5. F. Kühnen and P. Fürtwangler, *Veröffentl. Königl. Preuss. Goedat. Inst. Potsdam No. 27* (1906).
6. P. R. Heyl and G. S. Cook, *J. Res. Nat. Bur. Std.* **17,** 805 (1936).
7. J. S. Clark. *Phil. Trans. Roy. Soc. London Ser. A* **238,** 65 (1939).
8. These laboratories were the Physikalisch-Technische Bundesanstalt, Braunschweig; the Mendeleev Institute of Metrology, Leningrad; the National Research Council, Ottawa; the Bureau International des Poids et Mesures, Sèvers; the National Bureau of Standards, Washington, D.C.; and the National Physical Laboratory, Teddington, England.
9. J. E. Faller, thesis, Princeton Univ. (1963); *J. Geophys. Res.* **70**, 4035 (1965).
10. A. Sakuma, in *Bull. Inform. Bur. Gravimetrique Intern. No. 14* (1966), pp. I-8 and I-9.
11. A. H. Cook, *Phil. Trans. Roy. Soc. London Ser. A* **261**, 211 (1967).
12. D. Tate, *Bull. Inform. Bur. Gravimetrique Intern. No. 14* (1966), pp. I-6 and I-7.
13. A. Thulin, *Ann. Geophys.* **16**, First Part, 105 (1960).
14. B. M. Yanovskii, *Trudy Vses. Nauchn. Issled. Inst. Metrol. No. 32* (1958).
15. H. Preston-Thomas, L. G. Turnbull, E. Green, T. M. Dauphinee, S. N. Kalra, *Can J. Phys.* **38**, 824 (1960).
16. I thank the staff at the National Bureau of Standards (NBS) and the Joint Institute for Laboratory Astrophysics (JILA) for their interest and encouragement during early phases of work on the laser-interferometer apparatus. I also thank James Hammond and Dr. Ralph Baierlein of Wesleyan University for a number of helpful suggestions concerning this manuscript. To Mr. Hammond goes a good deal of credit for the design of the overall instrument and for the progress made to date. The mechanical parts of the instrument are the handywork of Mr. Dave Hendry of NBS–JILA and Mr. Jack White of Wesleyan. This research is supported by the National Bureau of Standards and by the Air Force Cambridge Research Laboratory.

Concept of a National Measurement System

The systems approach is being applied to improve understanding of the nation's measurement activities.

R. D. Huntoon

Concurrently with the growth and industrialization of this nation, there has developed within it a vast, complex system of measurement which has made possible the very growth that brought the system into being. This National Measurement System (NMS) stands today as one of the key elements in a worldwide measurement system that links all major nations together in a consistent, compatible network for communication and trade.

Our National Measurement System is one of a number of mutually interacting systems within our technologically based society that form the environment in which the individual citizen must live and function. Familiar examples are the communication, transportation, educational, medical, and legal systems, all of which may be included under the general heading of social systems.

In view of the demonstrated value of the systems approach for the understanding and improvement of hardware such as computers and weapons, some of these social systems are being subjected to the same type of analysis. The National Measurement System, which evolved in this country with little formal recognition as a system, is now being examined in this way at the National Bureau of Standards (NBS) which undertook the study of NMS partly because of a growing realization of the all-pervasive nature and great economic importance of the nation's measurement activities, and partly because of the challenge to NBS in putting its splendid new facilities to optimum use for the benefit of the nation. Such optimum use can be approached only when NMS, of which NBS is a central element, and the services it requires for effective operation are sufficiently well understood.

The magnitude and scope of NMS appear to justify such a study. All of us make measurements and use them; within the United States, this activity is roughly estimated at some 20 billion measurements per day. In the industrial sector, we find (from 1965 data) that the industries that account for two-thirds of the gross national product ($400 billion) invest annually about $14 billion of operating expenditures and 1.3 million man-years in measurement activity. We have about $25 billion invested in instruments for measuring, and we are increasing this investment at the rate of $4½ billion per year. Another $20 billion is invested in completed data on properties of matter and materials, and we are adding approximately $3 billion per year to this amount. Those industries that are growing most rapidly in their contribution to the gross national product are generally those that invest the most in measurement in proportion to output. Hence, the growth sectors of the economy are those that are technologically more sophisticated and therefore more directly dependent upon an advanced measurement capability.

If we judge the value of a service by what the user is willing to pay for it, then the value of the National Measurement System to the nation is in excess of $15 billion a year. More than 90 percent of this cost is paid by NMS through charges to the user in the marketplace; the federal government contributes by providing a central facility for measurement standards (NBS) and the national standards upon which NMS is based.

Like other social systems, the National Measurement System consists of two basically different interacting structures which we designate as the "conceptual system" and the "operational system." In general, the conceptual system is a rational, ordered structure of rules, definitions, laws, conventions, or procedures which provides the fundamental basis upon which the operational system can be built. It is universally applicable, like the laws of physics and chemistry. The International System of Units (Système International

The author is director of the Institute for Basic Standards, National Bureau of Standards, Washington, D.C.

or SI) exemplifies the basic structure of the conceptual system that governs the operation of the NMS (*1*). The SI is, of course, universal insofar as international agreements can make it so. The operational system is an ordered structure of functional elements —that is, organizations of people—interacting with one another under central guidance to perform a function. It is national in scope; it assumes a character suited to the nation it serves, and one that is consistent with the requirements of the conceptual system.

In our examination of the National Measurement System, we begin with the needs that it seeks to meet and the essential functions that it performs. We then proceed to a consideration of its foundations in the conceptual system, the nature of the operational system, and finally the role of NBS as a key functional element in the latter system.

Basic Social Needs

Three general, ever-present needs of our society have brought NMS into being. The NMS, working with other social systems, meets these needs, thereby enabling our society to accomplish its national objectives, such as space exploration, better education, adequate defense, a higher standard of living, or consumer welfare. There is need for: (i) basic measurements and standards, (ii) data and standards on materials, and (iii) technological measurements and standards. The nationwide need for a complete and consistent system of physical measurement, properly coordinated with those of other nations, requires the ability to make accurate, reliable, precise, and compatible measurements in terms of a common language of units and methodology. Another nationwide need is for a systematic and readily accessible body of accurate, reliable, precise, and consistent data on the properties of materials in different environments, and for information, reference materials, and conceptual knowledge that will make possible the effective use of such data. To an increasing extent, the economy has come to depend on the exchange, in the marketplace, of products and services having a high technological content. This creates a need both for uniformity of product characteristics and for a language for stating requirements of users in terms of the performance capabilities of products and standards.

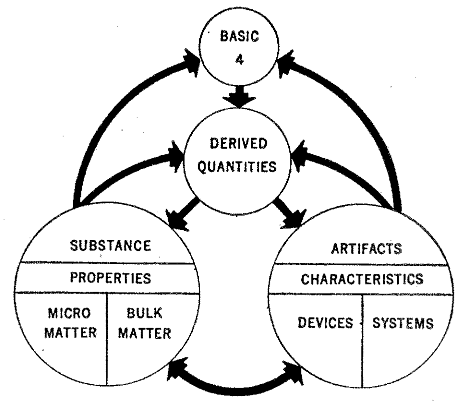


Fig. 1. Conceptual measurement system.

As indicated, the National Measurement System provides the services to meet these needs. Briefly stated, the essential function of the NMS is to provide a quantitative basis in measurement for (i) interchangeability and (ii) decisions for action in all aspects of our daily life—public affairs, commerce, industry, science, and engineering. As soon as we have a measurement system with a set of established units and standards, we have a firm basis for the interchange of goods and services in the mass markets of modern commerce, of machine parts and devices in industry, and of scientific and technical information. This system also provides a basis for such vital decisions as those made by an airplane pilot in flight, by the control room at a launching pad, or by an engineer designing a chemical plant.

Conceptual and Operational Systems

The NMS is built on the principle that "things equal to the same thing are equal to each other." Such is the nature of the measurement process that compatible measurements through NMS are achieved by a hierarchy of comparisons, or calibrations, at ever-increasing levels of accuracy until, for each quantity, all measurements are ultimately referred to a common tie point or standard.

The anchor points for the entire structure (Fig. 1) are the standards for the four basic quantities: mass, length, time, and temperature (*3*). The units for all other physical quantities are linked to the units for these four quantities (the kilogram, meter, second, and degree Kelvin) through the definitions and equations of physics. This fact insures that the units of SI will be consistent with the equations of physical science as we know them.

The basic and derived physical quantities form a set of some 50 general measurement quantities, in terms of which the other measurement quantities of science, industry, and commerce are developed. Those measurement quantities concerned with the properties of substances, such as density or viscosity, form one characteristic set which meets the need for a body of reliable data on the properties of matter and materials. Those that relate to man-made artifacts—devices, subsystems, and systems—rather than substances, form another characteristic set which meets the need for technological measurements and standards. In this set are such measurable quantities as the amplification factor of a vacuum tube, the sharpness of a razor blade, or the reliability of a computer.

The upward feedback (Fig. 1) takes place in two ways. First, there is the feedback of information regarding the needs for refinement of the quantities at each level. Then there is the feedback of capability and knowledge developed in the various parts of the system. For instance, information on properties is essential to the definition and development of the four basic units and to the measurement of the derived units. Likewise, information obtained by use of devices or systems enables us to improve the part of the program represented by the upper circles and its transmission down to the lower circles. We turn now to the operational system—a structure of functional elements, each of which is an organization of people and resources to accomplish a function. Figure 2 illustrates, in a very general way, the operation of NMS in this country, its relation to the international measurement system, its pool of unmet needs, and its reservoir of capability that users draw upon. It also shows the three major networks of NMS. First, there is the instrument network (Fig. 3) which provides calibrated, traceable instrumentation, consistent and compatible with the national standards, for making measurements.

Then there is the data network (Fig. 4) which provides the user of NMS with critically evaluated data on the intrinsic properties of materials—data that investigators have obtained in measurements based on the national standards. This network thus gives to the user, in many cases, a ready-made answer to his measurement problem, so that he does not need to make the measurement himself.

We also envision a corresponding data network for data on the characteristics of devices or systems to meet the need for technological measurements and standards. This network, however, is not yet sufficiently well analyzed to permit adequate representation here.

Finally, there is the techniques network (Fig. 5) which tells the user of NMS how to make meaningful measurements. This network disseminates knowledge to the user through publications and other means, so that he knows (i) how to make a given measurement and (ii) what he should measure in order that the measurement be meaningful.

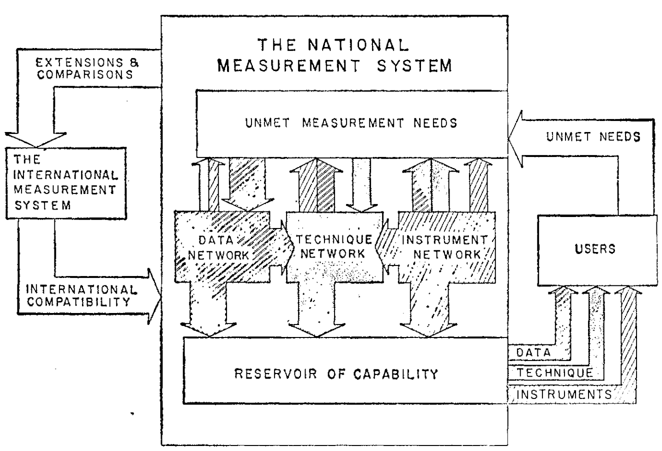
Role of NBS

We now indicate the function of NBS in the NMS structure. (i) We note that the instrument and data networks require the operation of a central measurement facility to tie the activities of NMS in a consistent manner to the national standards and to provide these networks with a means of disseminating their outputs to the rest of the NMS. (ii) We see a need for some organization to lead NMS—to study it, evaluate its effectiveness and deficiencies, and to initiate corrective action where necessary. The leadership function falls naturally within the scope of activities of the central measurement facility. Thus, the role of NBS as a key functional element of the NMS may be stated as follows: (i) to provide the central basis in the United States for a complete, consistent system for physical measurement; and (ii) to provide federal leadership to insure effective and efficient performance of NMS.

The role of NBS requires it to work with and through NMS to see that NMS provides the services that its users require. In general, NBS deals with other NMS elements and not directly with individuals who comprise the large body of users. Thus, in providing the central basis for NMS, NBS concentrates on NMS needs, relying upon NMS to serve ultimate users. Each of the three networks of NMS presents its own set of requirements, but each depends on a strong central core of national standards.

Central Core and Three Networks

In providing the national standards which serve as tie points for NMS, the central measurement facility must, of course, develop and maintain the standards for the four basic quantities and for the set of some 50 quantities whose units are derived in accordance with the conceptual system (*1*). All these standards must be properly co-



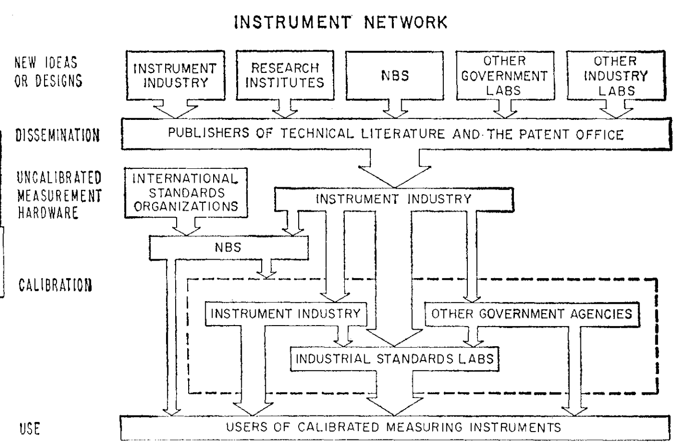
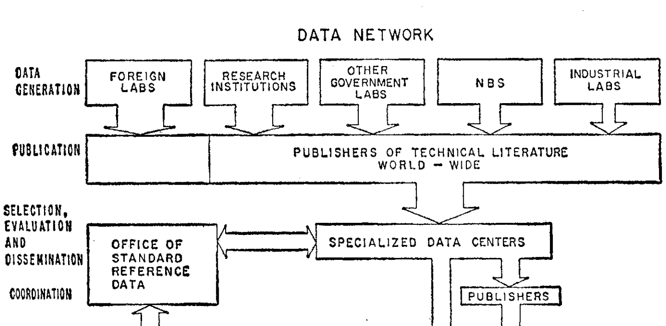


Fig. 2 (left). Operation of the National Measurement System. Fig. 3 (right). A schematic representation of the instrument network.



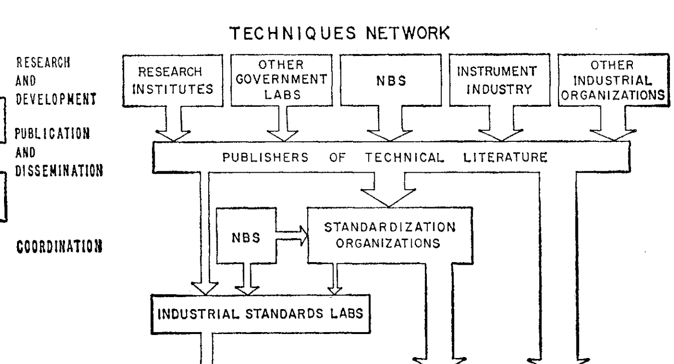


Fig. 4 (left). Flow chart for the data network. Fig. 5 (right). Present conception of the techniques network.

ordinated with those of other nations to insure compatibility in scientific and engineering data and in world trade. [The international basis for uniform measurement is explained by Howlett (*2*).] Our national standards must be as good as, or better than, those of other nations so that they may receive proper recognition in international negotiations. To provide such standards, NBS must have a broad research and development capability of a high order. This capability, of course, provides a strong basis for leadership of the National Measurement System.

Leading outward from the central core of national standards, there must be a chain of measurement for all magnitudes. For example, the range extends from the mass of the earth, or even beyond, down to the mass of the electron, neutron, or subparticle. Hence, we have a vast spectrum of some 50 or 60 orders of magnitude that must be connected through a measurement chain to the defined unit, the kilogram, so as to provide the accuracy required by science and industry at any particular magnitude. Some of these magnitudes can be measured directly by taking multiples or submultiples of the standard; but as we leave the central part of the range, we find it necessary to use indirect methods, with a corresponding reduction in accuracy.

Of course, it is impossible for a single institution such as NBS to make calibrations over the complete range for mass, length, or any other quantity. Hence, the Bureau of Standards must make basic decisions on how far to go and how much to do. Its policy is to pick calibration points (or, in some cases, calibration regions) at intervals over the range so that the measurement activities of the country can be coupled to NBS at these points. The NBS must rely upon the rest of NMS to build upon these points and to extend the calibration between them so as to cover the range as needed. The basis for making the necessary decisions with the aid of accuracy charts has been explained (*1*).

The network for data on properties deals with well-understood, well-characterized materials upon which it is meaningful to make precise property measurements. Values of these properties must be carefully measured and disseminated to users of NMS in units consistent with those of the basic and derived physical quantities. No single institution such as NBS could, or should, attempt to develop all the information that is required on thousands of properties for millions of substances. Thus, in this network the role of the central measurement facility is to select certain key materials, to characterize these materials carefully, and to make precise measurements of their properties. The NMS can then couple to these key data points and use them as points of reference in building a reservoir of data to meet the remaining needs.

If this central function is effectively carried out, it provides a basis for leadership of NMS by the central measurement facility. At the same time, it supplies NMS with the basic information needed for self-calibration of instruments and measurement procedures, and it gives scientists and engineers necessary data for designing and building apparatus and equipment. Obviously, to do the job properly, the central measurement facility must have broad competence in materials research and in measurement science.

The corresponding data network for design specifications or performance characteristics of devices and systems is at present quite broad and diffuse. Thus, at this stage of the network's development, NBS can best devote its efforts to providing the technical basis for the setting of meaningful design or performance standards, leaving the actual setting of the standards to the voluntary cooperation of the other elements of NMS (except for standards that NBS is legally required to set). Of course, even this activity by NBS must be limited to those sectors of industry that do not have bodies for setting standards in other parts of the government (for example, the Interstate Commerce Commission and the Federal Aviation Agency). In general, it is the policy of NBS to exert leadership to encourage the development and promulgation of performance standards, as opposed to design standards, in order to remove those barriers to innovation and progress that are characteristic of some design standards.

The techniques network is that part of the NMS through which all its users can be told how to make optimum use of the measurement capability developed in the instrument and data networks. It is composed of a great many institutions and organizations, each aimed at proper utilization of NMS for the making of meaningful measurements. The techniques network has not been as well examined or understood as the instrumentation and data networks. However, it obviously includes professional journals and other publications; meetings of professional societies; organizations and institutions that provide training in measurement techniques; standardizing bodies such as the U.S.A. Standards Institute, the American Society for Testing and Materials, and the International Standards Organization; standards of practice which include agreed-upon procedures for making measurements; and the educational institutions that provide the trained manpower to operate NMS.

Because the government has wisely refrained from assigning leadership of NMS to NBS by law or executive order, the Bureau of Standards must maintain this leadership through demonstrated competence and general acceptance of its capability. This situation presents both a challenge and a responsibility. The NBS must make a continuous effort to understand the structure and operation of the NMS, to assess the value of its services for national objectives, and to develop means for evaluating its effectiveness. It must exert leadership to correct any deficiencies it finds and to adjust relative emphasis among the different elements. The NBS should also stimulate and encourage all other elements of NMS to study their respective roles to increase their effectiveness and to provide NBS with necessary information on NMS operation.

An example shows how this leadership function is carried out in practice. Recently, the need for leadership arose because the process of critical evaluation and compilation of data within NMS had lagged far behind the generation of data in the literature. A large backlog of unevaluated data had been built up, and, as this backlog continued to grow, it had become increasingly difficult for scientists and engineers to find the data they needed. Lack of critically evaluated data in conveniently available form had thus become an important and wasteful deficiency of NMS.

To remedy this, the Office of Science and Technology, acting upon information presented by NBS and other organizations within NMS, established a

National Standard Reference Data System (NSRDS) in 1963 and assigned to NBS the responsibility for its administration and coordination. The activities, goals, and accomplishments of the NSRDS are described by Brady (*4*).

Trends in the System

Our study of the National Measurement System is still in its early stages. There remains much work to characterize inputs and outputs, interactions with other social systems, involvement with national objectives, the functions of NMS elements, and couplings between the elements. Nonetheless, some of the trends within NMS are becoming clearer. For example, it seems evident that the inherent advantages of simplicity and coherence in the International System of Units will lead eventually to widespread use of this modern version of the metric system within the United States as in other countries. In addition to the electrical and electronic industries, which have been based on SI since the system was adopted, the drug industry has turned to SI, and there are signs of impending change elsewhere, including bills for study of the metric system that have been introduced in Congress.

At present, the SI units for all the derived quantities are defined in terms of the basic units and appropriately established values for the physical constants such as the magnetic constant for electrical quantities. However, one of the basic units, the kilogram, is not independently reproducible. If the kilogram could also be defined in this way, then units for all physical quantities would, in principle, be independently reproducible in any laboratory. Whether or not these units should be independently reproduced by individual laboratories would depend on the state of the art and the relative cost of doing so as opposed to that of the conventional means of calibration.

We can also see a definite trend toward "self-calibration." Increasingly, industrial laboratories will carry out their calibrations in their own laboratories with standard materials, measurement data, or transportable standards supplied by NBS. Thus, the role of the central measurement laboratory may be expected to undergo a slow, progressive change as the emphasis shifts from hardware to software, that is, from the exact comparison of instruments at NBS to the provision of means, information, and computer assistance that will enable the user of NMS to calibrate his own instrument with his own techniques and to evaluate his own measurement capabilities at the same time.

In general, the character of the NBS contribution to the National Measurement System will be shaped in the future, as in the past, by what might be called "the principle of stringency." This principle says that in general, once the most stringent needs for measurement have been met, lesser requirements can also be met. Of course, it does not automatically follow that the lesser needs *will* be met, as the means to do this may not be immediately at hand.

The stringency principle requires NBS to undertake to meet the most stringent requirements of NMS wherever there is enough need to justify the necessary investment in research. This poses certain problems, inasmuch as the great majority of users of NMS do not have the greatest need for accuracy. In fact, the users of NMS might be considered as a huge pyramid, with the few requiring the most highly accurate measurements at the top, and more and more, further down the pyramid, of those who require less and less accuracy. So the question is: How far toward the top of the pyramid should NBS push its measurement program? The Bureau's operating policy is to focus on the more stringent measurement requirements that represent a real, important need sufficient to justify the necessary investment and to encourage the remainder of the National Measurement System to extend the service at the lower levels of accuracy and precision insofar as it is economically more efficient to do so. However, NBS must provide those calibration services that are necessary to make the overall system function economically and efficiently. In some cases this may mean that NBS should provide calibration well down into NMS; in other cases it may only be necessary for NBS to provide services at the highest levels of precision and accuracy. Economy and efficiency in the operation of the overall system are the deciding factors.

Already, some elements of NMS, notably those represented by the National Conference of Standards Laboratories, are giving serious, productive consideration to their respective roles and are generating recommendations for improvement in its operation. If such efforts can be continued on a broad scale, they will build a strong base for a highly improved National Measurement System in the years to come, with great potentialities for raising our standard of living and for aiding in the achievement of national objectives.

References and Notes

1. R. D. Huntoon, *Science* **150**, 169 (1965).
2. L. E. Howlett, *Science*, this issue.
3. The six "base units" of the International System of Units comprise the four *basic* units, together with two additional units—the ampere and the candela. The ampere has been given this status as an aid to dimensional analysis although it is defined in terms in length, mass, time, and a particular value of the magnetic constant μ_0 which is taken as 4×10^{-7} henry per meter. The candela, which is used for measurements of visual light, is not purely physical nor uniquely defined as it involves an average human observer.
4. E. L. Brady and M. B. Wallenstein, *Science* **156**, 754 (1967).

5. I thank W. K. Gautier for assistance.