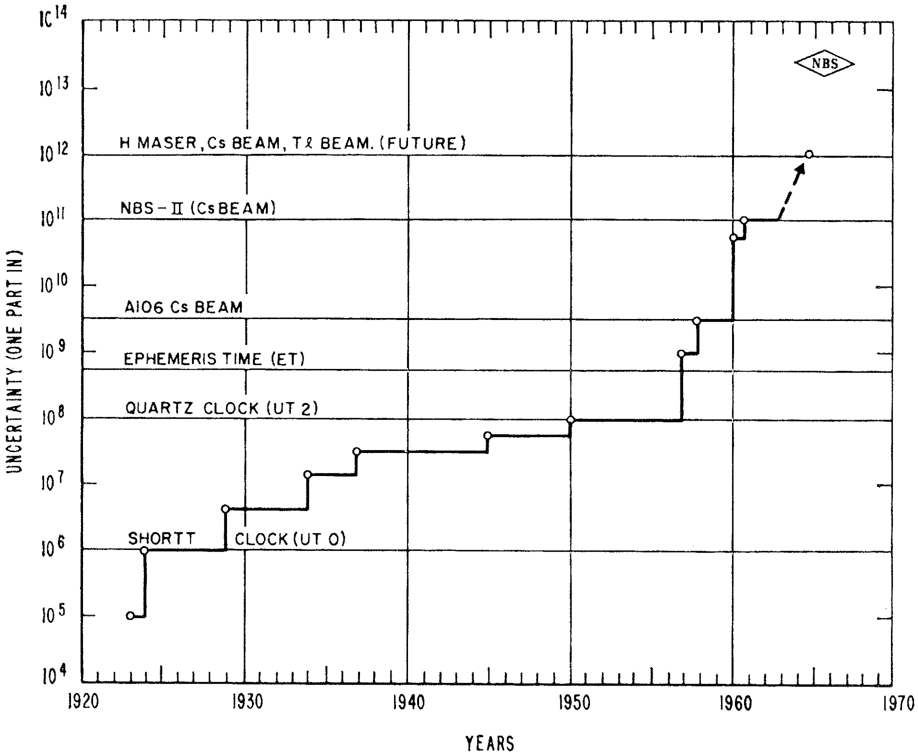

Fig. 3. Chart showing improvements in the accuracy of the U.S. frequency standard.

or weeks of comparison to smooth out the fluctuations caused by variations in the speed of propagation of the waves through the atmosphere. Reflecting the waves from a satellite cuts the atmospheric fluctuations by a considerable factor.

Also, the broadcasting of standard frequencies with high accuracies poses severe problems for the broadcasting station. A phase shift buildup of 7° per day, due to tuning variations in the antenna circuit, can cause an apparent frequency shift of 1 in 10^{11}. To prevent this, in standard-frequency broadcasts from NBS station WWVL the radiated signals are monitored at a distance and compared with the National Frequency Standard, and phase corrections are introduced at the transmitter to hold the phase at the receiver within 0.7° of the frequency standard. Widespread availability of cheap but accurate clocks could eliminate this expensive procedure. They could be set, perhaps annually, by comparison with a roving standard.

The Degree Kelvin

The earliest attempts to establish temperature scales demonstrated the desire to achieve an independently reproducible unit. Fahrenheit selected the temperature of the human body to be 100° and the lowest temperature obtainable with a salt-ice mixture to be 0°. The Centigrade scale (now called Celsius) was established by setting the boiling point of water, under standard conditions, to be 100° and the freezing point of water to be 0°. On each scale, interpolations were to be made by means of an expanding-liquid thermometer, and the degree was defined as the temperature difference which gave 1/100 of the linear expansion observed in the thermometer for the basic defining interval.

Later, studies of the properties of gases made with these scales showed that there was indeed a true zero of temperature, and Lord Kelvin showed that a fundamental or thermodynamic scale of temperature could be established. This, the Kelvin or absolute scale of temperature, was adopted as a basic definition, with the degree Kelvin set at 1/100 the interval between the boiling and the freezing points of water on this scale. Measurement showed that the absolute zero was close to −273.15°K. Also, it became clear that selection of only one fixed point would establish the thermodynamic scale. By action taken in 1954, the General Conference of Weights and Measures agreed upon the temperature of pure water at its triple point as the best natural value for the fixed point (see Fig. 5), and set the size of the degree by assigning the value 273.16°K, or 0.01°C, to this temperature. Thus, the unit of temperature was arbitrarily defined in an independently reproducible way.

But it turned out that the higher and lower temperatures could be compared more precisely than they could be related to the defining thermodynamic scale, so a compromise was made. An International Practical Temperature Scale (IPTS) was established by assigning temperatures, as closely as they

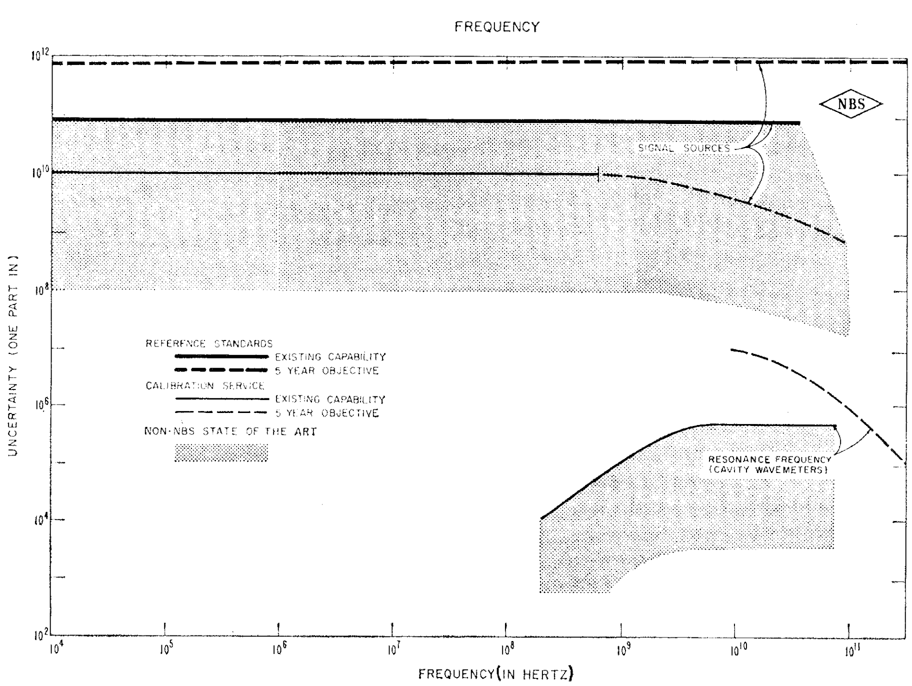

Fig. 4. Chart showing present accuracies in measuring frequencies.

were known with respect to the thermodynamic scale, to a number of natural fixed points under standard conditions: boiling point of oxygen, −182.97°C; triple point of water, +0.01°; boiling point of water, +100.0°; boiling point of sulfur, +444.6°; freezing point of silver, +960.8°; freezing point of gold, +1063.0°. Modes of interpolation to give temperatures between these fixed points were specified in terms of platinum resistance thermometers and thermocouples (*11*). Above 1063°C, temperature values on the IPTS are obtained from optical pyrometer readings. The International Practical Scale is used for all temperature measurement, although its relation to the true thermodynamic scale is not precisely known. The two scales agree exactly at one point, the triple point of water. Readjustment of the fixed points is made from time to time as the values with respect to the thermodynamic scale become better known. Refinement of the scale is a continuing process at all the national standardizing laboratories and in other laboratories having a strong interest in temperature measurement.

In 1948 the General Conference of Weights and Measures agreed to designate the name of the scale on which the triple point has a value of 0.01 as Celsius, the name of the scientist who first proposed it, thus avoiding the implication, inherent in the term *centigrade*, of 100 degrees as the basic interval. Actually, on the Celsius scale the temperature difference between boiling and freezing water may no longer be precisely 100 degrees.

There are thus four temperature scales:

1) Thermodynamic Kelvin (triple point of water = 273.16°K).

2) Thermodynamic Celsius (triple point of water = 0.01°C); T (deg C) = T (deg K) − 273.15.

3) International Practical Celsius, as defined by the fixed points listed above.

4) International Practical Kelvin; T (deg K) = T (deg C) + 273.15.

The size of the degree of temperature is presumably invariant throughout the thermodynamic scale. The size of the degree in the International Practical Scale is not in principle constant throughout the scale, and the relation between a degree on the thermodynamic scale and a degree on the practical scale is slightly different in different parts of the scale.

Accurate measurement of temperatures below 20°K is becoming increasingly important to the aerospace and other industries. However, extension of the temperature scales into this region has been a troublesome problem. At present the lowest temperature defined by the International Practical Scale is 90.18°K (−182.97°C). For use over the range from 90.18°K down to 12°K, until such time as international agreement may be reached on a generally accepted scale, the National Bureau of Standards has established the NBS Provisional Scale of 1955. This scale is defined in terms of the resistance-temperature relationship for a group of resistance thermometers, as determined with respect to the thermodynamic scale by use of a gas thermometer. In the extreme low-temperature range from 2° to 5°K, a third scale, known as the Helium-4 Vapor Pressure Scale (*12*), is used. Within the past year, IBS has bridged the gap between 5° and 12°K by the establishment of a scale based upon the newly developed acoustical thermometer (*13*; also see p. 155, this issue), and has initiated a calibration service from 2° to 20°K based on this thermometer.

For use at high temperatures, a photoelectric pyrometer has been developed which will improve the precision with which IBS can realize the International Practical Scale above 1063°C (the gold point) (*14*). This development, coupled with careful attention to other sources of error, has so enhanced our capability that we shall soon be able to measure temperatures with uncertainties (with respect to the International Scale) of 0.1° at 1063°C, 0.5° at 2000°C, and 3.0° at 4000°C.

Table 1. Units of the International System.

Quantity	Unit
Elemental units	
Length	meter
Mass	kilogram
Time	second
Electric current	ampere
Temperature	degree Kelvin
Luminous intensity	candela
Supplementary units	
Plane angle	radian
Solid angle	steradian
Derived units	
Area	square meter
Volume	cubic meter
Frequency	hertz
Density	kilogram per cubic meter
Velocity	meter per second
Angular velocity	radian per second
Acceleration	meter per second squared
Angular acceleration	radian per second squared
Force	newton
Pressure	newton per square meter
Kinematic viscosity	square meter per second
Dynamic viscosity	newton-second per square meter
Work, energy, quantity of heat	joule
Power	watt
Electric charge	coulomb
Voltage, potential difference, electromotive force	volt
Electric field strength	volt per meter
Electric resistance	ohm
Electric capacitance	farad
Magnetic flux	weber
Inductance	henry
Magnetic flux density	tesla
Magnetic field strength	ampere per meter
Magnetomotive force	ampere
Luminous flux	lumen
Luminance	candela per square meter
Illumination	lux

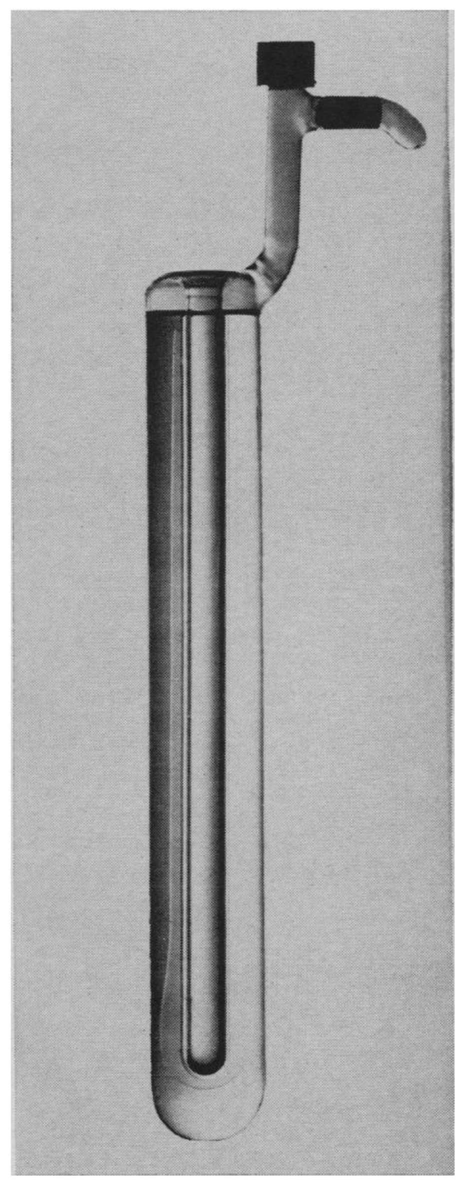

Fig. 5. Typical triple point cell used by the National Bureau of Standards to achieve a fixed point (0.01°C) on the International Practical Temperature Scale.

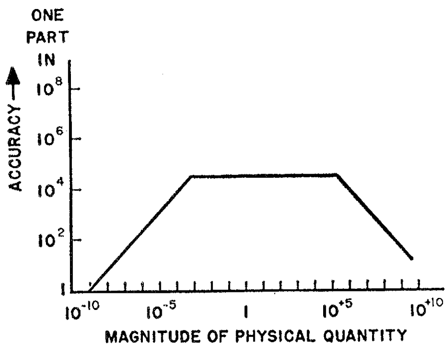

Fig. 6. A generalized accuracy chart.

As we go to higher temperatures, such as those of interest in rockets and fusion processes, the realization of equilibrium implicit in the definition of temperature becomes increasingly difficult, and different methods of measurement lead to quite different answers for the same physical system. Here the situation requires careful thinking. New concepts need to be formulated, new definitions devised, and new measurement schemes developed.

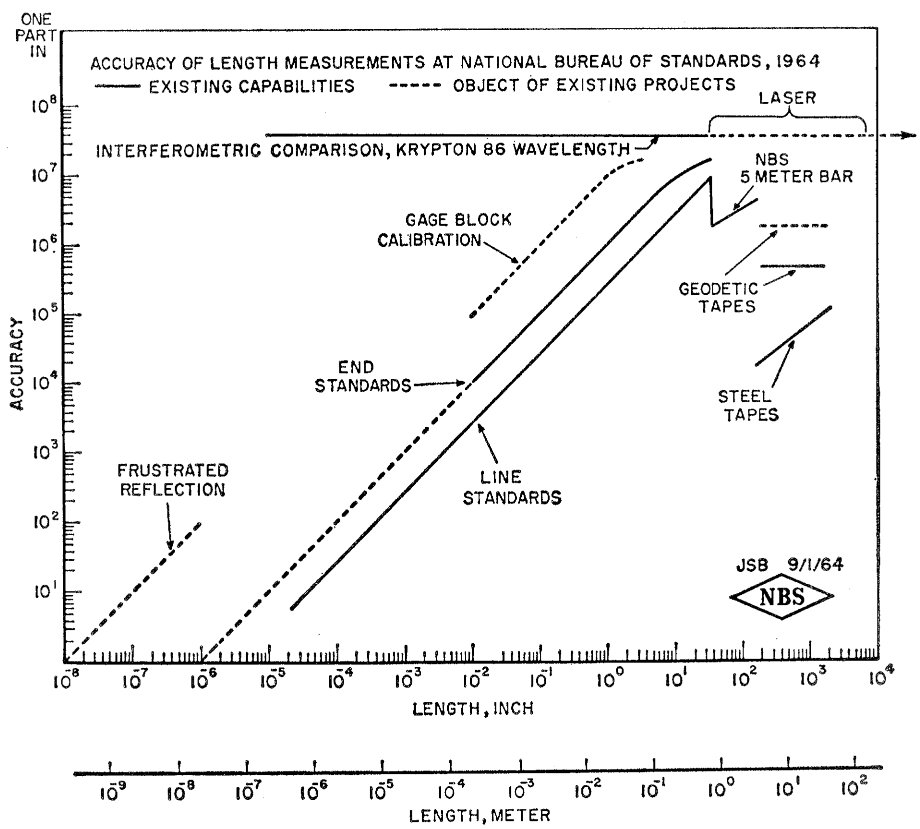

Fig. 7. The Institute for Basic Standards chart for length.

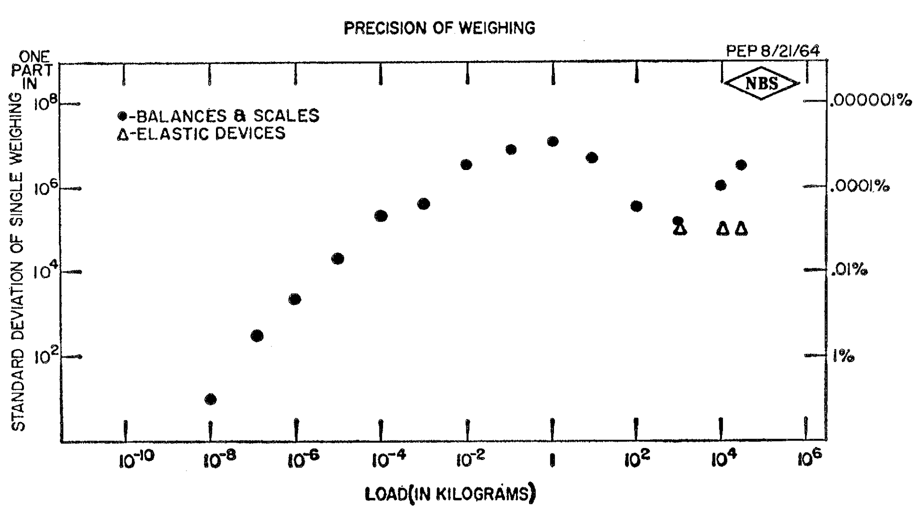

Fig. 8. The Institute for Basic Standards chart for mass.

The Measurement Chain

Once the units have been selected (Table 1) and the standards realized, there must be a chain of measurement that will provide for measuring all the magnitudes we must deal with. These magnitudes may extend from very small fractions of the unit to large multiples of it—in the case of length, from the diameter of the atomic nucleus (10^{-15} meter) to the dimensions of the universe (10^{25} meters). Not all this range can be covered in one central standards laboratory, but a great part of it must be. As we depart from unity in the magnitude to be measured, the chain becomes extended, and each measurement stage in this extension introduces additional uncertainty in the final measurement (Table 2).

Also, vastly different magnitudes require different measurement techniques with differing chances for error or uncertainty. (Here we use *error* to mean unknown systematic discrepancies, while *uncertainty* pertains to the random fluctuations in the measurement process itself.) It then becomes both a necessity and a challenge to provide measurement capability over the entire range of magnitudes with an accuracy or precision that is adequate to meet the needs of science and technology.

In assessing our measurement capability in any particular area, it is helpful to plot an "accuracy chart." A generalized accuracy chart is shown in Fig. 6. It is a log-log plot in which the ordinate represents the uncertainty of measurement (decreasing upward) and the abscissa represents the magnitude of the quantity for which the chart is constructed. (Logarithmic scales are convenient for this use because the range to be covered is so great.) On such a chart the smallest uncertainty is commonly at the point where the measured quantity is unity.

Accuracy charts are coming into general use. They now exist for all of the 40 physical quantities with which we deal at the National Bureau of Standards (*15*). By means of such charts it is possible to display, in compact form, a great deal of information about the state of the measurement system. They are thus of great value in helping us locate the areas into which we should channel our resources for improvement of the system.

With the continued advancement and increasing sophistication of science and technology, the ends of each accuracy curve are continually being extended to cover a greater range of variables; at the same time there is usually pressure to raise the whole curve to regions of smaller uncertainties. Progress on either of these fronts tends to be extremely costly. The more complex or refined techniques needed to extend range or accuracy usually require extensive research and development, the costs of which rise exponentially with each additional step forward.

Figure 7 is the IBS chart for length. Relative to this chart, the greatest pressure of present-day demand is directed toward raising the center of the curve, over the range 10^{-2} to 10^4 meters, by about an order of magnitude.

Figure 8 is the IBS chart for mass. Here the pressures for greater accuracy are not at the center but in the regions 10^{-3} to 10^{-6} kilogram and 10^1 and 10^2 kilograms.

Provision of this chain of measurement for all quantities, for all required accuracies, and for all ranges is clearly an impossible task for any single laboratory. The IBS does not and should not attempt to do it all. It should, however, provide capability at selected crucial points, upon which others can build and extend the range to meet their own needs. Thus the users of the national measurement system—industry, science, technology, and government—must, and do, carry a large portion of the load. The basic responsibilty of IBS is to provide centralization and leadership toward the attainment of common measurement goals for American science and industry.

Even if IBS were able to provide full-scale measurement capability for all physical quantities under ideal conditions of measurement, there would still remain the more extensive and difficult problem of measurement under practical working conditions. Consider just one quantity—temperature, for example. It is one thing to be able to measure temperature in the laboratory under convenient, ideal conditions. It is quite another thing to attempt to measure the temperature of a strip of sheet steel in a rolling mill while the strip is moving rapidly along, with winds blowing, the surface jumping, scale forming, and a general acoustical uproar in progress. How far a central standards laboratory such as IBS should go in developing techniques for practical measurement is a question that requires basic policy decisions.

The Future

A discussion of the national measurement system would be incomplete without a brief look toward the future. Certain trends are evident which permit reasonable predictions. First, it seems clear that needs for extension of the range of magnitudes and for precision will continue to increase and that we shall be faced with continuing demands for more accurate standards on all fronts. We can expect significant changes in the standard of length within the next 3 to 5 years. In the measurement of time, accuracies should increase by two or three orders of magnitude within the next decade. Perhaps by the end of the decade we shall have reached some kind of fundamental limit to the precision with which time and frequency can be measured without refinement and redefinition of our concepts.

Our measurement system will probably continue for some time to be based on six quantities, the units for all other quantities being defined in terms of the base units and independently reproducible from these six. Within the next decade the number of units that are established on an independent basis may decrease to three, or possibly two, but we shall probably continue to consider the six International System physical quantities, with their units, the base of our system.

The next two decades may well provide some sort of uniform approach to the national problems arising from the use of standards which can be compared with each other more precisely than they can be related to the conceptual definition of the unit.

Meanwhile, the whole system should be moving toward its inherent goals of simplicity, uniformity, and consistency. Eventually, advances in instrumentation and measurement, brought about by events such as the discovery of the Mössbauer effect and the development of lasers, will permit definition of all units by arbitrary assignment of values to the fundamental constants.

As progress is made in this direction, the national standards laboratories will become less and less concerned with the job of calibration. Eventually, perhaps, the day may come when it will no longer be necessary to ship instruments to a central standards laboratory for comparison with standards. Of course, the expense of providing in every laboratory the equipment nec-

Table 2. Estimates of accuracy and precision attainable in measuring physical quantities.

Physical quantity	Device	Magnitude	Uncertainty (in parts per million)	
			Accuracy*	Precision†
Length‡	Meter bar	1 meter		0.03
Length	Gage block	0.1 meter	0.1	.01
Length	Geodetic tape	50 meters	.3	.10
Mass	Cylinder	1 kilogram		.005
Mass	Cylinder	1 gram	1	.03
Mass	Cylinder	20 kilograms	0.5	.1
Temperature	Triple-point cell	273.16°K		.3
Temperature	Gas thermometer	90.18°K	100	20
Temperature	Optical pyrometer	3000°K	1300	300
Resistance	Resistor	1 ohm	5	0.1
Resistance	Resistor	1000 ohms	7	1
Resistance	Resistor	0.001 ohm	7	1
Voltage	Std. cell	1 volt	7	0.1
Voltage	Volt box-std. cell	1000 volts	25	10
Power: DC	Std. cell-resistor	1 watt	11	1.5
60 cycle	Wattmeter	10–1000 watts	100	50
X-band	Microcalorimeter	0.01 watt	1000	100

* Estimated "overall probable error," including allowances for systematic errors. † Probable error.
‡ The data here represent conditions before the meter was redefined in terms of light waves.

essary for self-sufficiency will certainly prevent the attainment of this goal within the foreseeable future. Still, it remains a goal toward which we are moving.

Meanwhile, we may expect to see the development of a number of self-sufficient regional calibration centers. With such centers in existence, the national standards laboratories may no longer need to make many calibrations; they can then concentrate more on the development and dissemination of procedures that will permit every major laboratory to reproduce accurately the standard for each quantity.

References and Notes

1. Unfortunately the word *standard* has multiple meanings in English. In this article the word is used to mean a standard for physical measurement; that is to say, the physical realization of an agreed-upon unit (such as the meter or kilogram) for the expression of physical measurements.
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16. I wish to acknowledge with gratitude the extensive assistance and participation of Mr. W. K. Gautier in the preparation of this manuscript.

Automated Synthesis of Peptides

Solid-phase peptide synthesis, a simple and rapid synthetic method, has now been automated.

R. B. Merrifield

The science and art of peptide synthesis have flourished remarkably in recent years. Achievements such as the synthesis of insulin (*1*) and several other peptide hormones (*2*) show that the present methodology has been very effective and suggest that it will be extended even further. But in spite of these accomplishments the conventional procedures have certain inherent characteristics which will tend to set practical limits on the size of polypeptides which can be synthesized in reasonable time and with reasonable yield. The standard technique depends on building up long chains by repeated condensations of individual amino acids or on combining a series of small peptides to form a single large one. Such multistep processes are very laborious and require large numbers of separate reactions. For that reason synthetic methods of the greatest simplicity and efficiency are essential.

Following earlier work from this laboratory on the synthesis of peptides by conventional methods (*3*), experiments were begun in June 1959 on the general problem of finding a new approach to the synthesis of this important class of compounds. The primary objective was to devise a simple and rapid method, and the ultimate aim was to so simplify the procedures that they could be performed and controlled automatically. Automation was expected to offer a great advantage for the synthesis of large polypeptides, and it appeared to be the only reasonable hope for the eventual attempts to synthesize proteins. By 1962 it was possible to describe the basic idea for a new approach, to demonstrate its feasibility, and to predict its adaptability to automation (*4*). The process was named "solid-phase peptide synthesis" because all the reactions proceeded in a two-phase system in which the peptide was always present in the insoluble solid phase. The present article is intended to outline the principle behind the method, to describe the development of the method, and to show how it was, in fact, automated and how it has been applied to the synthesis of certain biologically active peptides.

Before discussion of the new approach, perhaps it would be best first to review the general procedures involved in standard peptide synthesis and to point out some of the difficulties and limitations (*5*). In essence the problem is simply to form a series of peptide bonds; that is, to prepare amides derived from the carboxyl group of one α-amino acid and the amino group of the neighboring one. Before this can be done, however, it is necessary to block the other functional groups of both amino acids to prevent them from entering into the coupling reaction. The selection of blocking groups which will provide the necessary protection but which subsequently can be effectively removed without disrupting the peptide bond is a major problem. Another is the activation of the carboxyl group in such a way that it will couple in high yield, without side reactions. Furthermore, it is essential to select conditions which will avoid racemization of the asymmetric centers of the component amino acids. The peptide chemist is now in command of a large arsenal of reagents and methods which enable him to accomplish these objectives. But the successful synthesis of the peptide bonds is only part of the overall task. In the standard methods it is equally important to isolate and purify each intermediate product before it can be used for the next step in the synthesis. Each product must be separated from starting materials, reagents, and by-products which, in many instances, will have very similar properties. This

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