Replace Kilogram Artifact Now With Definition Based on Nature, Experts Say

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It’s time to replace the 115-year-old kilogram artifact as the world's official standard for mass, even though experiments generally thought necessary to achieve this goal have not yet reached their targeted level of precision, according to an upcoming Metrologia journal article* authored by five eminent scientists from the United States, United Kingdom and France that is being discussed during a scientific meeting** beginning at the Royal Society of London.

The authors of this Metrologia paper suggest replacing the kilogram artifact—a cylinder of platinum-iridium alloy about the size of a plum—with a definition based on one of two unchanging natural phenomena, either a quantity of light or the mass of a fixed number of atoms.

The five authors, including three from the U.S. National Institute of Standards and Technology (NIST), one from the University of Reading in the United Kingdom, and a former director of the Bureau International des Poids et Mesures (BIPM) near Paris, conclude that redefining the kilogram now in terms of an invariable property of nature rather than a material object could immediately have many benefits. For instance, it would improve the precision of certain electrical measurements 50-fold and would enable physicists to make more precise calculations in studying the fundamental quantum properties of atoms and other basic particles. The paper outlines how this could be accomplished without impairing the current international system of mass measurements.

This paper reflects the authors' collective opinion rather than the official policy positions of their respective institutions. The proposal is intended to provoke discussion of what is expected to be a controversial issue, the authors say. Any decision about when and how to redefine the kilogram can be made only by an international group, the International Committee for Weights and Measures, and finally ratified by a General Conference on Weights and Measures, which meets every four years. The next meeting of the General Conference will be held in October 2007 in Paris.

The kilogram is the only one of the seven basic units of the international measurement system defined by a physical artifact rather than a natural phenomenon. The meter, for example, is defined as the distance light travels in a vacuum during one 299,792,458th of a second, and the second is defined in terms of the natural oscillations of the cesium atom. Even though the kilogram cylinder is housed in a special vault under controlled conditions at the BIPM, its mass can drift slightly over the years and it is subject to changes in mass because of contamination, material loss from surface cleaning, or other effects. A property of nature is, by definition, always the same and can in theory be measured anywhere, whereas the kilogram is accessible only at BIPM and could be damaged or destroyed.

For the last 25 years, a small international group of measurement specialists has been conducting laboratory experiments to find a definition based in nature to represent the kilogram. Conventional wisdom in the field has held that any new definition for the kilogram should not be implemented until it could be measured with the same or better accuracy than the current kilogram mass artifact.

Even though no research group has yet met this goal, the authors of the Metrologia paper argue that the time is, nevertheless, ripe for a redefinition. Due to the complex interrelationships of the kilogram with other basic measuring units, they found that for the great majority of scientific applications the benefits of using unchanging natural phenomena to define the kilogram far outweigh any drawbacks of slightly greater uncertainty in mass measurements. They propose retaining the kilogram artifact, for the time being, as the working reference for the highly precise comparisons to individual countries' national kilogram standards.

“We did not think this would be our recommendation when we started writing the paper,” says Ed Williams, one of three NIST authors. “This started out as a study of the effects of redefining the kilogram. During the research, the more we discussed it, the more we thought it made sense to redefine the kilogram now. It should obviously be redefined; the question is whether it should be done in the near future or 10 or more years from now."

Other authors of the paper include Terry Quinn, emeritus director of BIPM and Ian Mills of the University of Reading in the United Kingdom, who chairs the committee that would make any recommendation to the International Committee regarding the proposal. The additional NIST authors, Peter Mohr and Barry Taylor, recently headed an international effort to determine the best values for the fundamental physical constants consistent with measurements and theory. The fundamental constants are an extensive set of invariable quantities, such as the charge of the electron, which scientists use to predict a very wide range of phenomena.

** I.M. Mills, P.J. Mohr, T.J. Quinn, B. Taylor, E. Williams, "Redefinition of the kilogram: A decision whose time has come," Metrologia, expected online publication, Feb. 2005.*

** *Discussion meeting on: "Fundamental Constants of Physics, Precision Measurements, and the Base Units of the SI."*

Background Information on the Proposal
The new paper proposes that the next General Conference on Weights and Measures adopt either one of two definitions for the kilogram to effectively fix its value by selecting a specific value for either the Planck constant or the Avogadro constant. Two types of experiments are leading the effort to realize either of these definitions. The first one measures a kilogram against the amount of magnetic force required to balance a 1-kilogram mass against the pull of Earth's gravity. The experimental apparatus used to make the measurement is called a watt balance. A kilogram mass is placed on a balance plate that is surrounded by a coil of copper wire, which in turn is surrounded by a coil of superconducting wire. Magnetic fields produced by sending electricity through the coils push on the balance plate to offset the artifact's weight. The amount of electric current and its voltage then is used in defining a kilogram. Electrical power can be related to the Planck constant, defined as the ratio between the frequency of an electromagnetic particle such as a photon of light and its energy. This experimental method of defining the kilogram relies on selecting a fixed value for the Planck constant, which is currently determined experimentally based on the fixed value of the kilogram artifact.

The second proposed way to re-define the kilogram involves counting the number of atoms of a specific atomic mass that equal the mass of 1 kilogram. This method involves using X-rays to measure the spacing between atoms in a perfect crystal to estimate the volume of each atom, and measuring the density of the crystal and weight of the atoms, to arrive at a number of atoms equivalent to 1 kilogram. This experimental method for defining the kilogram depends on selecting a fixed value for the Avogadro constant, which describes the number of atoms or molecules in a specified amount of a substance.

Either method for redefining the kilogram would have positive ripple effects on many other physical constants such as the charge and mass of the electron. The specifics would depend on which definition is chosen. Either way, the uncertainties of some constants would be reduced to 0, while others would be reduced by factors ranging from about 7 to over 1,300, according to the paper.

Physical constants are used by scientists and engineers to make innumerable types of calculations, and also are used in designing and calibrating quantum-based measurement systems. Such systems are becoming more important in technology development and the growth of trade that relies increasingly on electronic testing, quality control and environmental monitoring. Reduced uncertainty in the values of many quantum-based constants also may stimulate new experimental and theoretical work aimed at testing fundamental theories of physics.

The last time a base unit of the SI was redefined was in 1983, when the meter was formally redefined in terms of a new value for the speed of light. In this case, the scientific community decided to fix the value for a physical constant—the speed of light—at a specific value so that length measurements could be made with greater precision. The speed of light is equal to the wavelength multiplied by its frequency. The meter previously was defined by wavelength only; the new definition was made possible by more precise frequency measurements. By redefining the meter to equal the distance light travels in a vacuum in a specific time, scientists were able to determine distance by measuring time and frequency, the two quantities of nature that can be measured experimentally with the greatest precision.

In a similar way, redefinition of the kilogram by assigning a specific value to the Planck constant or to the Avogadro constant will allow scientists to make mass calculations for a wide range of quantum physics problems much more precisely than previously possible.

The authors stress that regardless of which redefinition of the kilogram is chosen, efforts should continue to reduce the measurement uncertainty of both the watt balance and X-ray crystal experiments. Currently, both methods are 10 to 100 times less precise than the measurement uncertainty produced when comparing the kilogram artifact to national standards. What's more, the results of the two approaches disagree by nearly 1 part per million. Eventually, when uncertainties of experiments with the watt balance or X-ray crystal density method reach a sufficiently low level, the cylinder artifact would no longer be needed.

Source: NIST

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