The Kilogram is no Longer a Kilogram!

The ‘kilogram’ is being redefined. Read on to find out more.

In the International System of Units, which is used all over the globe, the base unit of mass is the kilogram. It is defined as the mass of an object known as the International Prototype Kilogram (IPK), which is carefully preserved since 1889 at the International Bureau for Weights and Measures (BIPM in French) in France. All the mass standards around the world are calibrated from time to time against this base standard to ensure worldwide uniformity of measurements.

The IPK, colloquially known as the ‘Le Grand K’, is an alloy of 90% platinum and 10% iridium, machined into a right circular cylinder of 39.17 mm diameter and equal height. The alloy is extremely hard, of high density (21 times that of water), resistant to oxidation and a good thermal and electrical conductor. It has been preserved in an environmentally safe condition enclosed under three bell jars. Three independently controlled keys are required to take it out!

A subset, known as the “official copies” of the IPK, has also been produced and stored under similar conditions. In addition, dozens of replicas have been made available to different countries to serve as their national standard. India has one such standard, kept at the CSIR-National Physical Laboratory (CSIR-NPL), a constituent of the Council of Scientific and Industrial Research (CSIR), New Delhi.

One of the most important requirements of a base standard is that it remains stable over time. To check its stability, once every few decades scientists clean it by rubbing lightly with a soft leather cloth soaked in equal parts of ether and ethanol, followed by steam cleaning with distilled water. Then it is put in a precise balance known as a comparator to compare its mass with the Bureau’s official copies, which are cleaned the same way. These official copies, in turn are compared with national standards. Thus, the IPK’s mass trickles down to set the standards of mass for the rest of the world. This has been done on three occasions – 1889, 1946 and 1989.

While it was expected that there would be no difference between the mass of the IPK and its official copies, scientists were surprised to see a drift in the mass of the official copies relative to the IPK. Majority of them showed an increase in their mass with respect to the IPK over the past one hundred years.

What causes this drift in mass? Though IPK and each of its official copies have been stored in three nested bell jars, they are not airtight. Hence, they may gain mass through adsorption of atmospheric contamination on to their surface, oxidation, sloughing of atoms from the surface and so on. It has been found that the cleaning process by itself is not the source of mass divergence. Thus, metrologists are not sure what is causing this.

It is not clear from these measurements whether the IPK is losing mass or the official copies are gaining mass. A distinct possibility is that all the prototypes might have gained weight over the past one hundred years and the two of them, including the IPK, might have gained less than the others. The overall picture is that in a relative sense the IPK has lost about 50 micrograms.

Traceability

The National Physical Laboratory, New Delhi is the standards laboratory in India. It maintains standards of all the SI Units. The national standard of mass – the kilogram – is copy number 57 of the International Prototype Kilogram (IPK) supplied by the International Bureau of Weights and Measures (BIPM), France. In the present system, the national standard is recalibrated from time to time against the IPK at the BIPM and the offset value noted.

All the weights used in the country are traceable to this national standard. This is achieved by a chain of laboratories across the country. First, Regional Reference Laboratories have been established at four places – Ahmedabad, Bangalore, Bhubaneshwar and Faridabad. The reference standards in these laboratories are periodically checked against the national standard. In the next stage, every State or Union Territory has a Secondary Standard Laboratory, which maintains secondary standard, which, in turn, is verified against the reference standard at the corresponding Regional Reference Laboratory. In the third stage, working standards, calibrated against the secondary standard, are produced. They are used by inspectors to verify and stamp the weights possessed by individual traders. Through this chain every weight can be traced back to the national standard and through it to the international standard.
Implications

Scientists who have measured the IPK and its official copies say the difference in mass among them is less than that of a grain of sand! Then, what is all the fuss about, one may ask. Yes. It will not have any effect on day-to-day measurements. A kilogram of potatoes will still be a kilogram. However, for scientists, who carry out precise measurements it is a big deal. For, they measure time in sub-nanoseconds, length in sub-nanometers and so measurement of mass must match that precision. That can be achieved by redefining kilogram on the basis of an invariant parameter rather than on a man-made artifact like IPK.

The International System of Units has seven base units. The definition of all, except that of the kilogram, are based on some fundamental constants of nature, which are invariant. The last one to be redefined was the unit of length – the meter. Earlier, like kilogram, the meter was based on a man-made artifact. It was defined as the distance between two marks on a platinum rod. In 1983, it was redefined in terms of the speed of light. Accordingly, meter is defined as the distance in vacuum, traveled by light in 1/299,792,458 seconds – a tiny fraction of time indeed!

Since the speed of light in vacuum is a fundamental constant (and measurement of time is based on another fundamental constant) the standard of length does not change with time. By thus linking the definition of base units to the fundamental constants of nature, scientists have been able to develop GPS satellites, gravity-wave detectors and may other precision technologies that would not have been possible otherwise.

There are other compelling reasons for redefining the kilogram on the basis of a fundamental constant of nature. The definitions of a number of other SI Units are directly or indirectly dependent on the stability of the kilogram. For example, ‘newton’ is defined as the amount of force necessary to accelerate a mass of one kilogram at one meter per second square. Any instability in the kilogram will proportionately destabilize the newton. The SI unit of pressure ‘pascal’ and ‘joule’ the SI Unit of energy are defined in terms of newton.

In the measurement of electricity, the unit of power ‘watt’ and of current ‘ampere’, the unit of luminosity ‘candela’ all indirectly involve the kilogram. With these base units affected, so are the derived units like the coulomb, volt, tesla, weber, lumen and lux. Thus redefining the kilogram would not only put the unit of mass on a firm scientific basis, but also stabilize many other SI Units.

The International Committee on Weights and Measures recommended in 2005 that the kilogram be redefined on the basis of a fundamental constant. While the new definition will liberate the kilogram’s dependence on IPK, it will have some requirements. For example, it must aid the development of a practical realization of the kilogram that can be reproduced in different laboratories around the world following a written specification. The units of measure in such a practical realization should also be based on some fundamental physical constant and should be known with an accuracy of 20ppb.

With these requirements in view, several new definitions have been proposed. Two fundamental constants that have been considered are Avogadro constant and Planck constant.

### Base International System (SI) of Units

According to the BIPM, "The International system of Units is a set of units of measurement comprising of both base and derived units. The base units are a choice of well-defined units, which by convention are regarded as dimensionally independent. Derived units are those formed by combining base units according to algebraic relations linking the corresponding quantities." The seven base units defined by the BIPM are:

| Unit of length | meter | The meter is the length of the path travelled by light in vacuum during a time interval of 1/299 792 458 of a second. |
| Unit of mass | kilogram | The kilogram is the unit of mass; it is equal to the mass of the international prototype of the kilogram. |
| Unit of time | second | The second is the duration of 9 192 631 770 periods of the radiation corresponding to the transition between the two hyperfine levels of the ground state of the cesium 133 atom. |
| Unit of electric current | ampere | The ampere is that constant current which, if current maintained in two straight parallel conductors of infinite length, of negligible circular cross-section, and placed 1 meter apart in vacuum, would produce between these conductors a force equal to 2 x 10^-7 newton per meter of length. |
| Unit of thermodynamic temperature | kelvin | The kelvin, unit of thermodynamic is the fraction 1/273.16 of the thermodynamic temperature temperature of the triple point of water. |
| Unit of amount | mole | 1. The mole is the amount of substance of a of substance system that contains as many elementary entities as there are atoms in 0.012 kilogram of carbon 12; its symbol is “mol.” 2. When the mole is used, the elementary entities must be specified and may be atoms, molecules, ions, electrons, other particles, or specified groups of such particles. |
| Unit of luminous intensity | candela | The candela is the luminous intensity, in a given direction, of a source that emits monochromatic radiation of frequency 540 x 10^12 hertz and that has a radiant intensity in that direction of 1/683 watt per steradian. |
Planck constant (h) links the energy (E) of light photons to their frequency (ν) by the famous formula $E=\hbar \nu$. Since energy could be linked to mass through Einstein’s famous formula $E=mc^2$, and Planck constant is linked to energy, it would be possible to define the kilogram in terms of Planck constant. Considering all these aspects, The General Conference on Weights and Measures in its 24th Meeting in October 2011 agreed in principle to redefine the kilogram in terms of Planck constant.

**The Watt Balance**

Both the National Physical Laboratory, UK and the National Institute of Standards Technology, USA have developed an equipment known as ‘watt balance’, capable of delineating kilogram in terms of Planck constant. Rather than weighing one mass against another, such a balance weighs an object against the amount of electromagnetic force needed to balance the object against gravitational pull.

According to the Dr. B.P. Kibble of NPL, the experiment is conducted in two parts in watt balance – the weighing experiment and the moving experiment. In the weighing experiment a mass (it could be IPK itself) and a coil are suspended from the balance. The coil is placed in a magnetic field and the gravitational force on the mass is balanced by an equal and opposite electromagnetic force by sending a current through the coil.

In the moving experiment, the coil is moved at a vertical speed $v$ through the magnetic field so that a voltage $U$ is induced.

$$Mg = IBL$$

$$F_n = mg$$

$$I = B/L$$

$$U = BLV$$

In the weighing experiment, a mass and a coil are suspended from a balance. The coil (wire length $L$) is placed in a magnetic field of flux density $B$. The gravitational force on the mass $m$ is balanced by an equal and opposite electromagnetic force on the coil by sending a current $I$ through it.

In the moving experiment the coil is moved at a vertical speed $v$ through the magnetic field so that a voltage $U$ is induced.

The final decision on redefinition of kilogram will be taken in the next meeting of the General Conference of Weights and Measures scheduled for 2014. Once agreed upon, the kilogram will no longer be the mass of IPK, but the electrical power necessary to counter the mechanical power caused by the oscillation of a test mass against local gravitational acceleration. It will be defined in a manner that is directly traceable to the fundamental constants of nature – the Planck constant.

The dissemination of kilogram will no longer depend upon the stability of the kilogram prototypes. Instead, close approximation to mass standards would simply be weighed and documented as being equal to one kilogram plus/minus some offset value.

The watt balance has not yet achieved the required accuracy of 20 ppb. In addition, every aspect of it requires state-of-the-art technology, which only very few countries can afford. Hence, after the redefinition takes place, the BIPM will operate a watt balance to provide a realization of the new definition of the kilogram for the national metrology institutes of each member country.

It is not just the kilogram, but other units like the ampere, the mole and the kelvin are also likely to be redefined in the coming years.