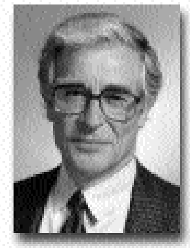
The Bureau International des Poids et Mesures: Establishing Standards in the Physical Sciences

by Ian Mills



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In a vault on the outskirts of Paris, a cylinder of platinum-iridium sits in a safe under three layers of glass. It is *the kilogram*, kept by the Bureau International des Poids et Mesures (BIPM), which is the international home of metrology. Metrology is the science of measurement, and it is of fundamental importance to us all. It is essential for trade, commerce, navigation, transport, communication, surveying, engineering, and construction. It is essential for medical diagnosis and treatment, health and safety, food and consumer protection, and for preserving the environment—e.g., measuring ozone in the atmosphere. Many of these applications are of particular relevance to chemistry and thus to IUPAC. In all these activities we need to make measurements reliably—to an appropriate and known level of uncertainty. The financial implications of metrology are enormous. In the United States, for example, some 15% of the gross domestic product is spent on healthcare, involving reliable quantitative measurements for both diagnosis and treatment.

BIPM is headquartered in the Pavillon de Breteuil, a historic and beautiful chateau overlooking the Seine at Sèvres, on the outskirts of Paris. Surrounding the chateau is a number of laboratories in which the world's measurement standards are maintained and researched, and in which results are collated between the National Metrology Institutes of the world. BIPM recently opened a new chemical laboratory, which specializes in the chemistry of the atmosphere.

The Convention of the Metre

The metric system was born at the time of the French revolution. At that time a Commission on Metrication was established (of which the mathematician Joseph Lagrange was the president and the chemist Antoine Lavoisier was a member) to consider the best way to define the base units. The commission recommended definitions for the metre as 10^{-7} of the distance from the pole to the equator, and the kilogram as the mass of a cubic decimetre of water at 4 °C. Two members of the commission were entrusted to "realize" the definition of the metre by measuring the distance from the pole to the equator. This they did, but it took them five years and led them through many adventures. By climbing church towers and measuring the angle to neighboring towers (with revolutionary battles taking place beneath them) and then walking on to the next tower, they surveyed and determined the distance over the ground from Dunkirk to Barcelona. Dunkirk is due north of Barcelona, and from the latitude of each city determined astronomically, they were then able to scale up this distance to obtain the arc distance from the pole to the equator. They returned with a metre stick, which they claimed was "according to the definition." The definition was never realized a second time!

The Bureau International des Poids et Mesures at Pavillon de Breteuil, Paris, France.

The definition of the kilogram as the mass of a cubic decimetre of water was easier to realize, but proved difficult to measure reproducibly, with accuracy comparable to that of comparing masses using a balance. Thus, neither of these definitions proved satisfactory.

In 1875, the government of France invited every technologically advanced nation to send representatives to Paris to establish and to sign the Metre Convention, which is now the basis of our internationally agreed upon standards of measurement. The French government then presented the Pavillon de Breteuil, with the small park that surrounds it, as international land with the status of an embassy, for the use of the BIPM. In the years that followed, the kilogram and the metre were redefined in terms of platinum-iridium prototypes, which were kept at BIPM. Copies of these were distributed around the world. Thus the first lesson of establishing a standard was learned: it must be easy to reproduce, with an accuracy comparable to that with which the quantity can be measured.

There are now 51 countries that are signatories to the Convention of the Metre. They support and govern the BIPM through the Conférence Générale des Poids et Mesures, held once every four years. They appoint the Comité International des Poids et Mesures, the International Committee, which meets regularly to supervise the operation of the BIPM, and to appoint the Director—presently Dr. Terry Quinn from England. The International Committee also takes advice from 10 Consultative Committees with expertise in the various specialized fields. Members of the Consultative Committees are drawn from metrology institutes around the world, and the Consultative Committee for Units (CCU), in particular, has representatives from most of the international unions such as IUPAC. CCU is responsible for advising the International Committee on changes and developments to be made to the International System of Units (SI), and particularly on choosing the standards that define the base units of the SI.

Defining Our Units in Terms of Fundamental Physical Constants

The definitions of the base units are continually in need of revision as we develop more precise methods of measurement. The kilogram is, today, the only base unit still defined in terms of a material artifact. We now strive to define units in terms of fundamental constants or the properties of atoms, which—as an act of faith—we believe to be invariant. Thus, for example, the metre, defined in 1889 as the distance between two scratches on the prototype metre stick, was redefined in 1960 to be a multiple of the wavelength of the red krypton atomic line. This change was made because it was found that distances could be measured interferometrically in terms of the atomic wavelength more accurately and reproducibly than the distance between the scratches on the prototype stick could be measured. Similarly, the base unit of time,

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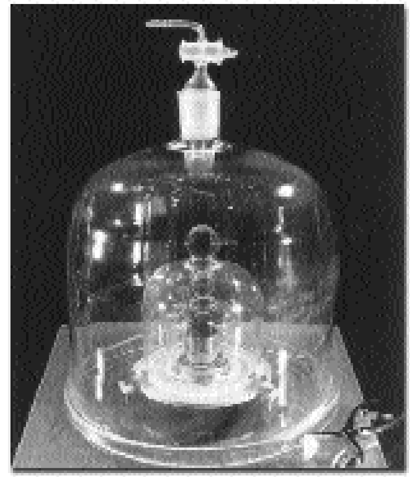
the second, used to be defined as 1/86,400 of the mean solar day. But even in the 19th century it was known that the rotation of the earth was slowing down due to tidal friction, and when quartz clocks and then atomic clocks were developed, other irregularities in the rotation of the earth were discovered. Thus, in 1967 the second was redefined as the duration of 9,192,631,770 periods of the hyperfine transition in the caesium atom. This was both more stable and easier to realize than the earlier definition, and it can be realized with much higher precision using an atomic clock. Finally, the metre was redefined again in 1983 to be the distance that light travels in 1/299,792,458 of a second, for exactly similar reasons.



The kilogram, kept by the Bureau International des Poids et Mesures.

Each of these changes was made because the precision with which we could make the measurements became greater than the precision with which we could realize, or make use of, the previous definition. Today, we choose definitions based on fundamental physical constants and atomic properties because they provide more stable and universally available standards. They may also generally be measured relatively easily and with high precision. Each change of definition is chosen to maintain unchanged the previous value of the standard, to the accuracy with which it had previously been known.

It is important to note that the effect of each new definition is to set a fixed value for some relevant constant. Thus, the present definition of the second sets the value of the frequency of the caesium transition to be exactly 9,192,631,770 Hertz, and the present definition of the metre sets the speed of light to be exactly 299,792,458 metres per second. The 1793 definition of the metre set the distance from the pole to the equator, but it is a definition that is difficult to realize! The 1889 definition of the metre set the distance between the scratches on the metre stick, and the 1960 definition set the wavelength of the red krypton line. The present definitions of the base units, and the general specification of the International System of units, is presented in the SI Brochure (*The SI Brochure*, 7th Edition, T.J. Quinn and I.M. Mills, BIPM 1998, ISBN 92-822-2154-7).

The present definition of the metre can be realized to approximately one part in 10^{12}, and the present definition of the second to approximately five parts in 10^{16}—which is equivalent to one second in 60 million years. You may well ask, what is the point? Why do we need all this precision? One answer is that you will never stop scientists from developing more accurate methods of measurement any more than you will stop men wishing to climb Mount Everest or travel to the moon. It then becomes necessary to develop standards that reflect the precision of our measurements. A more pragmatic answer is that more precise methods of measurement are invariably followed by new applications not previously foreseen. An example is the development of the global positioning system (GPS) based on signals from satellites. This is entirely dependent on the fact that each satellite carries an atomic clock, used to broadcast its position and time with the highest precision. From the difference between the time signals received by the observer, the differences between the distances from the satellites can be calculated, and from the known positions of the satellites the position of the observer can then be calculated.

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Although our ability to make more precise measurements has been advancing rapidly in the last hundred years, metrology is not a new subject. Many of the foremost 19th century physicists concerned themselves with this subject. James Clerk Maxwell wrote in 1870, “If, then, we wish to obtain standards of length, time, and mass which shall be absolutely permanent, we must seek them not in the dimensions, or the motion, or the mass of our planet, but in the wavelength, the period of vibration, and the absolute mass of these imperishable and unalterable and perfectly similar molecules.” Today we accept the truth of this statement, but in making it Maxwell showed great foresight, because at that time we had not yet developed methods of measuring the wavelengths, frequencies, and masses of the atoms!

Tomorrow’s Kilogram

Today, the race is on to find an acceptable new definition of the kilogram. This is because we know that the prototype kilogram can change in mass at the level of a few parts in 10^8, due to surface chemistry and wear and tear, over a period of months. However, we can actually weigh the kilogram (i.e., compare the mass of two kilogram artifacts) with a precision of better than one part in 10^{11} using the best modern balances. A possible new definition would be to say that the kilogram is the mass of a specified number of carbon-12 atoms, which would set the value of the Avogadro constant. However, at present we cannot quite realize this definition (i.e., weigh the carbon atom, or determine the Avogadro constant) with the necessary accuracy. The present best estimate of the Avogadro constant is uncertain to about one part in 10^7, but this is obtained indirectly from other fundamental constants. Direct measurements are based on the silicon crystal density method, in which the spacing of the atoms in a single crystal sphere of silicon is determined by X-ray interferometry, and the mass and volume of the sphere is measured, so that the number of atoms in the sphere may be calculated. The uncertainty in the Avogadro constant needs to be reduced by at least one order of magnitude, and preferably two, before we adopt an atomic mass as the definition of the kilogram. There is also a possible electrical definition of the kilogram that may prove to be preferable, realized by a Watt balance, in which a mass is balanced against the force on a coil in a magnetic field, so that an electrical energy is balanced against a mechanical energy. The decision on a new definition of the kilogram will probably be made sometime in the next 10 years. The present best estimates of all the fundamental constants, and further information on this subject, may be found in the paper by Mohr and Taylor (P.J. Mohr and B.N. Taylor, *J. Phys. Chem. Ref. Data* **28**, pp. 1715-1852 [1999]).

In 1992, I was appointed to be the IUPAC representative on the CCU, and in 1995 I was appointed President of the CCU. It is a job that I find fascinating—meeting and discussing with some of the world’s best scientists and evaluating the latest experiments that improve our ability to make measurements. The results impact upon every activity of IUPAC, most particularly on the importance of making valid estimates of the uncertainty in the measurements upon which we all depend. Another aspect of the work is its international nature: the need for us all to speak the same language of science so that we understand one another without ambiguity and use internationally agreed upon names and symbols for the quantities and units involved. Like many of the activities of the BIPM, these are also problems that are close to the heart of IUPAC’s existence, so that IUPAC and the BIPM have strong common interests.

Ian Mills has been the IUPAC Representative on BIMP since 1996. He is a professor at the University of Reading, UK.

http://www.bipm.org