DeWayne B. Sharp. "Measurement Standards."

Measurement Standards

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Shape of Things

Measurement standards are those devices, artifacts, procedures, instruments, systems, protocols, or processes that are used to define (or to realize) measurement units and on which all lower echelon (less accurate) measurements depend. A measurement standard may also be said to store, embody, or otherwise provide a physical quantity that serves as the basis for the measurement of the quantity. Another definition of a standard is the physical embodiment of a measurement unit, by which its assigned value is defined, and to which it can be compared for calibration purposes. In general, it is not independent of physical environmental conditions, and it is a true embodiment of the unit only under specified conditions. Another definition of a standard is a unit of known quantity or dimension to which other measurement units can be compared.

5.1 A Historical Perspective

Many early standards were based on the human body: the length of man's hand, the width of his thumb, the distance between outstretched fingertips, the length of one's foot, a certain number of paces, etc. In the beginning, while groups were small, such standards were convenient and uniform enough to serve as the basis for measurements.

The logical person to impose a single standard was the ruler of the country — hence, our own 12-inch or other short measuring stick is still called a *ruler*. The establishment of measurement standards thus became the prerogative of the king or emperor, and this right has since been assumed by all governments.

History is replete with examples that show the importance of measurements and standards. In a report to the U.S. Congress in 1821, John Quincy Adams said, "Weights and measures may be ranked among the necessaries to every individual of human society." Our founding fathers thought them so important that the United States Constitution expressly gives the Congress the power to fix uniform standards of weights and measures. The need for weights and measures (standards) dates back to earliest recorded history and are even mentioned in the Old Testament of the Bible. Originally, they were locally decreed to serve the parochial needs of commerce, trade, land division, and taxation. Because the standards were defined by local or regional authorities, differences arose that often caused problems in commerce and early scientific investigation. The rapid growth of science in the late 17th century highlighted a number of serious deficiencies in the system of units then in use and, in 1790, led the French National Assembly to direct the French Academy of Sciences to "deduce an invariable standard for all measures and all the weights." The Academy proposed a system of units, the metric system, to define the unit of length in terms of the earth's circumference, with the units of volume and mass being derived from the unit of length. Additionally, they proposed that all multiples of each unit be a multiple of 10.

In 1875, the U.S. and 16 other countries signed the "Treaty of the Meter," establishing a common set of units of measure. It also established an International Bureau of Weights and Measures (called the BIPM). That bureau is located in the Parisian suburb of Sèvres. It serves as the worldwide repository of all the units that maintain our complex international system of weights and measures. It is through this system that compatibility between measurements made thousands of miles apart is currently maintained.

The system of units set up by the BIPM is based on the meter and kilogram instead of the yard and the pound. It is called the Système International d'Unités (SI) or the International System of Units. It is used in almost all scientific work in the U.S. and is the only system of measurement units in most countries of the world today.

Even a common system of units does not guarantee measurement agreement, however. Therein lies the crux of the problem. We must make measurements, and we must know how accurately (or, to be more correct, with what uncertainty) we made those measurements. In order to know that, there must be standards. Even more important, everyone must agree on the values of those standards and use the same standards.

As the level of scientific sophistication improved, the basis for the measurement system changed dramatically. The earliest standards were based on the human body, and then attempts were made to base them on "natural" phenomena. At one time, the basis for length was supposed to be a fraction of the circumference of the earth but it was "maintained" by the use of a platinum/iridium bar. Time was maintained by a pendulum clock but was defined as a fraction of the day and so on. Today, the meter is no longer defined by an artifact. Now, the meter is the distance that light travels in an exactly defined fraction of a second. Since the speed of light in a vacuum is now defined as a constant of nature with a specified numerical value (299, 792, 458 m/s), the definition of the unit of length is no longer independent of the definition of the unit of time.

Prior to 1960, the second was defined as 1/86,400th of a mean solar day. Between 1960 and 1967, the second was defined in terms of the unit of time implicit in the calculation of the ephemerides: "The second is the fraction 1/31, 556, 925.9747 of the tropical year for January 0 at 12 hours of ephemeris time." With the advent of crystal oscillators and, later, atomic clocks, better ways were found of defining the second. This, in turn, allowed a better understanding of things about natural phenomena that would not have been possible before. For example, it is now known that the earth does not rotate on its axis in a uniform manner. In fact, it is erratically slowing down. Since the second is maintained by atomic clocks it is necessary to add "leap seconds" periodically so that the solar day does not gradually change with respect to the time used every day. It was decided that a constant frequency standard was preferred over a constant length of the day.

5.2 What Are Standards?

One problem with standards is that there are several kinds. In addition to "measurement standards," there are "standards of practice or protocol standards" that are produced by the various standards bodies such as the International Organization for Standardization (ISO), the International Electrotechnical Commission (IEC), the American National Standards Institute (ANSI), and the Standards Council of Canada (SCC). See Figure 5.1.

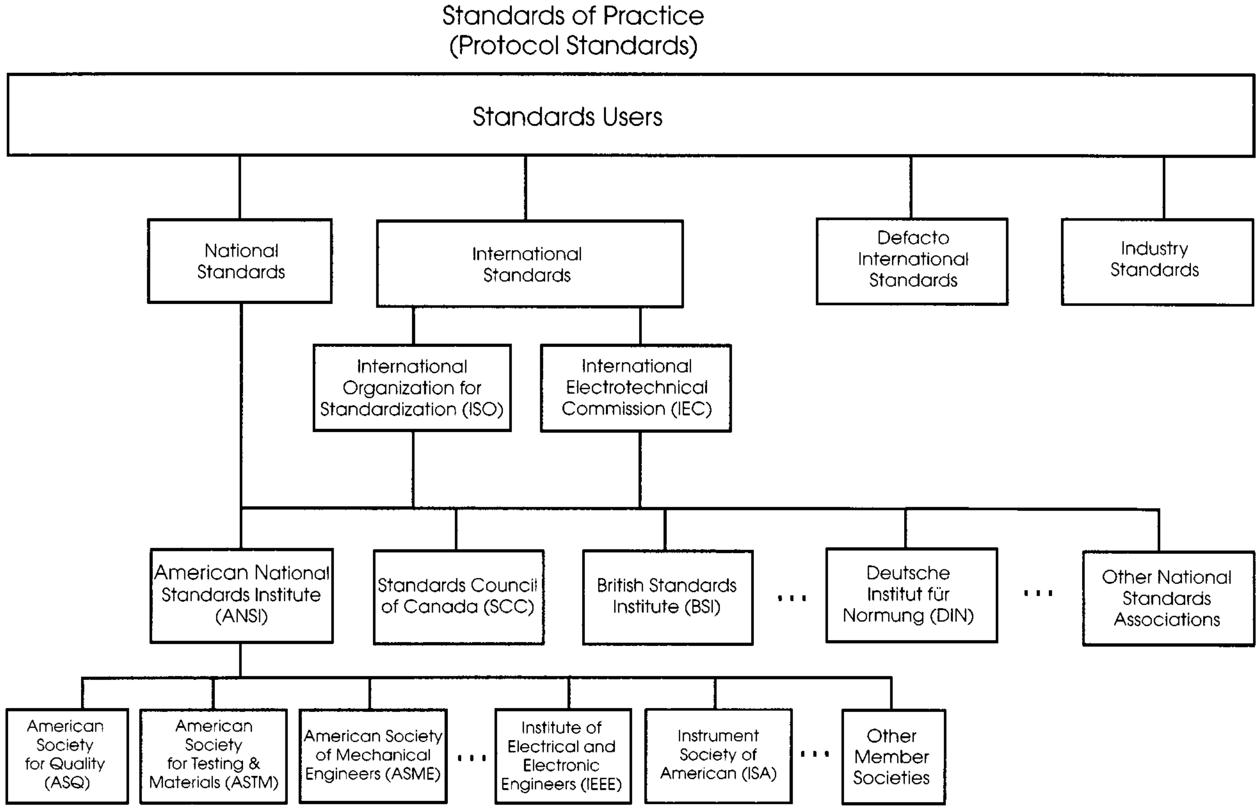
Standards of Practice
(Protocol Standards)
Standards Users
National Standards
International Standards
Defacto International Standards
Industry Standards
International Organization for Standardization (ISO)
International Electrotechnical Commission (IEC)
American National Standards Institute (ANSI)
Standards Council of Canada (SCC)
British Standards Institute (BSI)
...
Deutsche Institut für Normung (DIN)
...
Other National Standards Associations
American Society for Quality (ASQ)
American Society for Testing & Materials (ASTM)
American Society of Mechanical Engineers (ASME)
...
Institute of Electrical and Electronic Engineers (IEEE)
Instrument Society of American (ISA)
...
Other Member Societies

FIGURE 5.1

Standards of Practice (Protocol Standards)

These standards define everything from the dimensions and electrical characteristics of a flashlight battery to the shape of the threads on a machine screw and from the size and shape of an IBM punched card to the Quality Assurance Requirements for Measuring Equipment. Such standards can be defined as documents describing the operations and processes that must be performed in order for a particular end to be achieved. They are called a "protocol" by Europeans to avoid confusion with a physical standard.

Legal Metrology

The application of measurement standards to the control of the daily transactions of trade and commerce is known as Legal Metrology; within the U.S., it is more commonly known as Weights and Measures. Internationally, coordination among nations on Legal Metrology matters is, by international agreement, handled by a quasi-official body — the International Organization for Legal Metrology (OIML).

Within the U.S., domestic uniformity in legal metrology matters is the responsibility of National Institute of Standards and Technology (NIST) acting through its Office of Weights and Measures. Actual enforcement is the responsibility of each of the 50 states and the various territories. These, in turn, generally delegate the enforcement powers downward to their counties and, in some cases, to large cities.

Forensic Metrology

Forensic Metrology is the application of measurements and hence measurement standards to the solution and prevention of crime. It is practiced within the laboratories of law enforcement agencies throughout the world. Worldwide activities in Forensic Metrology are coordinated by Interpol (*Inter*national *Pol*ice; the international agency that coordinates the police activities of the member nations). Within the U.S., the Federal Bureau of Investigation (FBI), an agency of the Department of Justice, is the focal point for most U.S. forensic metrology activities.

Standard Reference Materials

Another type of standard that should be mentioned here are Standard Reference Materials (SRM). Standard Reference Materials are discrete quantities of substances or minor artifacts that have been certified as to their composition, purity, concentration, or some other characteristic useful in the calibration of the measurement devices and the measurement processes normally used in the process control of those substances. SRMs are the essential calibration standards in stoichiometry (the metrology of chemistry).

In the U.S., the National Institute of Standards and Technology (NIST), through its Standard Reference Materials Program, offers for sale over 1300 SRMs. These range from ores to pure metals and alloys. They also include many types of gases and gas mixtures; and many biochemical substances and organic compounds. Among the artifact devices available are optical filters with precise characteristics and standard lamps with known emission characteristics.

5.3 A Conceptual Basis of Measurements

Lord Kelvin's oft-quoted statement may bear repeating here:

> I often say that when you can measure what you are speaking about, and can express it in numbers, you know something about it; but when you cannot measure it, cannot express it in numbers, your knowledge is of a meager and unsatisfactory kind; it may be the beginnings of knowledge, but you have scarcely, in your thoughts, advanced to the stage of science, whatever the matter may be. So therefore, if science is measurement, then without metrology there can be no science.

William Thomson (Lord Kelvin), May 6, 1886

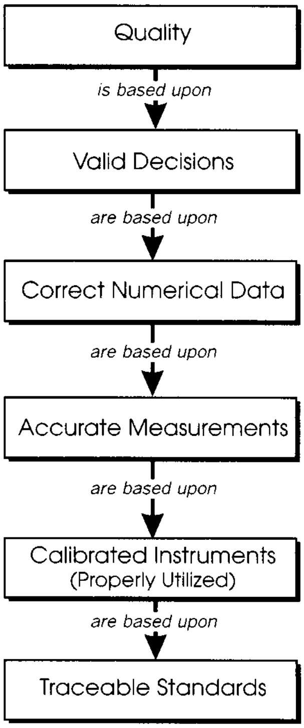

FIGURE 5.2

Lord Kelvin's statement has been quoted so many times that it has almost become trite, but looking at Figure 5.2 will show an interesting hierarchy. In order to achieve quality or "to do things right," it is necessary to make some decisions. The correct decisions cannot be made unless there are good numerical data on which to base those decisions. Those numerical data, in turn, must come from measurements and if "correct" decisions are really needed, they must be based on the "right" numbers. The only way to get "good" numerical data is to make accurate measurements using calibrated instruments that have been properly utilized. Finally, if it is important to compare those measurements to other measurements made at other places and other times, the instruments must be calibrated using traceable standards.

5.4 The Need for Standards

Standards define the units and scales in use, and allow comparison of measurements made in different times and places. For example, buyers of fuel oil are charged by a unit of liquid volume. In the U.S., this would be the gallon; but in most other parts of the world, it would be the liter. It is important for the buyer that the quantity ordered is actually received and the refiner expects to be paid for the quantity shipped. Both parties are interested in accurate measurements of the volume and, therefore, need to agree on the units, conditions, and method(s) of measurement to be used.

Persons needing to measure a mass cannot borrow the primary standard maintained in France or even the national standard from the National Institute of Standards and Technology (NIST) in the U.S. They must use lower-level standards that can be checked against those national or international standards. Everyday measuring devices, such as scales and balances, can be checked (calibrated) against working level mass standards from time to time to verify their accuracy. These working-level standards are, in turn, calibrated against higher-level mass standards. This chain of calibrations or checking is called "traceability." A proper chain of traceability must include a statement of uncertainty at every step.

5.5 Types of Standards

Basic or Fundamental Standards

In the SI system, there are seven basic measurement units from which all other units are derived. All of the units except one are defined in terms of their unitary value. The one exception is the unit of mass. It is defined as 1000 grams (g) or 1 kilogram (kg). It is also unique in that it is the only unit currently based on an artifact. The U.S. kilogram and hence all other standards of mass are based on one particular platinum/iridium cylinder kept at the BIPM in France. If that International Prototype Kilogram were to change, all other mass standards throughout the world would be wrong.

The seven basic units are listed in Appendix 1, Table 1. Their definitions are listed in Appendix 1, Table 2.

Derived Standards

All of the other units are derived from the seven basic units described in Appendix 1, Table 1. Measurement standards are devices that represent the SI standard unit in a measurement. (For example, one might use a zener diode together with a reference amplifier and a power source to supply a known voltage to calibrate a digital voltmeter. This could serve as a measurement standard for voltage and be used as a reference in a measurement.)

Appendix 1, Table 3 lists the most common derived SI units, together with the base units that are used to define the derived unit. For example, the unit of frequency is the hertz; it is defined as the reciprocal of time. That is, 1 hertz (1 Hz) is one cycle per second.

The Measurement Assurance System

Figure 5.3 illustrates the interrelationship of the various categories of standards throughout the world. While it gives more detail to U.S. structure, similar structures exist in other nations. Indeed, a variety of regional organizations exist that help relate measurements made in different parts of the world to each other.

5.6 Numbers, Dimensions, and Units

A measurement is always expressed as a multiple (or submultiple) of some unit quantity. That is, both a numeric value and a unit are required. If electric current were the measured quantity, it might be expressed as some number of milliamperes or even microamperes. It is easy to take for granted the existence of the units used, because their names form an indispensable part of the vocabulary.

5.7 Multiplication Factors

Since it is inconvenient to use whole units in many cases, a set of multiplication factors has been defined that can be used in conjunction with the units to bring a value being measured to a more reasonable size. It would be difficult to have to refer to large distances in terms of the meter; thus, one defines longer distances in terms of kilometers. Short distances are stated in terms of millimeters, micrometers, nanometers, etc. See Appendix 1, Table 4.

Defining Terms

Most of the definitions in this listing were taken from the *International Vocabulary of Basic and General Terms in Metrology*, published by the ISO, 1993 (VIM) [7]. They are indicated by the inclusion (in brackets) of their number designation in the VIM. The remainder of the definitions are not intended to

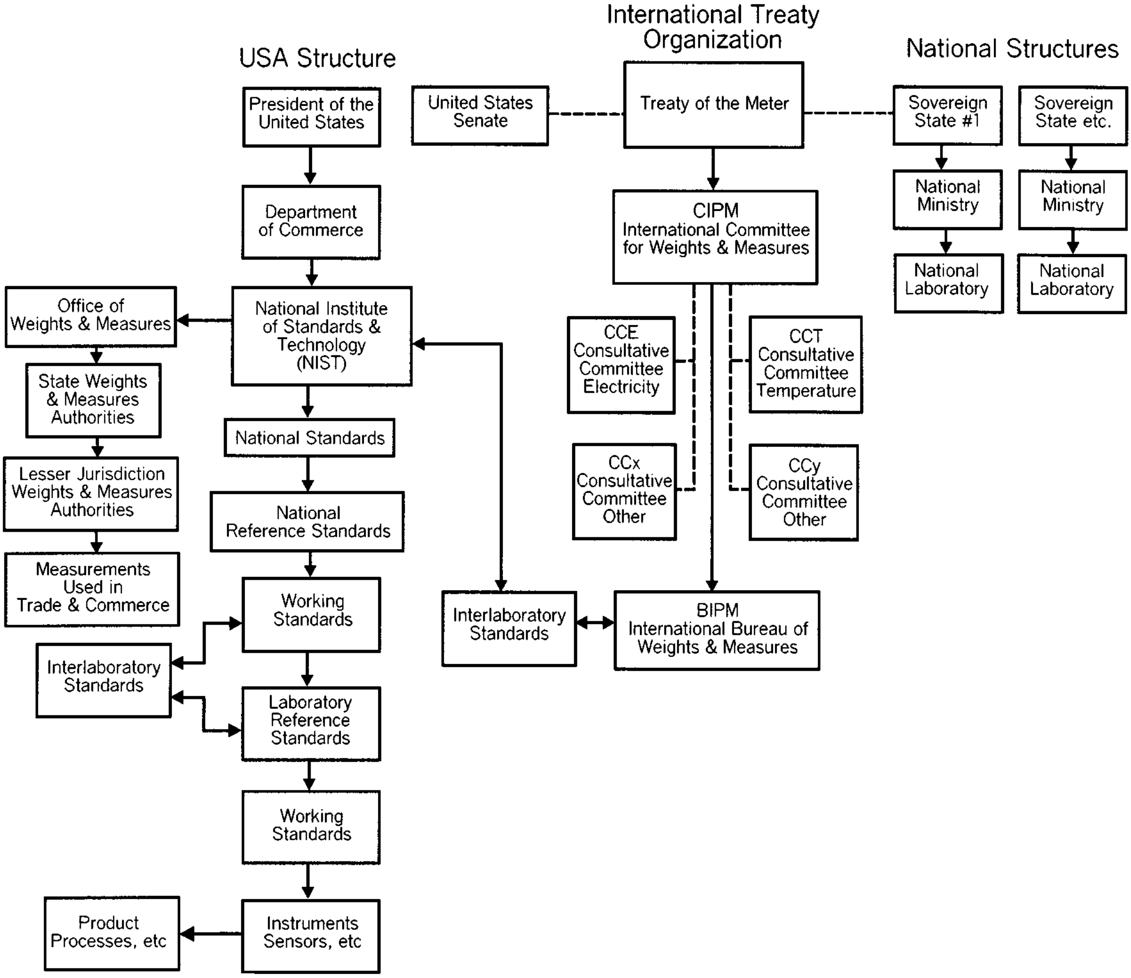

FIGURE 5.3

represent any official agency but are ones widely accepted and are included to help in the understanding of this material. More detailed and rigorous definitions can be found in other works available from ANSI, IEC, ISO, and NIST. Words enclosed in parentheses "(…)" may be omitted from the term if it is unlikely that such omission will cause confusion.

Accuracy of measurement [3.5]:* The closeness of the agreement between the result of a measurement and a true value of the measurand.

NOTES:

1. *Accuracy* is a qualitative concept.
2. The term *precision* should not be used for *accuracy.* (Precision only implies repeatability.)

Note, that to say an instrument is accurate to 5% (a common way of stating it) is wrong. One would not find such an instrument very useful if it, in fact, were only accurate 5% of the time. What is meant when such a statement is made is that the instrument's inaccuracy is less than 5% and it is accurate to better than 95%. Unfortunately, this statement is almost as imprecise as "accurate to 5%." An instrument would not be useful if it were accurate only 95% of the time; but this is not what is implied by "5% accuracy." What is meant is that, (almost) all of the time, its indication is within 5% of the "true" value.

Calibration [6.11]: A set of operations that establish, under specified conditions, the relationship between values of quantities indicated by a measuring instrument or measuring system, or values represented by a material measure or a reference material, and the corresponding values realized by standards.

NOTES:

1. The result of a calibration permits either the assignment of values of measurands to the indicators or the determination of corrections with respect to indications.
2. A calibration can also determine other metrological properties, such as the effect of influence quantities.
3. The result of a calibration can be recorded in a document, sometimes called a *calibration certificate* or a *calibration report.*

Calibration Laboratory: A work space, provided with test equipment, controlled environment and trained personnel, established for the purpose of maintaining proper operation and accuracy of measuring and test equipment. *Calibration laboratories* typically perform many routine calibrations, often on a production-line basis.

Certified Reference Material (CRM) [6.14]: A *reference material*, accompanied by a certificate, one or more of whose property values are certified by a procedure that established traceability to an accurate realization of the unit in which the property values are expressed, and for which each certified value is accompanied by an uncertainty at a stated level of confidence.

1. The definition of a *reference material* is given elsewhere in this vocabulary.
2. CRMs are generally prepared in batches for which the property values are determined within stated uncertainty limits by measurements on samples representative of the entire batch.
3. The certified properties of certified reference materials are sometimes conveniently and reliably realized when the material is incorporated into a specifically fabricated device, e.g., a substance of known triple-point into a triple-point cell, a glass of known optical density into a transmission filter, spheres of uniform particle size mounted on a microscope slide. Such devices can also be considered CRMs.
4. All CRMs lie within the definition of "measurement standards" given in the International Vocabulary of basic and general terms in metrology (VIM).
5. Some RMs and CRMs have properties that, because they cannot be correlated with an established chemical structure or for other reasons, cannot be determined by exactly defined physical and chemical measurement methods. Such materials include certain biological materials such as vaccines to which an International unit has been assigned by the World Health Organization.

This definition, including the Notes, is taken from ISO Guide 30:1992.

Coherent (derived) unit (of measurement) [1.10]: A derived unit of measurement that may be expressed as a product of powers of base units with the proportionality factor one (1).

NOTE: Coherency can be determined only with respect to the base units of a particular system. A unit can be coherent with respect to one system but not to another.

Coherent system of units (of measurement) [1.11]: A system of units of measurement in which all of the derived units are coherent.

Conservation of a (measurement) standard [6.12]: A set of operations, necessary to preserve the metrological characteristics of a measurement standard within appropriate limits.

NOTE: The operations commonly include periodic calibration, storage under suitable conditions, and care in use.

Interlaboratory Standard: A device that travels between laboratories for the sole purpose of relating the magnitude of the physical unit represented by the standards maintained in the respective laboratories.

International (measurement) standard [6.2]**:** A standard recognized by an international agreement to serve internationally as the basis for assigning values to other standards of the quantity concerned.

International System of Units (SI) [1.12]**:** The coherent system of units adopted and recommended by the General Conference on Weights and Measures (CGPM).

NOTE: The SI is based at present on the following seven base units: meter, kilogram, second, ampere, kelvin, mole, and candela.

Measurand [2.6]**:** A particular quantity subject to measurement.

EXAMPLE: Vapor pressure of a given sample of water at 20°C.

NOTE: The specification of a measurand may require statements about quantities such as time, temperature, and pressure.

Measurement [2.1]**:** A set of operations having the object of determining a value of a quantity.

NOTE: The operations may be performed automatically.

Method of Measurement [2.4]**:** A logical sequence of operations, described generically, used in the performance of measurements.

NOTE: Methods of measurement may be qualified in various ways, such as:

- Substitution method
- Differential method
- Null method

Metrology [2.2]**:** The science of measurement.

NOTE: Metrology includes all aspects, both theoretical and practical, with reference to measurements, whatever their uncertainty, and in whatever fields of science or technology they occur.

National (measurement) Standard [6.3]**:** A standard recognized by a national decision to serve, in a country, as the basis for assigning values to other standards of the quantity concerned.

National Reference Standard: A standard maintained by national laboratories such as the National Institute of Standards and Technology (NIST) in Gaithersburg, MD; the National Research Council (NRC) located in Ottawa, Canada; the National Physical Laboratory (NPL) in Teddington, U.K.; the Physikalisch-Technische Bundesanstalt (PTB) at Braunschweig, Germany; and which are the legal standards of their respective countries.

National Institute of Standards and Technology (NIST): The U.S. national standards laboratory, responsible for maintaining the physical standards upon which measurements in the U.S. are based.

Primary Standard [6.4]**:** A standard that is designated or widely acknowledged as having the highest metrological qualities and whose value is accepted without reference to other standards of the same quantity.

NOTE: The concept of primary standard is equally valid for base quantities and derived quantities.

Principle of Measurement [2.3]**:** The scientific base of a measurement.

EXAMPLES:

- The thermoelectric effect applied to the measurement of temperature
- The Josephson effect applied to the measurement of electric potential difference
- The Doppler effect applied to the measurement of velocity
- The Raman effect applied to the measurement of the wave number of molecular vibrations

Reference Standard [6.6]**:** A standard, generally having the highest metrological quality available at a given location or in a given organization, from which measurements made there are derived.

Reference Material [6.13]: A material or substance, one or more of whose property values are sufficiently homogeneous and well established to be used for the calibration of an apparatus, the assessment of a measurement method, or for assigning values to materials.

NOTE: A reference material can be in the form of a pure or mixed gas, liquid or solid. Examples are water for the calibration of viscometers, sapphire as a heat-capacity calibrant in calorimetry, and solutions used for calibration in chemical analysis.

This definition, including the Note, is taken from ISO Guide 30:1992.

Repeatability (of results of measurements) [3.6]: The closeness of the agreement between the results of successive measurements of the same measurand carried out under the same conditions of measurement.

NOTES:

1. These conditions are called *repeatability conditions.*
2. Repeatability conditions include:
   a. The same measurement process
   b. The same observer
   c. The same measuring instrument, used under the same conditions
   d. The same location
   e. Repetition over a short period of time
3. Repeatability can be expressed quantitatively in terms of the dispersion of characteristics of the results.

Reproducibility (of results of measurements) [3.7]: The closeness of the agreement between the results of measurements of the same measurand carried out under changed conditions of measurement.

NOTES:

1. A valid statement of reproducibility requires specification of the conditions changed.
2. The changed conditions include:
   a. Principle of measurement
   b. Method of measurement
   c. Observer
   d. Measuring instrument
   e. Reference standard
   f. Location
   g. Condition of use
   h. Time
3. Reproducibility can be expressed quantitatively in terms of the dispersion characteristics of the results.
4. Results here are usually understood to be corrected results.

Secondary Standard [6.5]: A standard whose value is assigned by comparison with a primary standard of the same quantity.

Standards Laboratory: A work space, provided with equipment and standards, a properly controlled environment, and trained personnel, established for the purpose of maintaining traceability of standards and measuring equipment used by the organization it supports. Standards laboratories typically perform fewer, more specialized and higher accuracy measurements than Calibration Laboratories.

Tolerance: In metrology, the limits of the range of values (the uncertainty) that apply to a properly functioning measuring instrument.

Traceability [**6.10**]**:** The property of the result of a measurement or the value of a standard whereby it can be related to stated references, usually national or international standards, through an unbroken chain of comparisons all having stated uncertainties.

NOTE:

1. The concept is often expressed by the adjective *traceable.*
2. The unbroken chain of comparisons is called a *traceability chain.*

Even though the ISO has published (and accepted) the definition listed above, many practitioners endeavor to make this term more meaningful. They feel that the definition should introduce the aspect of evidence being presented on a continuing basis, to overcome the idea that if valid traceability is achieved, it could last forever. A definition similar to the following one would meet that requirement.

Traceability is a characteristic of a calibration or a measurement. A traceable measurement or calibration is achieved only when each instrument and standard, in a hierarchy stretching back to the national (or international) standard was itself properly calibrated and the results properly documented including statements of uncertainty on a continuing basis. The documentation must provide the information needed to show that all the calibrations in the chain of calibrations were appropriately performed.

Transfer Standard [**6.8**]**:** A standard used as an intermediary to compare standards.

NOTE: The term *transfer device* should be used when the intermediary is not a standard.

Traveling Standard [**6.9**]**:** A standard, sometimes of special construction, intended for transport between locations.

EXAMPLE: A portable battery-operated cesium frequency standard.

Uncertainty of Measurement [**3.9**]**:** A parameter, associated with the result of a measurement, that characterizes the dispersion of the values that could reasonably be attributed to the measurand.

NOTES:

1. The parameter can be, for example, a standard deviation (or a given multiple of it), or the half-width of an interval having a stated level of confidence.
2. Uncertainty of measurement comprises, in general, many components. Some of these components can be evaluated from the statistical distribution of the results of series of measurements and can be characterized by experimental standard deviations. The other components, which can also be characterized by standard deviations, are evaluated from assumed probability distributions based on experience or other information.
3. It is understood that the result of the measurement is the best estimate of the value of the measurand, and that all components of uncertainty (including those arising from systematic effects) such as components associated with corrections and reference standards, contribute to the dispersion.

This definition is that of the *Guide to the Expression of Uncertainty in Measurement,* in which its rationale is detailed (see, in particular, 2.2.4 and annex D).[4]

Value (of a quantity) [**1.18**]**:** The magnitude of a particular quantity generally expressed as a unit of measurement multiplied by a number.

EXAMPLES:

- Length of a rod: 5.34 m or 534 cm
- Mass of a body: 0.152 kg or 152 g
- Amount of substance of a sample of water (H_2O): 0.012 mol or 12 mmol

NOTES:

1. The value of a quantity can be positive, negative, or zero.
2. The value of a quantity can be expressed in more than one way.

3. The values of quantities of dimension one are generally expressed as pure numbers.
4. A quantity that cannot be expressed as a unit of measurement multiplied by a number can be expressed by reference to a conventional reference scale or to a measurement procedure or both.

Working Standard [6.7]: A standard that is used routinely to calibrated or check material measures, measuring instruments or reference materials.

NOTES:

1. A working standard is usually calibrated against a *reference standard.*
2. A working standard used routinely to ensure that a measurement is being carried out correctly is called a *check standard.*

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