Defining a kilogram

by

Vinatha Viswanathan

Earlier this year, scientists from Canada declared that they were a step closer to redefining the kilogram. What did they mean? Why does the kilogram need to be redefined? What was wrong with the old kilogram?

The problem with the old kilogram was that it had changed. Over 25 years ago metrologists[1] in Paris found that this unit of mass had gotten lighter. Let us see how this came to be.

The kilogram or kilo is almost exactly equal to the mass of one litre of water. However, it is defined by a platinum-iridium cylinder 39 millimetres (approximately four centimetres) in height and diameter, cast in 1889. This is the International Prototype Kilogram and is the single existing reference for the definition of a kilogram.

The 90% platinum-10% iridium alloy was chosen for its high density (and low surface area) and inertness, making it less prone to contamination and corrosion. To protect it from any damage, it is kept locked in a high security safe at the *Bureau International des Poids et Mesures* in Paris. Any change in the prototype and all the weights across the world instantly turn wrong.

The prototype has several official copies all over the world. Every 40 years or so these copies are brought to Paris and their mass is compared to that of the prototype. In 1992, after one such process of verification, scientists said that the copies weighed more than the prototype. It was difficult to tell whether the prototype had decreased in mass or whether the copies had gained mass, or both. Despite several precautions, for reasons unknown, the prototype had gotten relatively lighter….by 20 millionths of a gram, less than even a grain of salt.

To you and me, this sounds like a trivial change in mass. It can be important as any change in the definition of mass will be carried over to all quantities and units derived from mass. The main issue however, was that the kilogram had exhibited a capacity to change and was therefore the only SI unit (as per the International System of Units) that lacked an essential trait of any standard unit – precision or consistency in measurement.

[1] Those working in the field of metrology, the science of measurement.

Also, since by definition the mass of the prototype is always one kilogram, no one can ever measure any change in or error in its mass.

Over the years, other SI units have been redefined using fundamental constants. This means that they are now described by measures that are universal in nature as well as precise and constant in time. For example, in 1983 the metre (based on a length of platinum-iridium stored in Paris) was redefined as the distance travelled by light in 1/299,792,458 of a second. The speed of light is a fundamental constant of nature. A second was redefined in 1967 as the time required by a Cesium-133 atom to perform 9,192,631,770 complete oscillations at a temperature of 0 Kelvin.

The definitions were changed by the General Conference on Weights and Measures (CGPM) which has members from countries all over the world. However, the kilogram continued to be defined by a man-made artefact.

Till 1992. Since then, there has been an effort to find a better definition for the kilogram. In general, the idea has been to relate a reference kilogram (the existing prototype) to a fundamental constant of nature that can be measured with a high degree of accuracy anywhere in the world. The kilogram can then be expressed in terms of that constant.

The chemistry approach has focused on the finding the mass of one atom of Silicon, a constant. Researchers in Germany have working towards this by using perfectly rounded, one kilogram balls of pure Silicon. With accurate estimates of the distance between atoms in a Silicon crystal, and the exact size of this Silicon ball, they hope to estimate the number of atoms in it (and the mass of one Silicon atom). The kilogram can then be expressed in terms of the mass of a Silicon atom. This research was originally begun to estimate the Avogadro constant and its potential to redefine the kilogram was later recognized. However, producing a perfectly rounded ball of high purity Silicon is challenging. Counting with accuracy the large number of atoms in this ball can also be very difficult.

The watt balance has been the basis for the other approach, the physics approach. Originally developed to measure mass in terms of electromagnetic force (in watts), it is now being used to measure, with as little uncertainty as possible, Planck's constant [this is a very small value: $6.62 \times 10^{-34}\ m^2kg/s^2$]. The mass of a reference kilogram too can be measured in watts. The kilogram can then be related to and expressed in terms of Planck's constant. Support for this approach came in October last year when the CGPM agreed that the kilogram will be redefined in terms of the Planck's constant.

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[2] SI symbols for metre, kilogram and second are 'm', 'kg' and 's'

However, the chemistry approach has not been abandoned. It is being used to verify results from the physics approach. This is possible as the Avogadro constant is directly related to Planck's constant.

In February this year, Canadian metrologists published values of the Avogadro constant based on the most accurate measurements of the atomic weight of Silicon to date. The value of the Avogadro constant from this method is also very close to the previous estimate of this constant. This means that the figure for the Avogadro constant is becoming more accurate and consistent (precise) with each study. Refinements to the watt balance have also meant that Planck's constant is being measured with less error. The difference in the values between the figures for Planck's constant from the chemistry and physics approach is getting smaller. The final step towards redefining the kilogram will require international agreement, a consensus on the value of Planck's constant and the acceptable level of uncertainty around it.

Till then, the little cylinder securely stored sixty feet under the ground in Paris will continue to define the kilogram for us.