Kilogram is History: Long Live the Kilogram

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0 May 2019 will remain etched in the annals of metrology (the science of measurement) in human history. On this historic day, which also happened to be the “World Metrology Day”, one of the most commonly used measurements for weights, the Kilogram (Kg) — the unit of the International System of Units (SI), which was defined on a material artefact — was redefined with a new measurement, which will be more precise and scientific than what we have been using for more than a century.

The change in the definition of the Kilogram will result in uniform and worldwide accessible measurement of weight for international trade, high-technology manufacturing, human health and safety, protection of the environment, global climate studies and the basic sciences underpinning these issues. The redefined Kilogram will be more stable in the long term, internally self-consistent and practically realisable, since it will be based on the present theoretical description of nature at the highest level.

**Historic Resolution at the CGPM**

Time measured in Seconds and Length, measured in Metres, two of the three most commonly used SI units, were changed earlier for a more precise measurement that depended on fundamental forces of nature. The measurement of time in seconds, which was earlier defined in terms of the swings of a pendulum clock, was redefined as the time it takes an atom of Cesium 133 to go through 9,192,631,770 cycles of releasing microwave radiation.

The measurement of length in Metres, which was earlier based on material object, was changed and redefined as the distance the light travels in 1/299,792,458th of a second. With the definition of the two of the three most commonly used SI units (Second and Metre) changed, the need for a change in the definition of the Kilogram was gaining momentum.

The genesis for this change was shaped by the International Bureau of Weights and Measures (BIPM) during their General Conference on Weights and Measures (CGPM). In its 26th meeting held during 13-16 November 2018 at Palais des Congrés, Versailles, France, most participating countries including India (represented by Shri Avinash K. Srivastava, Secretary, Department of Consumer Affairs, Government of India and Dr D.K. Aswal, Director, CSIR-National Physical Laboratory, New Delhi) voted for a resolution agreeing on the most significant revisions to the definition of the Kilogram.

CGPM, which comprises 60 countries including India and 42 other Associate Members, is the highest international body of the world that has the responsibility of defining the International System of Units (SI). Majority of the members, during the 26th extraordinary CGPM meeting, voted for the redefinition of the more than a century old Kilogram, “Le grand K – the SI unit of Kg” in terms of the fundamental Planck’s constant (h) and proclaimed that the new definitions will come into force on 20 May 2019.

This revision of the SI unit is the culmination of many years of intensive scientific cooperation between the National Metrology Institutes, including our CSIR-National Physical Laboratory, New Delhi, and the International Bureau of Weights and Measures (BIPM).

**Measurements Integral to Society**

Measurements are integral to the human way of life. Since time immemorial human society has been measuring things – how long, how heavy, how fast and so on – primarily because we need units of measurements for activities such as trade and commerce and so also for advancing of our worldly knowledge.

The challenge, however, has been getting an exactitude of standard measurements that ensures that all measurements – mine, yours and others – are precisely the very same. This is all the more a necessity because almost every one of us trusts the standards of measurements and takes what is displayed on our measuring instruments and devices for granted and always considers that a second is a second, Metre a Metre and Kilogram a Kilogram. For most of human history, however, measures of time, length and mass have been arbitrary, mostly defined according to the whims of local customs or rulers.

**Measurements in Ancient India**

Metrology, or the study of units of weights and measures, has a long history and has reference across civilisations including our very own Indus. The first systematic study of some kind of standardisation in weights and measures of the Indus period was undertaken by A.S. Hemmy (1931) on the basis of archaeological evidence from the cubical objects – chert and other stones – which were discovered from the Harappa site.

The use of standard measures during the Harappa times is now better understood courtesy scholarly research from experts in this field, which include among others Michel Danino, Kenoyer, and Balasubramaniam who have shown that there has been a continuing tradition of the use of standards in the measurements of length called *angula*, which span centuries stretching from the Harappa times right until the majestic Taj Mahal construction. Although there seem to have been some kind of standardised measurements of length in India, there has been no authoritative decree on the standardisation of measurements.

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Cubical weights from Harappa
(Courtesy: Harappa.com)

**Need for Standard Measurement**

One of the earliest recorded documents that reveal decrees that national measurements must be standardised came in 1215 AD, from the Magna Carta. Clause 35 of the Magna Carta proclaimed standard weights and measures for grain, wine, beer and cloth.

Due to years of unsuccessful foreign policies and heavy taxation demands, England’s King John was facing a possible rebellion by the country’s powerful barons. It was under duress that King John agreed to their demands for formulating a charter of liberties –
known as the Magna Carta (or Great Charter). This would place the King and all of England’s future royals within a rule of law. One of the clauses in this charter included some kind of a standard in measurements.

The commission recommended a new unit called a grave. This unit stems from the measurement of the mass of a litre of water at the ice point. This unit was adopted by the French Republic, with a few changes. Instead of a grave, they created a new standard, which they called the gramme, which became the unit Gram in English. The Gram was measured as an absolute mass of 1 cubic centimetre of water at 4 degrees Celsius, and a thousand grams were measured as a Kilogram.

Kilogram of the Archive
Although the French Republic had standardised the measurement of a gram, it was difficult for them to create a 1 gram artefact made of water. They had to work out a new practical idea to create a standard object, which was a precise measure of the gram they had just defined. This led to the creation of a solid metal artefact, which was a thousand times more massive than a gram, and was defined as a Kilogram.

Thus, two new standard measurements were introduced in France for the measurement of length in Metres and mass in Kilogram, both of which were defined on 22 June 1799, in Paris. The new Kilogram object was forged from platinum and was called the “Kilogram” and this object was stored in a building called Archives and thus the new object, representing a standard Kilogram, came to be known as the “Kilogram of the archives”. This new Kilogram remained a standard mass in France for almost a hundred years.

International Trade and BIPM
This was the time of the Industrial Revolution, which was led by the British, and as a result, the global economy started growing very rapidly in the 1800s. The ever-increasing growth in the economy led to multi-state trade and with this came the problems of different standards associated with the measurements. Until then each country had maintained its own standards, which were often incompatible with those of other countries. German mathematician Carl Friedrich Gauss advocated the idea of agreed global standards in measurements.

A major breakthrough in multi-state standardisation came when representatives of 17 States, during the final session of the Diplomatic Conference of the Metre, came together to create the International Bureau of Weights and Measures (BIPM), which was set up by the Metre Convention (Convention du Mètre) Treaty that was signed in Paris on 20 May 1875. The BIPM, one of the oldest international organisations located in Sèvres near Paris, acts as the custodian of the international prototypes of both the Metre and the Kilogram.

BIPM was formed to address the growing needs for reliable and uniform measurements in society, trade and industry. BIPM, which was the heart of the first international cooperation in the field of metrology, has been successfully expanding ever since. The BIPM activities are now central to the big challenges faced by today’s world, including climate change, health and energy sustainability. The BIPM carries out high-level scientific activities in the field of metrology and acts as a forum for its Member States.
The SI Units
The BIPM was responsible for the formation of the “International System of Units” universally abbreviated as SI (from the French Le Système International d’Unités), which became the modern metric system of measurement. The SI is a globally-agreed system of measurements, which has seven base units and a number of derived units defined in terms of the base units.

The SI units express measurements of any quantity, like physical size, temperature or time. This International System of Units is necessary to ensure that our everyday units of measurement, whether of a Metre or a Second, remain comparable and consistent worldwide. Being inaccurate by a fraction of a second might not matter for day to day activities but it does become very important in science and so also in competitive sports for determining who won the 100 metres at the Olympics, which is decided in 1/100th of a second.

Standardising measurements not only helps to keep them consistent and accurate but also helps society to build confidence. For instance, we use Kilogram in most items that we shop, including food items. So the precise definition of Kilogram helps consumers to trust that the shop is really providing the amount they say they are. This consistency is also relied on to ensure the correct dosage of medicine is taken, even when measurements are very small.

International Prototype Kilogram
The SI units defined the official unit of mass as the Kilogram and embodied it in a new metal artefact whose mass was essentially the same as the “Kilogram of the archives”. This new standard object was made from an alloy of platinum and iridium and was called the International Prototype Kilogram (IPK).

Ever since, the SI units have been predominantly used in science and this became the global dominant measurement system, which also made its way to international commerce. Copies of the IPK were sent to the countries which had signed the agreement. Subsequently, over 100 countries adopted the metric system of measurements, the SI units, which remains in vogue since 1889.

The alloy is extremely hard with high density (21 times heavier than water) and is resistant to oxidation and is also a good thermal and electrical conductor. The original IPK artefact has only been weighed three times before (1889, 1946 & 1989) against a number of near-identical copies. Most countries have an official copy of this object, which forms the standards for the measurement of the Kilogram in their respective countries.

Replicas of the IPK are made of the same material that is used at BIPM as reference or working standards and National Prototype of Kilogram (NPK), kept at different National Metrology Institutes (NMIs). India too based its measurement of the Kilogram on the IPK, an official NPK of which came to India in 1958 and is preserved at the CSIR-National Physical Laboratory, New Delhi.

National Prototype of Kilogram
The IPK artefact is carefully preserved – in two safes and three glass bell jars – since 1889 at the BIPM, in France. Three independently controlled keys are required to take it out. IPK is made of 90% platinum and 10% iridium and is machined into a right circular cylinder of 39.17 mm diameter and of equal height.

CSIR-National Physical Laboratory, in Delhi, is the custodian of the National Prototype of the Kilogram, copy No. 57 (NPK-57), which was provided by the BIPM in 1958 after its first calibration in 1955. The NPK-57 has been recalibrated in 1985, 1992, 2002 & 2012 so far at the BIPM. The NPK 57 has served as the primary standard for the uniform
measurements of weights (Kg) in India. The NPK-57 has successfully gone through the peer review in 2004 & 2008 and has been approved by the BIPM in 2011.

The IPK-metrology scientists started preparing to change the unit which was to be based on a constant that is nature dependent and not man-made.

It is interesting to note that the definitions of all the seven SI units, except that of the Kilogram, were based on some fundamental constants of nature and not based on an artefact object. The last measurement to be redefined was the unit of length, the Metre. Earlier, like the Kilogram, the measurement of the unit of length was based on a man-made object and was defined as the distance between two marks on a platinum rod. In 1983, the measurement of Metre was redefined in relation to the speed of light. Accordingly, the Metre is now defined as the distance in a vacuum, travelled by light in 1/299,792,458 seconds. Since both speed of light and also the second are based on natural universal constants, the Metre too will remain constant.

The IPK served mass metrology very well for more than 100 years, yet it had a number of disadvantages. Since the creation of the BIPM in 1875, three comparisons were carried out between the international prototype and its six official copies. The masses of the official copies were seen to increase relative to the original IPK at a rate of about 5 parts in 10^8 over 100 years. Despite exceedingly stringent storage conditions, scientists realised that the Kilogram gains weight from dust in the atmosphere. It was also estimated that the Kilogram gains about 50 micrograms every century, which compelled the scientists to redefine the basic metric unit of mass based on something that’s truly constant, similar to the measurement of the length in Metres.

Accordingly, in the year 2005, the International Committee on Weights and Measures recommended that the measurement of weight – the Kilogram – too needs to be redefined on the basis of some fundamental constant, which will help the measurement of the Kilogram liberate its dependence on IPK.

**Instability and IPK**

The IPK, which formed the world standards for measurement of the Kilogram, was mandated to remain stable over time, but that was not to be, notwithstanding the highest levels of climatic controlled conditions in which the original IPK has been stored. Over the decades scientists were surprised to see a drift in the mass of the official copies of weights relative to the original IPK.

Majority of the official copies of the IPK showed an increase in their mass with respect to the original IPK. This necessitated a rethinking among the scientists to redefine the Kilogram. Thus after more than 100 years of defining the Kilogram, according to a metal artefact, the scientists observed that the Kilogram could be linked to different fundamental constants or atomic masses and two approaches could be used for this. The most obvious approach was to compare the mass of a known object and a very large number of atoms of the same type with a macroscopic mass. This would establish the Kilogram as a known multiple of an atomic mass, which is
equivalent to a determination of the Avogadro constant if the molar mass of the atoms is known. This method came to be known as Avogadro’s project.

The project uses a pure Silicon-28 sphere, which has to be polished really well. The Silicon-28 sphere is now known as the world’s roundest object. Using this specially polished sphere, scientists can use X-ray crystallography and optical interferometry techniques to determine the structure of the sphere and spacing pattern and widths with great precision.

From this, the scientists can count the number of atoms in the sphere that weighs the same as the reference Kilogram and obtain an Avogadro’s constant. This can then be converted to Planck’s constant with low uncertainty. However, this is a very costly affair and the silicon sphere costs roughly 100 million rupees each.

Kibble Balance

However, it was soon observed that there is another class of electro-mechanical technique, which linked the Kilogram to the Planck constant \( h \). The most successful method, which uses the electro-mechanical technique for the Planck constant, is the Watt Balance.

Watt Balance compares the measurement of electrical and mechanical power. The electrical quantities are measured based on macroscopic quantum effects, the Josephson Effect and the quantum Hall Effect. These two effects link the electrical quantities to fundamental constants and allow one to establish a relation between a macroscopic mass, measured in the unit Kilogram, and the Planck constant \( h \).

The Planck constant describes how the tiniest bits of matter release energy in discrete steps or chunks called quanta. And from this fixed value of the Planck constant, scientists can derive the standard mass of a Kilogram. Redefining the Kilogram in terms of the Planck constant has been an immense challenge. The new Kilogram brings \( E=mc^2 \) and \( E=nh \) together, which will enable scientists to define mass in terms of Planck’s constant, an unchanging feature of the universe. An international coalition of science labs has come together to make the most precise measurements of Planck’s constant.

This work required careful measurements with an incredibly complicated Watt balance (Kibble balance) – named after Bryan Kibble from the UK’s National Physical Laboratory. Currently, only France, Canada and the US have Kibble balances capable of making the measurements needed to fix the Planck constant. The Kilogram will now be defined by taking the fixed numerical value of the Planck constant, \( h \), to be \( 6.62607015 \times 10^{-34} \), when expressed in the unit Joules, which is equal to kg metre square/second.

Indian Efforts

Metrology scientists at the CSIR-National Physical Laboratory, New Delhi, have started preliminary investigations for the development of a Kibble balance in India. They have successfully developed and established an experimental model in their laboratory. The setup has been experimentally evaluated for 1 gm and the Planck constant has also been evaluated. CSIR-NPL is now geared up for the development of an Indian version of the Kibble balance for 1 kg.

What all this means is that we need to say goodbye to the Kilogram, the last of the SI measurements which was based on the man-made object – IPK – that has served us well over 144 years. The Kilogram of yesteryears, from now on will be history, but then the Kilogram will live for eternity serving humankind in a more precise way.

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