Kilogram

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The **kilogram** or **kilogramme** (SI unit symbol: **kg**), is the base unit of mass in the International System of Units (SI) (the Metric system) and is defined as being equal to the mass of the *International Prototype of the Kilogram* (**IPK**).[2]

The gram, 1/1000th of a kilogram, was originally defined in 1795 as the mass of one cubic centimeter of water at the melting point of water.[3] The original prototype kilogram, manufactured in 1799 and from which the IPK is derived, had a mass equal to the mass of 1.000025 liters of water at 4 °C.

The kilogram is the only SI base unit with an SI prefix ("kilo", symbol "k") as part of its name. It is also the only SI unit that is still directly defined by an artifact rather than a fundamental physical property that can be reproduced in different laboratories. Three other base units in the SI system are defined relative to the kilogram so its stability is important.

The International Prototype Kilogram was commissioned by the General Conference on Weights and Measures (CGPM) under the authority of the Metre Convention (1875), and is in the custody of the International Bureau of Weights and Measures (BIPM) who hold it on behalf of the CGPM. After the International Prototype Kilogram had been found to vary in mass over time, the International Committee for Weights and Measures (CIPM) recommended in 2005 that the kilogram be redefined in terms of a fundamental constant of nature. At its 2011 meeting, the CGPM agreed in principle that the kilogram should be redefined in terms of the Planck constant. The decision was originally deferred until 2014; in 2014 it was deferred again until the next meeting.[4]

The International Prototype Kilogram (IPK) is rarely used or handled. Copies of the IPK kept by national metrology laboratories around the world were compared with the IPK in 1889, 1948, and 1989 to provide traceability of measurements of mass anywhere in the world back to the IPK.

The avoirdupois (or *international*) pound, used in both the Imperial system and U.S. customary units, is defined as exactly 0.45359237 kg, making one kilogram approximately equal to 2.2046 avoirdupois pounds. Other traditional units of weight and mass around the world are also defined in terms of the kilogram, making the IPK the primary standard for virtually all units of mass on Earth.

Kilogram

A domestic-quality one-kilogram weight made of cast iron (the credit card is for scale). The shape follows OIML recommendation R52 for cast-iron hexagonal weights[1]

Unit information	
Unit system	SI base unit
Unit of	Mass
Symbol	kg
Unit conversions	
1 kg in ...	*... is equal to ...*
Avoirdupois	≈ 2.205 pounds [Note 1]
Natural units	≈ 4.59×10^7 Planck masses $1.356392608(60) \times 10^{50}$ hertz [Note 2]

Contents

Name and terminology

The word *kilogramme* or *kilogram* is derived from the French *kilogramme*,[5] which itself was a learned coinage, prefixing the Greek stem of χίλιοι *khilioi* "a thousand" to *gramma*, a Late Latin term for "a small weight", itself from Greek γράμμα.[6] The word *kilogramme* was written into French law in 1795, in the *Decree of 18 Germinal*,[7] which revised the older system of units introduced by the French National Convention in 1793, where the *gravet* had been defined as weight (*poids*) of a cubic centimetre of water, equal to 1/1000th of a *grave*.[8] In the decree of 1795, the term *gramme* thus replaced *gravet*, and *kilogramme* replaced *grave*.

The French spelling was adopted in the United Kingdom when the word was used for the first time in English in 1797,[5] with the spelling *kilogram* being adopted in the United States. In the United Kingdom both spellings are used, with "kilogram" having become by far the more common.[9][Note 3] UK law regulating the units to be used when trading by weight or measure does not prevent the use of either spelling.[10]

In the 19th century the French word *kilo*, a shortening of *kilogramme*, was imported into the English language where it has been used to mean both kilogram[11] and kilometer.[12] While *kilo* is acceptable in many generalist texts, for example *The Economist*,[13] its use is typically considered inappropriate in certain applications including scientific, technical and legal writing, where authors should adhere strictly to SI nomenclature.[14][15] When the United States Congress gave the metric system legal status in 1866, it permitted the use of the word *kilo* as an alternative to the word *kilogram*,[16] but in 1990 revoked the status of the word *kilo*.[17]

During the 19th century, the standard system of metric units was the centimetre–gram–second system of units, treating the gram as the fundamental unit of mass and the *kilogram* simply as a derived unit. In 1901, however, following the discoveries by James Clerk Maxwell to the effect that electric measurements could not be explained in terms of the three fundamental units of length, mass and time, Giovanni Giorgi proposed a new standard system which would include a fourth fundamental unit to measure quantities in electromagnetism.[18] In 1935 this was adopted by the IEC as the *Giorgi system*, now also known as MKS system,[19] and in 1946 the CIPM approved a proposal to adopt the Ampere as the electromagnetic unit of the "MKSA system".[20] In 1948 the CGPM commissioned the CIPM "to make recommendations for a single practical system of units of measurement, suitable for adoption by all countries adhering to the Metre Convention".[21] This led to the launch of SI in 1960 and the subsequent publication of the "SI Brochure," which stated that "It is not permissible to use abbreviations for unit symbols or unit names ...".[22][Note 4] The CGS and MKS systems co-existed during much of the early-to-mid 20th century, but as a result of the decision to adopt the "Giorgi system" as the international system of units in 1960, the kilogram is now the SI base unit for mass, while the definition of the gram is derived from that of the kilogram.

Nature of mass

Measurement of *weight* - gravitational attraction of the measurand causes a distortion of the spring

Measurement of *mass* - the gravitational force on the measurand is balanced against the gravitational force on the weights.

The kilogram is a unit of mass, a property which corresponds to the common perception of how “heavy” an object is. Mass is an *inertial* property; that is, it is related to the tendency of an object at rest to remain at rest, or if in motion to remain in motion at a constant velocity, unless acted upon by a force. According to "Newton's laws of motion" and the equation $F = ma$, when acted upon by a force F of one newton, an object with mass m of one kilogram will accelerate a at the rate of one meter per second per second (1 m/s^2)—about one-tenth the acceleration due to Earth's gravity[Note 5]

While the *weight* of an object is dependent upon the strength of the local gravitational field, the *mass* of an object is independent of gravity, as mass is a measure of how much matter an object contains.[Note 6] Accordingly, for astronauts in microgravity, no effort is required to hold objects off the cabin floor; they are “weightless”. However, since objects in microgravity still retain their mass and inertia, an astronaut must exert ten times as much force to accelerate a 10-kilogram object at the same rate as a 1-kilogram object.

Because at any given point on Earth the weight of an object is proportional to its mass, the mass of an object in kilograms is usually measured by comparing its weight to the weight of a standard mass, whose mass is known in kilograms, using a device called a weighing scale. The ratio of the force of gravity on the two objects, measured by the scale, is equal to the ratio of their masses.

Kilogramme des Archives

On April 7, 1795, the gram was decreed in France to be "the absolute weight of a volume of pure water equal to the cube of the hundredth part of the metre, and at the temperature of melting ice."[23] The concept of using a unit volume of water to define a unit measure of mass was proposed by the English philosopher John Wilkins in his 1668 essay as a means of linking mass and length.[24][25]

The Arago kilogram, an exact copy of the "Kilogramme des Archives" commissioned in 1821 by the US under supervision of French physicist François Arago that served as the US's first kilogram standard of mass until 1889, when the US converted to primary metric standards and received its current kilogram prototypes, K4 and K20.

Since trade and commerce typically involve items significantly more massive than one gram, and since a mass standard made of water would be inconvenient and unstable, the regulation of commerce necessitated the manufacture of a *practical realization* of the water-based definition of mass. Accordingly, a provisional mass standard was made as a single-piece, metallic artifact one thousand times as massive as the gram—the kilogram.

At the same time, work was commissioned to precisely determine the mass of a cubic decimeter (one liter) of water.[Note 7][23] Although the decreed definition of the kilogram specified water at 0 °C—its highly stable *temperature* point—the French chemist Louis Lefèvre-Gineau and the Italian naturalist Giovanni Fabbroni after several years of research chose to redefine the standard in 1799 to water's most stable *density* point: the temperature at which water reaches maximum density, which was measured at the time as 4 °C.[Note 8][26] They concluded that one cubic decimeter of water at its maximum density was equal to 99.9265% of the target mass of the provisional kilogram standard made four years earlier.[Note 9][27] That same year, 1799, an all-platinum kilogram prototype was fabricated with the objective that it would equal, as close as was scientifically feasible for the day, the mass of one cubic decimeter of water at 4 °C. The prototype was presented to the Archives of the Republic in June and on December 10, 1799, the prototype was formally ratified as the *kilogramme des Archives* (Kilogram of the Archives) and the kilogram was defined as being equal to its mass. This standard stood for the next 90 years.

International prototype kilogram

Since 1889 the magnitude of the kilogram has been defined as the mass of an object called the *international prototype kilogram*,[28] often referred to in the professional metrology world as the "IPK". The IPK is made of a platinum alloy known as "Pt‑10Ir", which is 90% platinum and 10% iridium (by mass) and is machined into a right-circular cylinder (height = diameter) of 39.17 millimeters to minimize its surface area.[29] The addition of 10% iridium improved upon the all-platinum Kilogram of the Archives by greatly increasing hardness while still retaining platinum's many virtues: extreme resistance to oxidation, extremely high density (almost twice as dense as lead and more than 21 times as dense as water), satisfactory electrical and thermal conductivities, and low magnetic susceptibility. The IPK and its six sister copies are stored at the International Bureau of Weights and Measures (known by its French-language initials BIPM) in an environmentally monitored safe in the lower vault located in the basement of the BIPM's Pavillon de Breteuil in Sèvres on the outskirts of Paris (see *External images*, below, for photographs). Three independently controlled keys are required to open the vault. Official copies of the IPK were made available to other nations to serve as their national standards. These are compared to the IPK roughly every 40 years, thereby providing traceability of local measurements back to the IPK.[30]

A CGI of the international prototype kilogram (the inch ruler is for scale). The prototype is manufactured from a platinum–iridium alloy and is 39.17 mm in both diameter and height, its edges have a four-angle (22.5°, 45°, 67.5° and 79°) chamfer to minimize wear.

The Metre Convention was signed on May 20, 1875 and further formalized the metric system (a predecessor to the SI), quickly leading to the production of the IPK. The IPK is one of three cylinders made in 1879 by Johnson Matthey, which continues to manufacture nearly all of the national prototypes today.[31][32] In 1883, the mass of the IPK was found to be indistinguishable from that of the *Kilogramme des Archives* made eighty-four years prior, and was formally ratified as *the* kilogram by the 1st CGPM in 1889.[29]

Modern measurements of Vienna Standard Mean Ocean Water, which is pure distilled water with an isotopic composition representative of the average of the world's oceans, show it has a density of 0.999975 $\pm 1 \times 10^{-6}$ kg/L at its point of maximum density (3.984 °C) under one standard atmosphere (760 torr) of pressure.[33] Thus, a cubic decimeter of water at its point of maximum density is only 25 parts per million less massive than the IPK; that is to say, the 25 milligram difference shows that the scientists over 216 years ago managed to make the mass of the Kilogram of the Archives equal that of a cubic decimeter of water at 4 °C, with a margin of error *at most* within the mass of a single excess grain of rice.

Copies of the international prototype kilogram

The various copies of the international prototype kilogram are given the following designations in the literature:

- The IPK itself. Located in Sèvres, France.
- Six sister copies, numbered: K1, 7, 8(41),[Note 10] 32, 43 and 47.[34] Located in Sèvres, France.
- Three unofficial copies, numbered: 25, 88 and 91 (numbers 9 and 31 were used before 2004 but were replaced by 88 and 91[35]). Located in Sèvres, France.

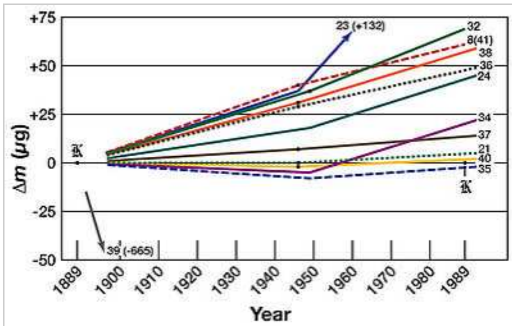
- National prototypes, stored in[36][37][38][39] Australia (44 and 87), Austria (49), Belgium (28 and 37), Brazil (66), Canada (50 and 74), China (60 and 64; 75 in Hong Kong), Czech Republic (67), Denmark (48), Egypt (58), Finland (23), France (35), Germany (52, 55 and 70), Hungary (16), India (57), Indonesia (46), Israel (71), Italy (5 and 76), Japan (6 and 94), Kazakhstan, Kenya (95), Mexico (21, 90 and 96), Netherlands (53), North Korea (68), Norway (36), Pakistan (93), Poland (51), Portugal (69), Romania (2), Russia (12 and 26[40]), Singapore (83), Slovakia (41 and 65), South Africa (56), South Korea (39, 72 and 84), Spain (24 and 3), Sweden (86), Switzerland (38 and 89), Taiwan (78), Thailand (80), Turkey (54[41]), United Kingdom (18,[42] 81 and 82) and the United States (20,[43] 4, 79, 85 and 92).
- Some additional copies held by non-national organizations, such as the French Academy of Sciences in Paris (34) and the Istituto di Metrologia G. Colonnetti in Turin (62).[36]

National prototype kilogram K20, one of two prototypes stored at the US National Institute of Standards and Technology in Gaithersburg, Maryland, which serve as primary standards for defining all units of mass and weight in the United States. This is a replica for public display, shown as it is normally stored, under two bell jars.

Stability of the international prototype kilogram

By definition, the error in the measured value of the IPK's mass is exactly zero; the IPK *is* the kilogram. However, any changes in the IPK's mass over time can be deduced by comparing its mass to that of its official copies stored throughout the world, a rarely undertaken process called "periodic verification". The only three verifications occurred in 1889, 1948, and 1989. For instance, the U.S. owns four 90% platinum / 10% iridium (Pt‑10Ir) kilogram standards, two of which, K4 and K20, are from the original batch of 40 replicas delivered in 1884.[Note 11] The K20 prototype was designated as the primary national standard of mass for the U.S. Both of these, as well as those from other nations, are periodically returned to the BIPM for verification.[Note 12]

Note that none of the replicas has a mass precisely equal to that of the IPK; their masses are calibrated and documented as offset values. For instance, K20, the U.S.'s primary standard, originally had an official mass of 1 kg − 39 micrograms (μg) in 1889; that is to say, K20 was 39 µg less than the IPK. A verification performed in 1948 showed a mass of 1 kg − 19 µg. The latest verification performed in 1989 shows a mass precisely identical to its original 1889 value. Quite unlike transient variations such as this, the U.S.'s check standard, K4, has persistently declined in mass relative to the IPK—and for an identifiable reason. Check standards are used much more often than primary standards and are prone to scratches and other wear. K4 was originally delivered with an official mass of 1 kg − 75 µg in 1889, but as of 1989 was officially calibrated at 1 kg − 106 µg and ten years later was 1 kg − 116 µg. Over a period of 110 years, K4 lost 41 µg relative to the IPK.[44]



Mass drift over time of national prototypes K21–K40, plus two of the IPK's sister copies: K32 and K8(41).[Note 10] All mass changes are relative to the IPK. The initial 1889 starting-value offsets relative to the IPK have been nulled.[36] The above are all *relative* measurements; no historical mass-measurement data is available to determine which of the prototypes has been most stable relative to an invariant of nature. There is the distinct possibility that *all* the prototypes gained mass over 100 years and that K21, K35, K40, and the IPK simply *gained less* than the others.

Beyond the simple wear that check standards can experience, the mass of even the carefully stored national prototypes can drift relative to the IPK for a variety of reasons, some known and some unknown. Since the IPK and its replicas are stored in air (albeit under two or more nested bell jars), they gain mass through adsorption of atmospheric contamination onto their surfaces. Accordingly, they are cleaned in a process the BIPM developed between 1939 and 1946 known as "the BIPM cleaning method"[45] that comprises firmly rubbing with a chamois soaked in equal parts ether and ethanol, followed by steam cleaning with bi-distilled water, and allowing the prototypes to settle for 7–10 days before verification.[Note 13] Cleaning the prototypes removes between 5 and 60 µg of contamination depending largely on the time elapsed since the last cleaning. Further, a second cleaning can remove up to 10 µg more. After cleaning—even when they are stored under their bell jars—the IPK and its replicas immediately begin gaining mass again. The BIPM even developed a model of this gain and concluded that it averaged 1.11 µg per month for the first 3 months after cleaning and then decreased to an average of about 1 µg per year thereafter. Since check standards like K4 are not cleaned for routine calibrations of other mass standards—a precaution to minimize the potential for wear and handling damage—the BIPM's model of time-dependent mass gain has been used as an "after cleaning" correction factor.

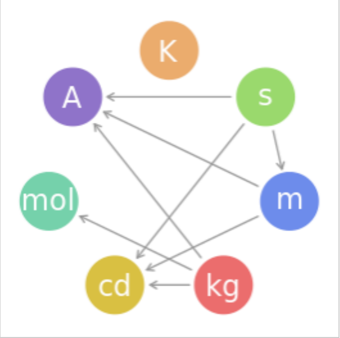
Because the first forty official copies are made of the same alloy as the IPK and are stored under similar conditions, periodic verifications using a large number of replicas—especially the national primary standards, which are rarely used—can convincingly demonstrate the stability of the IPK. What has become clear after the third periodic verification performed between 1988 and 1992 is that masses of the entire worldwide ensemble of prototypes have been slowly but inexorably diverging from each other. It is also clear that the mass of the IPK lost perhaps 50 µg over the last century, and possibly significantly more, in comparison to its official copies.[36][46] The reason for this drift has eluded physicists who have dedicated their careers to the SI unit of mass. No plausible mechanism has been proposed to explain either a steady decrease in the mass of the IPK, or an increase in that of its replicas dispersed throughout the world.[Note 14][47][48][49] This *relative* nature of the changes amongst the world's kilogram prototypes is often misreported in the popular press, and even some notable scientific magazines, which often state that the IPK simply "lost 50 µg" and omit the very important caveat of "*in comparison to its official copies*". [Note 15] Moreover, there are no technical means available to determine whether or not the entire worldwide ensemble of prototypes suffers from even greater long-term trends upwards or downwards because their mass "relative to an invariant of nature is unknown at a level below 1000 µg over a period of 100 or even 50 years".[46] Given the lack of data identifying which of the world's kilogram prototypes has been most stable in absolute terms, it is equally valid to state that the first batch of replicas has, as a group, gained an average of about 25 µg over one hundred years in comparison to the IPK. [Note 16]

What *is* known specifically about the IPK is that it exhibits a short-term instability of about 30 µg over a period of about a month in its after-cleaned mass.[50] The precise reason for this short-term instability is not understood but is thought to entail surface effects: microscopic differences between the prototypes' polished surfaces, possibly aggravated by hydrogen absorption due to catalysis of the volatile organic compounds that slowly deposit onto the prototypes as well as the hydrocarbon-based solvents used to clean them.[49][51]

It has been possible to rule out many explanations of the observed divergences in the masses of the world's prototypes proposed by scientists and the general public. The BIPM's FAQ explains, for example, that the divergence is dependent on the amount of time elapsed between measurements and not dependent on the number of times the artifacts have been cleaned or possible changes in gravity or environment.[52] Reports published in 2013 by Peter Cumpson of Newcastle University based on the X-ray photoelectron spectroscopy of samples that were stored alongside various prototype kilograms suggested that one source of the divergence between the various prototypes could be traced to mercury that had been absorbed by the prototypes being in the proximity of mercury-based instruments. The IPK has been stored within centimeters of a mercury thermometer since at least as far back as the late 1980s.[53] In this Newcastle University work six platinum weights made in the nineteenth century were all found to have mercury at the surface, the most contaminated of which had the equivalent of 250 µg of mercury when scaled to the surface area of a kilogram prototype.

Scientists are seeing far greater variability in the prototypes than previously believed. The increasing divergence in the masses of the world's prototypes and the short-term instability in the IPK has prompted research into improved methods to obtain a smooth surface finish using diamond turning on newly manufactured replicas and has intensified the search for a new definition of the kilogram. See *Proposed future definitions*, below. [54]

Dependency of the SI on the IPK



The magnitude of many of the units comprising the SI system of measurement, including most of those used in the measurement of electricity and light, are highly dependent upon the stability of a 136-year-old, golf-ball-sized cylinder of metal stored in a vault in France.

The stability of the IPK is crucial because the kilogram underpins much of the SI system of measurement as it is currently defined and structured. For instance, the newton is defined as the force necessary to accelerate one kilogram at one meter per second squared. If the mass of the IPK were to change slightly, so too must the newton by a proportional degree. In turn, the pascal, the SI unit of pressure, is defined in terms of the newton. This chain of dependency follows to many other SI units of measure. For instance, the joule, the SI unit of energy, is defined as that expended when a force of one newton acts through one meter. Next to be affected is the SI unit of power, the watt, which is one joule per second. The ampere too is defined relative to the newton, and ultimately, the kilogram.

With the magnitude of the primary units of electricity thus determined by the kilogram, so too follow many others, namely the coulomb, volt, tesla, and weber. Even units used in the measure of light would be affected; the candela—following the change in the watt—would in turn affect the lumen and lux.

Because the magnitude of many of the units comprising the SI system of measurement is ultimately defined by the mass of a 136-year-old, golf-ball-sized piece of metal, the quality of the IPK must be diligently protected to preserve the integrity of the SI system. Yet, despite the best stewardship, the average mass of the worldwide ensemble of prototypes and the mass of the IPK have likely diverged another 6 µg since the third periodic verification 26 years ago.[Note 17] Further, the world's national metrology laboratories must wait for the fourth periodic verification to confirm whether the historical trends persisted.

Fortunately, *definitions* of the SI units are quite different from their *practical realizations.* For instance, the meter is *defined* as the distance light travels in a vacuum during a time interval of $^{1}/_{299,792,458}$ of a second. However, the meter's *practical realization* typically takes the form of a helium–neon laser, and the meter's length is *delineated*—not defined—as 1,579,800.298728 wavelengths of light from this laser. Now suppose that the official measurement of the second was found to have drifted by a few parts per billion (it is actually extremely stable with a reproducibility of a few parts in 10^{15}).[55] There would be no automatic effect on the meter because the second—and thus the meter's length—is abstracted via the laser comprising the meter's practical realization. Scientists performing meter calibrations would simply continue to measure out the same number of laser wavelengths until an agreement was reached to do otherwise. The same is true with regard to the real-world dependency on the kilogram: if the mass of the IPK was found to have changed slightly, there would be no automatic effect upon the other units of measure because their practical realizations provide an insulating layer of abstraction. Any discrepancy would eventually have to be reconciled though, because the virtue of the SI system is its precise mathematical and logical harmony amongst its units. If the IPK's value were definitively proven to have changed, one solution would be to simply redefine the kilogram as being equal to the mass of the IPK plus an offset value, similarly to what is currently done with its replicas; e.g., "the kilogram is equal to the mass of the IPK + 42 parts per billion" (equivalent to 42 µg).

The long-term solution to this problem, however, is to liberate the SI system's dependency on the IPK by developing a practical realization of the kilogram that can be reproduced in different laboratories by following a written specification. The units of measure in such a practical realization would have their magnitudes precisely defined and expressed in terms of fundamental physical constants. While major portions of the SI system would still be based on the kilogram, the kilogram would in turn be based on invariant, universal constants of nature. Much work towards that end is ongoing, though no alternative has yet achieved the uncertainty of 20 parts per billion (~20 µg) required to improve upon the IPK. However, as of April 2007, the U.S.'s National Institute of Standards and Technology (NIST) had an implementation of the watt balance that was approaching this goal, with a demonstrated uncertainty of 36 µg.[56] See *Watt balance* below.

The avoirdupois pound, used in both the imperial system and U.S. customary units, is defined as exactly 0.45359237 kg,[57] making one kilogram approximately equal to 2.2046 avoirdupois pounds.

Proposed future definitions

In the following sections, wherever numeric equalities are shown in 'concise form'—such as $1.85487(14) \times 10^{13}$—the two digits between the parentheses denote the uncertainty at 1σ standard deviation (68% confidence level) in the two least significant digits of the significand. A final X in a proposed definition denotes digits yet to be agreed on.

As of 2014 the kilogram was the only SI unit still defined by an artifact. In 1960 the meter, having previously also been defined by reference to an artifact (a single platinum-iridium bar with two marks on it) was redefined in terms of invariant, fundamental physical constants (the wavelength of a particular emission of light emitted by krypton,[58] and later the speed of light) so that the standard can be reproduced in different laboratories by following a written specification. At the 94th Meeting of the International Committee for Weights and Measures (2005)[59] it was recommended that the same be done with the kilogram.

In October 2010, the International Committee for Weights and Measures (known by its French-language initials CIPM) voted to submit a resolution for consideration at the General Conference on Weights and Measures (CGPM), to "take note of an intention" that the kilogram be defined in terms of the Planck constant, h (which has dimensions of energy times time) together with other fundamental units.[60][61] This resolution was accepted by the 24th conference of the CGPM[62] in October 2011 and in addition the date of the 25th conference was moved forward from 2015 to 2014.[63] Such a definition would theoretically permit any apparatus that was capable of delineating the kilogram in terms of the Planck constant to be used as long as it possessed sufficient precision, accuracy and stability. The watt balance (discussed below) may be able to do this.

In the project to replace the last artifact that underpins much of the International System of Units (SI), a variety of other very different technologies and approaches were considered and explored over many years. They too are covered below. Some of these now-abandoned approaches were based on equipment and procedures that would have enabled the reproducible production of new, kilogram-mass prototypes on demand (albeit with extraordinary effort) using measurement techniques and material properties that are ultimately based on, or traceable to, fundamental constants. Others were based on devices that measured either the acceleration or weight of hand-tuned kilogram test masses and which expressed their magnitudes in electrical terms via special components that permit traceability to fundamental constants. All approaches depend on converting a weight measurement to a mass, and therefore require the precise measurement of the strength of gravity in laboratories. All approaches would have precisely fixed one or more constants of nature at a defined value.

The watt balance

The NIST's watt balance is a project of the U.S. Government to develop an "electronic kilogram." The vacuum chamber dome, which lowers over the entire apparatus, is visible at top.

The watt balance is essentially a single-pan weighing scale that measures the electric power necessary to oppose the weight of a kilogram test mass as it is pulled by Earth's gravity. It is a variation of an ampere balance in that it employs an extra calibration step that nulls the effect of geometry. The electric potential in the watt balance is delineated by a Josephson voltage standard, which allows voltage to be linked to an invariant constant of nature with extremely high precision and stability. Its circuit resistance is calibrated against a quantum Hall resistance standard.

The watt balance requires exquisitely precise measurement of the local gravitational acceleration $\boldsymbol{g}$ in the laboratory, using a gravimeter. (See "FG‑5 absolute gravimeter" in *External images*, below). For instance, the NIST compensates for Earth's gravity gradient of 309 µGal per meter when the elevation of the center of the gravimeter differs from that of the nearby test mass in the watt balance; a change in the weight of a one-kilogram test mass that equates to about 316 µg/m.

In April 2007, the NIST's implementation of the watt balance demonstrated a combined relative standard uncertainty (CRSU) of 36 µg and a short-term resolution of 10^{-15} µg.[56][Note 18] The UK's National Physical Laboratory's watt balance demonstrated a CRSU of 70.3 µg in 2007.[64] That watt balance was disassembled and shipped in 2009 to Canada's Institute for National Measurement Standards (part of the National Research Council), where research and development with the device could continue.

If the CGPM adopts the new proposal and the new definition of the kilogram becomes part of the SI, the value in SI units of the Planck constant (h), which is a measure that relates the energy of photons to their frequency, would be precisely fixed (the currently accepted value of $6.626\,069\,57(29) \times 10^{-34}$ J s[65] has an uncertainty of ± about 1 in 23 million).[Note 19] Once agreed upon internationally, the kilogram would no longer be defined as the mass of the IPK. All the remaining units in the International System of Units (the SI) that today have dependencies upon the kilogram and the joule would also fall in place, their magnitudes ultimately defined, in part, in terms of photon oscillations rather than the IPK.

The local gravitational acceleration ***g*** is measured with exceptional precision with the help of a laser interferometer. The laser's pattern of interference fringes—the dark and light bands above—blooms at an ever faster rate as a free-falling corner reflector drops inside an absolute gravimeter. The pattern's frequency sweep is timed by an atomic clock.

Gravity and the nature of the watt balance, which oscillates test masses up and down against the local gravitational acceleration ***g***, are exploited so that mechanical power is compared against electrical power, which is the square of voltage divided by electrical resistance. However, ***g*** varies significantly—by nearly 1%—depending on where on the Earth's surface the measurement is made (see *Earth's gravity*). There are also slight seasonal variations in ***g*** due to changes in underground water tables, and larger semimonthly and diurnal changes due to tidal distortions in the Earth's shape caused by the Moon. Although ***g*** would not be a term in the *definition* of the kilogram, it would be crucial in the *delineation* of the kilogram when relating energy to power. Accordingly, ***g*** must be measured with at least as much precision and accuracy as are the other terms, so measurements of ***g*** must also be traceable to fundamental constants of nature. For the most precise work in mass metrology, ***g*** is measured using dropping-mass absolute gravimeters that contain an iodine-stabilized helium–neon laser interferometer. The fringe-signal, frequency-sweep output from the interferometer is measured with a rubidium atomic clock. Since this type of dropping-mass gravimeter derives its accuracy and stability from the constancy of the speed of light as well as the innate properties of helium, neon, and rubidium atoms, the 'gravity' term in the delineation of an all-electronic kilogram is also measured in terms of invariants of nature—and with very high precision. For instance, in the basement of the NIST's Gaithersburg facility in 2009, when measuring the gravity acting upon Pt‑10Ir test masses (which are denser, smaller, and have a slightly lower center of gravity inside the watt balance than stainless steel masses), the measured value was typically within 8 ppb of 9.80101644 m/s^2.[66]

The virtue of electronic realizations like the watt balance is that the definition and dissemination of the kilogram would no longer be dependent upon the stability of kilogram prototypes, which must be very carefully handled and stored. It would free physicists from the need to rely on assumptions about the stability of those prototypes. Instead, hand-tuned, close-approximation mass standards would simply be weighed and documented as being equal to one kilogram plus an offset value. With the watt balance, while the kilogram would be *delineated* in electrical and gravity terms, all of which are traceable to invariants of nature; it would be *defined* in a manner that is directly traceable to just three fundamental constants of nature. The Planck constant defines the kilogram in terms of the second and the meter. By fixing the Planck constant, the *definition* of the kilogram would depend only on the *definitions* of the second and the meter. The definition of the second depends on a single defined physical constant: the ground state hyperfine splitting frequency of the caesium 133 atom $\Delta\nu(^{133}\mathrm{Cs})_{\mathrm{hfs}}$. The meter depends on the second and on an additional defined physical constant: the speed of light *c*. If the kilogram is redefined in this manner, mass artifacts—physical objects calibrated in a watt balance, including the IPK—would no longer be part of the definition, but would instead become *transfer standards*.

Scales like the watt balance also permit more flexibility in choosing materials with especially desirable properties for mass standards. For instance, Pt‑10Ir could continue to be used so that the specific gravity of newly produced mass standards would be the same as existing national primary and check standards (≈21.55 g/ml). This would reduce the relative uncertainty when making mass comparisons in air. Alternatively, entirely different materials and constructions could be explored with the objective of producing mass standards with greater stability. For instance, osmium-iridium alloys could be investigated if platinum's propensity to absorb hydrogen (due to catalysis of VOCs and hydrocarbon-based cleaning solvents) and atmospheric mercury proved to be sources of instability. Also, vapor-deposited, protective ceramic coatings like nitrides could be investigated for their suitability to isolate these new alloys.

The challenge with watt balances is not only in reducing their uncertainty, but also in making them truly *practical* realizations of the kilogram. Nearly every aspect of watt balances and their support equipment requires such extraordinarily precise and accurate, state-of-the-art technology that—unlike a device like an atomic clock—few countries would currently choose to fund their operation. For instance, the NIST's watt balance used four resistance standards in 2007, each of which was rotated through the watt balance every two to six weeks after being calibrated in a different part of NIST headquarters facility in Gaithersburg, Maryland. It was found that simply moving the resistance standards down the hall to the watt balance after calibration altered their values 10 ppb (equivalent to 10 µg) or more.[67] Present-day technology is insufficient to permit stable operation of watt balances between even biannual calibrations. If the kilogram is defined in terms of the Planck constant, it is likely there will only be a few—at most—watt balances initially operating in the world.

Alternative approaches to redefining the kilogram that were fundamentally different from the watt balance were explored to varying degrees with some abandoned, as follows:

Atom-counting approaches

Carbon-12

Though not offering a practical realization, this definition would precisely define the magnitude of the kilogram in terms of a certain number of carbon‑12 atoms. Carbon‑12 (^{12}C) is an isotope of carbon. The mole is currently defined as "the quantity of entities (elementary particles like atoms or molecules) equal to the number of atoms in 12 grams of carbon‑12." Thus, the current definition of the mole requires that $^{1000}/_{12}$ (83⅓) moles of ^{12}C has a mass of precisely one kilogram. The number of atoms in a mole, a quantity known as the Avogadro constant, is experimentally determined, and the current best estimate of its value is $6.022\ 141\ 29(27) \times 10^{23}$ entities per mole.[68] This new definition of the kilogram proposed to fix the Avogadro constant at precisely $6.022\ 14X \times 10^{23}$ with the kilogram being defined as "the mass equal to that of $^{1000}/_{12} \cdot 6.022\ 14X \times 10^{23}$ atoms of ^{12}C."

The accuracy of the measured value of the Avogadro constant is currently limited by the uncertainty in the value of the Planck constant—a measure relating the energy of photons to their frequency. That relative standard uncertainty has been 50 parts per billion (ppb) since 2006. By fixing the Avogadro constant, the practical effect of this proposal would be that the uncertainty in the mass of a ^{12}C atom—and the magnitude of the kilogram—could be no better than the current 50 ppb uncertainty in the Planck constant. Under this proposal, the magnitude of the kilogram would be subject to future refinement as improved measurements of the value of the Planck constant become available; electronic realizations of the kilogram would be recalibrated as required. Conversely, an electronic *definition* of the kilogram (see *Electronic approaches*, below), which would precisely fix the Planck constant, would continue to allow 83⅓ moles of ^{12}C to have a mass of precisely one kilogram but the number of atoms comprising a mole (the Avogadro constant) would continue to be subject to future refinement.

A variation on a ^{12}C-based definition proposes to define the Avogadro constant as being precisely $84{,}446{,}889^3$ ($\approx 6.02214162 \times 10^{23}$) atoms. An imaginary realization of a 12-gram mass prototype would be a cube of ^{12}C atoms measuring precisely 84,446,889 atoms across on a side. With this proposal, the kilogram would be defined as "the mass equal to $84{,}446{,}889^3 \times 83⅓$ atoms of ^{12}C."[69][Note 20]

Avogadro project

Achim Leistner at the Australian Centre for Precision Optics (http://www.acpo.csiro.au/) (ACPO) is holding a 1 kg, single-crystal silicon sphere for the Avogadro project. These spheres are among the roundest man-made objects in the world. If the best of these spheres were scaled to the size of Earth, its high point—a continent-size area —would rise to a maximum elevation of 2.4 meters above "sea level".[Note 21]

Another Avogadro constant-based approach, known as the International Avogadro Coordination's *Avogadro project*, would define and delineate the kilogram as a softball-size (93.6 mm diameter) sphere of silicon atoms. Silicon was chosen because a commercial infrastructure with mature processes for creating defect-free, ultra-pure monocrystalline silicon already exists to service the semiconductor industry. To make a practical realization of the kilogram, a silicon boule (a rod-like, single-crystal ingot) would be produced. Its isotopic composition would be measured with a mass spectrometer to determine its average relative atomic mass. The boule would be cut, ground, and polished into spheres. The size of a select sphere would be measured using optical interferometry to an uncertainty of about 0.3 nm on the radius—roughly a single atomic layer. The precise lattice spacing between the atoms in its crystal structure (≈192 pm) would be measured using a scanning X-ray interferometer. This permits its atomic spacing to be determined with an uncertainty of only three parts per billion. With the size of the sphere, its average atomic mass, and its atomic spacing known, the required sphere diameter can be calculated with sufficient precision and low uncertainty to enable it to be finish-polished to a target mass of one kilogram.

Experiments are being performed on the Avogadro Project's silicon spheres to determine whether their masses are most stable when stored in a vacuum, a partial vacuum, or ambient pressure. However, no technical means currently exist to prove a long-term stability any better than that of the IPK's because the most sensitive and accurate measurements of mass are made with dual-pan balances like the BIPM's FB‑2 flexure-strip balance (see *External links*, below). Balances can only compare the mass of a silicon sphere to that of a reference mass. Given the latest understanding of the lack of long-term mass stability with the IPK and its replicas, there is no known, perfectly stable mass artifact to compare against. Single-pan scales, which measure weight relative to an invariant of nature, are not precise to the necessary long-term uncertainty of 10–20 parts per billion. Another issue to be overcome is that silicon oxidizes and forms a thin layer (equivalent to 5–20 silicon atoms) of silicon dioxide (quartz) and silicon monoxide. This layer slightly increases the mass of the sphere, an effect which must be accounted for when polishing the sphere to its finished dimension. Oxidation is not an issue with platinum and iridium, both of which are noble metals that are roughly as cathodic as oxygen and therefore don't oxidize unless coaxed to do so in the laboratory. The presence of the thin oxide layer on a silicon-sphere mass prototype places additional restrictions on the procedures that might be suitable to clean it to avoid changing the layer's thickness or oxide stoichiometry.

All silicon-based approaches would fix the Avogadro constant but vary in the details of the definition of the kilogram. One approach would use silicon with all three of its natural isotopes present. About 7.78% of silicon comprises the two heavier isotopes: ^{29}Si and ^{30}Si. As described in *Carbon‑12* above, this method would *define* the magnitude of the kilogram in terms of a certain number of ^{12}C atoms by fixing the Avogadro constant; the silicon sphere would be the *practical realization*. This approach could accurately delineate the magnitude of the kilogram because the masses of the three silicon nuclides relative to ^{12}C are known with great precision (relative uncertainties of 1 ppb or better). An alternative method for creating a silicon sphere-based kilogram proposes to use isotopic separation techniques to enrich the silicon until it is nearly pure ^{28}Si, which has a relative atomic mass of 27.9769265325(19).[71] With this approach, the Avogadro constant would not only be fixed, but so too would the atomic mass of ^{28}Si. As such, the definition of the kilogram would be decoupled from ^{12}C and the kilogram would instead be defined as $^{1000}/_{27.9769265325} \cdot 6.02214179 \times 10^{23}$ atoms of ^{28}Si (≈35.74374043 fixed moles of ^{28}Si atoms). Physicists could elect to define the kilogram in terms of ^{28}Si even when kilogram prototypes are made of natural silicon (all three isotopes present). Even with a kilogram definition based on theoretically pure ^{28}Si, a silicon-sphere prototype made of only nearly pure ^{28}Si would necessarily deviate slightly from the defined number of moles of silicon to compensate for various chemical and isotopic impurities as well as the effect of surface oxides.[72]

The silicon spheres were also examined by known YouTuber Veritasium (https://www.youtube.com/watch?v=ZMByI4s-D-Y).

Ion accumulation

Another Avogadro-based approach, ion accumulation, since abandoned, would have defined and delineated the kilogram by precisely creating new metal prototypes on demand. It would have done so by accumulating gold or bismuth ions (atoms stripped of an electron) and counted them by measuring the electrical current required to neutralize the ions. Gold (^{197}Au) and bismuth (^{209}Bi) were chosen because they can be safely handled and have the two highest atomic masses among the mononuclidic elements that is effectively non-radioactive (bismuth) or is perfectly stable (gold). See also *Table of nuclides*.[Note 22]

With a gold-based definition of the kilogram for instance, the relative atomic mass of gold could have been fixed as precisely 196.9665687, from the current value of 196.9665687(6). As with a definition based upon carbon-12, the Avogadro constant would also have been fixed. The kilogram would then have been defined as "the mass equal to that of precisely $^{1000}/_{196.9665687} \cdot 6.02214179 \times 10^{23}$ atoms of gold" (precisely 3,057,443,620,887,933,963,384,315 atoms of gold or about 5.07700371 fixed moles).

In 2003, German experiments with gold at a current of only 10 µA demonstrated a relative uncertainty of 1.5%.[73] Follow-on experiments using bismuth ions and a current of 30 mA were expected to accumulate a mass of 30 g in six days and to have a relative uncertainty of better than 1 ppm.[74] Ultimately, ion-accumulation approaches proved to be unsuitable. Measurements required months and the data proved too erratic for the technique to be considered a viable future replacement to the IPK.[75]

Among the many technical challenges of the ion-deposition apparatus was obtaining a sufficiently high ion current (mass deposition rate) while simultaneously decelerating the ions so they could all deposit onto a target electrode embedded in a balance pan. Experiments with gold showed the ions had to be decelerated to very low energies to avoid sputtering effects—a phenomenon whereby ions that had already been counted ricochet off the target electrode or even dislodged atoms that had already been deposited. The deposited mass fraction in the 2003 German experiments only approached very close to 100% at ion energies of less than around 1 eV (<1 km/s for gold).[73]

If the kilogram had been defined as a precise quantity of gold or bismuth atoms deposited with an electric current, not only would the Avogadro constant and the atomic mass of gold or bismuth have to have been precisely fixed, but also the value of the elementary charge (*e*), likely to $1.602\,17X \times 10^{-19}$ C (from the currently recommended value of $1.602\,176\,565(35) \times 10^{-19}$ C[76]). Doing so would have effectively defined the ampere as a flow of $^{1}/_{1.602\,17X \times 10^{-19}}$ electrons per second past a fixed point in an electric circuit. The SI unit of mass would have been fully defined by having precisely fixed the values of the Avogadro constant and elementary charge, and by exploiting the fact that the atomic masses of bismuth and gold atoms are invariant, universal constants of nature.

Beyond the slowness of making a new mass standard and the poor reproducibility, there were other intrinsic shortcomings to the ion-accumulation approach that proved to be formidable obstacles to ion-accumulation-based techniques becoming a practical realization. The apparatus necessarily required that the deposition chamber have an integral balance system to enable the convenient calibration of a reasonable quantity of transfer standards relative to any single internal ion-deposited prototype. Furthermore, the mass prototypes produced by ion deposition techniques would have been nothing like the freestanding platinum-iridium prototypes currently in use; they would have been deposited onto—and become part of—an electrode imbedded into one pan of a special balance integrated into the device. Moreover, the ion-deposited mass wouldn't have had a hard, highly polished surface that can be vigorously cleaned like those of current prototypes. Gold, while dense and a noble metal (resistant to oxidation and the formation of other compounds), is extremely soft so an internal gold prototype would have to be kept well isolated and scrupulously clean to avoid contamination and the potential of wear from having to remove the contamination. Bismuth, which is an inexpensive metal used in low-temperature solders, slowly oxidizes when exposed to room-temperature air and forms other chemical compounds and so would not have produced stable reference masses unless it was continually maintained in a vacuum or inert atmosphere.

Ampere-based force

This approach would define the kilogram as "the mass which would be accelerated at precisely 2×10^{-7} m/s^2 when subjected to the per-meter force between two straight parallel conductors of infinite length, of negligible circular cross section, placed one meter apart in vacuum, through which flow a constant current of $^{1}/_{1.602\,17X \times 10^{-19}}$ elementary charges per second".

A magnet floating above a superconductor bathed in liquid nitrogen demonstrates perfect diamagnetic levitation via the Meissner effect. Experiments with an ampere-based definition of the kilogram flipped this arrangement upside-down: an electric field accelerated a superconducting test mass supported by fixed magnets.

Effectively, this would define the kilogram as a derivative of the ampere rather than present relationship, which defines the ampere as a derivative of the kilogram. This redefinition of the kilogram would specify elementary charge (*e*) as precisely $1.602\,17X \times 10^{-19}$ coulomb rather than the current recommended value of $1.602\,176\,565(35) \times 10^{-19}$ C.[76] It would necessarily follow that the ampere (one coulomb per second) would also become an electrical current of this precise quantity of elementary charges per second passing a given point in an electric circuit. The virtue of a practical realization based upon this definition is that unlike the watt balance and other scale-based methods, all of which require the careful characterization of gravity in the laboratory, this method delineates the magnitude of the kilogram directly in the very terms that define the nature of mass: acceleration due to an applied force. Unfortunately, it is extremely difficult to develop a practical realization based upon accelerating masses. Experiments over a period of years in Japan with a superconducting, 30 g mass supported by diamagnetic levitation never achieved an uncertainty better than ten parts per million. Magnetic hysteresis was one of the limiting issues. Other groups performed similar research that used different techniques to levitate the mass.[77][78]

SI multiples

Because SI prefixes may not be concatenated (serially linked) within the name or symbol for a unit of measure, SI prefixes are used with the *gram*, not the kilogram, which already has a prefix as part of its name.[79] For instance, one-millionth of a kilogram is 1 mg (one milligram), not 1 µkg (one microkilogram).

SI multiples for gram (g)

Submultiples				Multiples		
Value	**Symbol**	**Name**		**Value**	**Symbol**	**Name**
10^{-1} g	dg	decigram		10^{1} g	dag	decagram
10^{-2} g	**cg**	**centigram**		10^{2} g	hg	hectogram
10^{-3} g	**mg**	**milligram**		10^{3} g	**kg**	**kilogram**
10^{-6} g	µg	**microgram (mcg)**		10^{6} g	Mg	megagram (**tonne**)
10^{-9} g	**ng**	**nanogram**		10^{9} g	Gg	gigagram
10^{-12} g	**pg**	**picogram**		10^{12} g	Tg	teragram
10^{-15} g	fg	femtogram		10^{15} g	Pg	petagram
10^{-18} g	ag	attogram		10^{18} g	Eg	exagram
10^{-21} g	zg	zeptogram		10^{21} g	Zg	zettagram
10^{-24} g	yg	yoctogram		10^{24} g	Yg	yottagram
Common prefixed units are in bold face.[Note 23]						

- When the Greek lowercase "µ" (mu) in the symbol for microgram is typographically unavailable, it is occasionally—although not properly—replaced by Latin lowercase "u".
- The microgram is often abbreviated “mcg”, particularly in pharmaceutical and nutritional supplement labeling, to avoid confusion, since the "µ" prefix is not always well recognized outside of technical disciplines.[Note 24] (The expression "mcg" is also the symbol for an obsolete CGS unit of measure known as the "millicentigram", which is equal to 10 µg.)
- The decagram (dag in SI) is in much of Europe often abbreviated "dkg" (from the local spelling "dekagram") and is used for typical retail quantities of food (such as cheese and meat).
- The unit name "megagram" is rarely used, and even then typically only in technical fields in contexts where especially rigorous consistency with the SI standard is desired. For most purposes, the name "tonne" is instead used. The tonne and its symbol, "t", were adopted by the CIPM in 1879. It is a non-SI unit accepted by the BIPM for use with the SI. According to the BIPM, "In English speaking countries this unit is usually called 'metric ton'."[80] The unit name "megatonne" or "megaton" (Mt) is often used in general-interest literature on greenhouse gas emissions, whereas the equivalent unit in scientific papers on the subject is often the "teragram" (Tg).

Glossary

- **Abstracted**: Isolated and its effect changed in form, often simplified or made more accessible in the process.
- **Artifact**: A simple human-made object used directly as a comparative standard in the measurement of a physical quantity.
- **Check standard**:
  1. A standard body’s backup replica of the international prototype kilogram (IPK).
  2. A secondary kilogram mass standard used as a stand-in for the primary standard during routine calibrations.
- **Definition**: A formal, specific, and exact specification.
- **Delineation**: The physical means used to mark a boundary or express the magnitude of an entity.
- **Disseminate**: To widely distribute the magnitude of a unit of measure, typically via replicas and transfer standards.
- **IPK**: Abbreviation of "international prototype kilogram", the unique physical object, kept in France, which is internationally recognized as having the defining mass of precisely one kilogram.
- **Magnitude**: The extent or numeric value of a property
- **National prototype**: A replica of the IPK possessed by a nation.
- **Practical realization**: A readily reproducible apparatus to conveniently delineate the magnitude of a unit of measure.

- **Primary national standard**:
  1. A replica of the IPK possessed by a nation
  2. The least used replica of the IPK when a nation possesses more than one.
- **Prototype**:
  1. A human-made object that serves as the defining comparative standard in the measurement of a physical quantity.
  2. A human-made object that serves as *the* comparative standard in the measurement of a physical quantity.
  3. The IPK and any of its replicas
- **Replica**: An official copy of the IPK.
- **Sister copy**: One of six official copies of the IPK that are stored in the same safe as the IPK and are used as check standards by the BIPM.
- **Transfer standard**: An artifact or apparatus that reproduces the magnitude of a unit of measure in a different, usually more practical, form.

See also

- 1795 in science
- 1799 in science
- General Conference on Weights and Measures (CGPM)
- Gram
- Grave (orig. name of the kilogram, history of)
- Gravimetry
- Inertia
- International Bureau of Weights and Measures (BIPM)
- International Committee for Weights and Measures (CIPM)
- International System of Units (SI)
- Kilogram-force
- Liter
- Mass
- Mass versus weight
- Metric system
- Metric ton
- Milligram per cent
- National Institute of Standards and Technology (NIST)
- Newton
- SI base units
- Standard gravity
- Watt balance
- Weight

Notes

1. The avoirdupois pound is part of both United States customary system of units and the Imperial system of units.
2. One kilogram at rest has an equivalent energy approximately equal to the energy of photons whose frequencies sum to this value.
3. The spelling *kilogram* is the modern spelling used by the International Bureau of Weights and Measures (BIPM), the U.S. National Institute of Standards and Technology (NIST), the UK's National Measurement Office, National Research Council of Canada, and the National Measurement Institute, Australia.
4. The French text (which is the authoritiative text) states "*Il n'est pas autorisé d'utiliser des abréviations pour les symboles et noms d'unités* ..."
5. In professional metrology (the science of measurement), the acceleration of Earth's gravity is taken as standard gravity (symbol: g_n), which is defined as precisely 9.80665 meters per square second (m/s^2). The expression "1 m/s^2" means that *for every second that elapses*, velocity changes an additional 1 meter per second. In more familiar terms: an acceleration of 1 m/s^2 can also be expressed as a rate of change in velocity of precisely 3.6 km/h per second (≈2.2 mph per second).
6. Matter has invariant mass assuming it is not traveling at a relativistic speed with respect to an observer. According to Einstein's theory of special relativity, the relativistic mass (apparent mass with respect to an observer) of an object or particle with rest mass m_0 increases with its speed as $M = \gamma m_0$ (where γ is the Lorentz factor). This effect is vanishingly small at everyday speeds, which are many orders of magnitude less than the speed of light. For example, to change the mass of a kilogram by 1 µg (1 ppb, about the level of detection by current technology) would require moving it at 0.0045% of the speed of light relative to an observer, which is 13.4 km/s (30,000 mph). As regards the kilogram, relativity's effect upon the constancy of matter's mass is simply an interesting scientific phenomenon that has zero effect on the definition of the kilogram and its practical realizations.
7. The same decree also defined the liter as follows: "Liter: the measure of volume, both for liquid and solids, for which the displacement would be that of a cube [with sides measuring] one-tenth of a meter." Original text: "*Litre*, la mesure de capacité, tant pour les liquides que pour les matières sèches, dont la contenance sera celle du cube de la dixièrne partie du mètre."
8. Modern measurements show the temperature at which water reaches maximum density is 3.984 °C. However, the scientists at the close of the 18th century concluded that the temperature was 4 °C.
9. The provisional kilogram standard had been fabricated in accordance with a single, inaccurate measurement of the density of water made earlier by Antoine Lavoisier and René Just Haüy, which showed that one cubic decimeter of distilled water at 0 °C had a mass of 18,841 grains in France's soon-to-be-obsoleted *poids de marc* system. The newer, highly accurate measurements by Lefèvre-Gineau and Fabbroni concluded that the mass of a cubic decimeter of water at the new temperature of 4 °C—a condition at which water is denser—was actually *less massive*, at 18,827.15 grains, than the earlier inaccurate

value assumed for 0 °C water. France’s metric system had been championed by Charles Maurice de Talleyrand‑Périgord. On March 30, 1791, four days after Talleyrand forwarded a specific proposal on how to proceed with the project, the French government ordered a committee known as the Academy to commence work on accurately determining the magnitude of the base units of the new metric system. The Academy divided the task among five commissions. The commission charged with determining the mass of a cubic decimeter of water originally comprised Lavoisier and Haüy but their work was finished by Louis Lefèvre‑Gineau and Giovanni Fabbroni. Neither Lavoisier nor Haüy can be blamed for participating in an initial—and inaccurate—measurement and for leaving the final work to Lefèvre‑Gineau and Fabbroni to finish in 1799. As a member of the *Ferme générale*, Lavoisier was also one of France’s 28 tax collectors. He was consequently convicted of treason during the waning days of the Reign of Terror period of the French Revolution and beheaded on May 8, 1794. Lavoisier’s partner, Haüy, was also thrown into prison and was himself at risk of going to the guillotine but his life was spared after a renowned French naturalist interceded.

10. Prototype No. 8(41) was accidentally stamped with the number 41, but its accessories carry the proper number 8. Since there is no prototype marked 8, this prototype is referred to as 8(41).
11. The other two Pt‑10Ir standards owned by the U.S. are K79, from a new series of prototypes (K64–K80) that were diamond-turned directly to a finish mass, and K85, which is used for watt balance experiments (see *Watt balance,* above).
12. Extraordinary care is exercised when transporting prototypes. In 1984, the K4 and K20 prototypes were hand-carried in the passenger section of separate commercial airliners.
13. Before the BIPM's published report in 1994 detailing the relative change in mass of the prototypes, different standard bodies used different techniques to clean their prototypes. The NIST's practice before then was to soak and rinse its two prototypes first in benzene, then in ethanol, and to then clean them with a jet of bi-distilled water steam.
14. Note that if the 50 µg difference between the IPK and its replicas was entirely due to wear, the IPK would have to have lost 150 million billion more platinum and iridium atoms over the last century than its replicas. That there would be this much wear, much less a *difference* of this magnitude, is thought unlikely; 50 µg is roughly the mass of a fingerprint. Specialists at the BIPM in 1946 carefully conducted cleaning experiments and concluded that even *vigorous* rubbing with a chamois—if done carefully—did not alter the prototypes’ mass. More recent cleaning experiments at the BIPM, which were conducted on one particular prototype (K63), and which benefited from the then-new NBS‑2 balance, demonstrated 2 µg stability.

    Many theories have been advanced to explain the divergence in the masses of the prototypes. One theory posits that the relative change in mass between the IPK and its replicas is not one of loss at all and is instead a simple matter that the IPK has *gained less* than the replicas. This theory begins with the observation that the IPK is uniquely stored under three nested bell jars whereas its six sister copies stored alongside it in the vault as well as the other replicas dispersed throughout the world are stored under only two. This theory is also founded on two other facts: that platinum has a strong affinity for mercury, and that atmospheric mercury is significantly more abundant in the atmosphere today than at the time the IPK and its replicas were manufactured. The burning of coal is a major contributor to atmospheric mercury and both Denmark and Germany have high coal shares in electrical generation. Conversely, electrical generation in France, where the IPK is stored, is mostly nuclear. This theory is supported by the fact that the mass divergence rate—relative to the IPK—of Denmark’s prototype, K48, since it took possession in 1949 is an especially high 78 µg per century while that of Germany’s prototype has been even greater at 126 µg/century ever since it took possession of K55 in 1954. However, still other data for other replicas isn’t supportive of this theory. This mercury absorption theory is just one of many advanced by the specialists to account for the relative change in mass. To date, each theory has either proven implausible, or there are insufficient data or technical means to either prove or disprove it.
15. Even well respected organizations incorrectly represent the relative nature of the mass divergence as being one of mass loss, as exemplified by this site at Science Daily (http://www.sciencedaily.com/releases/2007/09/070921110735.htm), and this site at PhysOrg.com (http://www.physorg.com/news109595312.html), and this site at Sandia National Laboratories. (http://www.sandia.gov/LabNews/080201.html) The root of the problem is often the reporters' failure to correctly interpret or paraphrase nuanced scientific concepts, as exemplified by this 12 September 2007 story (http://www.physorg.com/news108836759.html) by the Associated Press published on PhysOrg.com. In that AP story, Richard Davis—who used to be the NIST's kilogram specialist and now works for the BIPM in France—was correctly quoted by the AP when he stated that the mass change is a relative issue. Then the AP summarized the nature of issue with this lead-in to the story: "*A kilogram just isn't what it used to be. The 118-year-old cylinder that is the international prototype for the metric mass, kept tightly under lock and key outside Paris, is mysteriously losing weight — if ever so slightly*". Like many of the above-linked sites, the AP also misreported the age of the IPK, using the date of its adoption as the mass prototype, not the date of the cylinder’s manufacture. This is a mistake even Scientific American fell victim to in a print edition.
16. The mean change in mass of the first batch of replicas relative to the IPK over one hundred years is +23.5 µg with a standard deviation of 30 µg. Per *The Third Periodic Verification of National Prototypes of the Kilogram (1988–1992)*, G. Girard, Metrologia **31** (1994) Pg. 323, Table 3. Data is for prototypes K1, K5, K6, K7, K8(41), K12, K16, K18, K20, K21, K24, K32, K34, K35, K36, K37, K38, and K40; and excludes K2, K23, and K39, which are treated as outliers. This is a larger data set than is shown in the chart at the top of this section, which corresponds to Figure 7 of G. Girard’s paper.
17. Assuming the past trend continues, whereby the mean change in mass of the first batch of replicas relative to the IPK over one hundred years was +23.5 σ 30 µg.
18. The combined relative standard uncertainty (CRSU) of these measurements, as with all other tolerances and uncertainties in this article unless otherwise noted, have a 1σ standard deviation, which equates to a confidence level of about 68%; that is to say, 68% of the measurements fall within the stated tolerance.

19. The Planck constant's unit of measure, the joule-second (J·s), may perhaps be more easily understood when expressed as a joule per hertz (J/Hz). Universally, an individual photon has an energy that is proportional to its frequency. This relationship is $6.626\,069\,57(29) \times 10^{-34}$ J/Hz.
20. The proposal originally was to redefine the kilogram as the mass of $84{,}446{,}886^3$ carbon-12 atoms.[70] The value 84,446,886 had been chosen because it has a special property; its cube (the proposed new value for the Avogadro constant) is evenly divisible by twelve. Thus with that definition of the kilogram, there would have been an integer number of atoms in one gram of ^{12}C: 50,184,508,190,229,061,679,538 atoms. The uncertainty in the Avogadro constant narrowed since this proposal was first submitted to *American Scientist* for publication. The 2010 CODATA value for the Avogadro constant ($6.02214129(27) \times 10^{23}$) has a relative standard uncertainty of 50 parts per billion and the only cube root values within this uncertainty must fall within the range of $84{,}446{,}887.4 \pm 1.2$; that is, there are only two integer cube roots (…87 and …88) in that range and the value 84,446,886 falls outside of it. Neither of the two integer values within that range possess the property of their cubes being divisible by twelve; one gram of ^{12}C could not comprise an integer number of atoms.
21. The sphere shown in the photograph has an out-of-roundness value (peak to valley on the radius) of 50 nm. According to ACPO, they improved on that with an out-of-roundness of 35 nm. On the 93.6 mm diameter sphere, an out-of-roundness of 35 nm (undulations of ±17.5 nm) is a fractional roundness ($\Delta r / r$) $= 3.7 \times 10^{-7}$. Scaled to the size of Earth, this is equivalent to a maximum deviation from sea level of only 2.4 m. The roundness of that ACPO sphere is exceeded only by two of the four fused-quartz gyroscope rotors flown on Gravity Probe B, which were manufactured in the late 1990s and given their final figure at the W.W. Hansen Experimental Physics Lab (http://hepl.stanford.edu/) at Stanford University. Particularly, “Gyro 4” is recorded in the Guinness database of world records (their database, not in their book) as *the* world’s roundest man-made object. According to a published report (221 kB PDF, here (http://aa.stanford.edu/aeroastro/posters2007/Polhode_Motion.pdf)) and the GP‑B public affairs coordinator at Stanford University, of the four gyroscopes onboard the probe, Gyro 4 has a maximum surface undulation from a perfect sphere of 3.4 ±0.4 nm on the 38.1 mm diameter sphere, which is a $\Delta r / r = 1.8 \times 10^{-7}$. Scaled to the size of Earth, this is equivalent to an undulation the size of North America rising slowly up out of the sea (in molecular-layer terraces 11.9 cm high), reaching a maximum elevation of 1.14 ±0.13 m in Nebraska, and then gradually sloping back down to sea level on the other side of the continent.
22. In 2003, the same year the first gold-deposition experiments were conducted, physicists found that the only naturally occurring isotope of bismuth, ^{209}Bi, is actually very slightly radioactive, with the longest known radioactive half-life of any naturally occurring element that decays via alpha radiation—a half-life of $(19 \pm 2) \times 10^{18}$ years. As this is 1.4 billion times the age of the universe, ^{209}Bi is considered a stable isotope for most practical applications (those unrelated to such disciplines as nucleocosmochronology and geochronology). In other terms, 99.999999983% of the bismuth that existed on Earth 4.567 billion years ago still exists today. Only two mononuclidic elements are heavier than bismuth and only one approaches its stability: thorium. Long considered a possible replacement for uranium in nuclear reactors, thorium can cause cancer when inhaled because it is over 1.2 billion times more radioactive than bismuth. It also has such a strong tendency to oxidize that its powders are pyrophoric. These characteristics make thorium unsuitable in ion-deposition experiments. See also *Isotopes of bismuth*, *Isotopes of gold* and *Isotopes of thorium*.
23. Criterion: A combined total of at least five occurrences on the British National Corpus and the Corpus of Contemporary American English, including both the singular and the plural for both the *-gram* and the *-gramme* spelling.
24. The practice of using the abbreviation "mcg" rather than the SI symbol "µg" was formally mandated in the US for medical practitioners in 2004 by the Joint Commission on Accreditation of Healthcare Organizations (JCAHO) in their “Do Not Use” List: Abbreviations, Acronyms, and Symbols (http://www.aapmr.org/hpl/pracguide/jcahosymbols.htm) because "µg" and "mg" when handwritten can be confused with one another, resulting in a thousand-fold overdosing (or underdosing). The mandate was also adopted by the Institute for Safe Medication Practices. (http://www.ismp.org/)

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3. *Gramme, le poids absolu d'un volume d'eau pure égal au cube de la centième partie du mètre , et à la température de la glace fondante.* ; The term *poids absolu* was at the time used alongside *masse* for the concept of "mass" (which latter term had first been introduced in its strict physical sense in English in 1704). See e.g. Mathurin Jacques Brisson, *Dictionnaire raisonné de toutes les parties de la Physique*, Volland, 1787, p. 401 (https://books.google.ch/books?id=1i0mJteVrOoC&pg=PA401).
4. http://www.bipm.org/utils/common/pdf/CGPM-2014/25th-CGPM-Resolutions.pdf
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www.perseus.tufts.edu/hopper/text?doc=Perseus:text:1999.04.0057:entry=gra/mma), citing the 10th-century work *Geoponica* and a 4th-century papyrus edited in L. Mitteis, *Griechische Urkunden der Papyrussammlung zu Leipzig*, vol. i (1906), 62 ii 27.

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External links

- NIST Improves Accuracy of ‘Watt Balance’ Method for Defining the Kilogram (http://www.nist.gov/public_affairs/releases/electrokilogram.cfm)
- The UK’s National Physical Laboratory (NPL): Are any problems caused by having the kilogram defined in terms of a physical artefact? (FAQ - Mass & Density) (http://www.npl.co.uk/reference/faqs/are-any-problems-caused-by-having-the-kilogram-defined-in-terms-of-a-physical-artefact-(faq-mass-and-density))
- NPL: *NPL watt balance (http://www.npl.co.uk/engineering-measurements/mass-force-pressure/mass/research/npl-watt-balance)*
- Metrology in France: *Watt balance (http://www.french-metrology.com/en/feature/watt-balance.asp)*

Wikimedia Commons has media related to ***Kilogram***.

External images

BIPM: The IPK in three nested bell jars (http://www.bipm.org/en/bipm/mass/image-ipk.html)

NIST: K20, the US National Prototype Kilogram (http://patapsco.nist.gov/imagegallery/retrieve.cfm?imageid=49&dpi=72&fileformat=jpg) resting on an egg crate fluorescent light panel

BIPM: *Steam cleaning a 1 kg prototype before a mass comparison (http://www.bipm.org/en/scientific/mass/pictures_mass/cleaning.html)*

- Australian National Measurement Institute: *Redefining the kilogram through the Avogadro constant (http://www.measurement.gov.au/SCIENCETECHNOLOGY/Pages/MassandRelatedQuantities.aspx)*
- International Bureau of Weights and Measures (BIPM): Home page (http://www.bipm.org/en/home/)
- NZZ Folio: *What a kilogram really weighs (http://www.nzzfolio.ch/www/d80bd71b-b264-4db4-afd0-277884b93470/showarticle/fb0ba22e-46b7-43a5-8320-ef16483b7e91.aspx)*
- NPL: *What are the differences between mass, weight, force and load? (http://www.npl.co.uk/reference/faqs/what-are-the-differences-between-mass,-weight,-force-and-load-(faq-mass-and-density))*
- BBC: *Getting the measure of a kilogram (http://news.bbc.co.uk/2/hi/science/nature/7084099.stm)*
- NPR: *This Kilogram Has A Weight-Loss Problem (http://www.npr.org/templates/story/story.php?storyId=112003322)*, an interview with National Institute of Standards and Technology physicist Richard Steiner
- Avogadro and molar Planck constants for the redefinition of the kilogram (http://www.inrim.it/Nah/Web_Nah/home.htm)
- Realization of the awaited definition of the kilogram (http://www.inrim.it/know/)

BIPM: The IPK and its six sister copies in their vault (http://www.bipm.org/en/scientific/mass/pictures_mass/vault.html)

The Age: Silicon sphere for the Avogadro Project (http://www.theage.com.au/ffximage/2007/06/14/rgN1506_csiro_wideweb__470x343,0.jpg)

NPL: The NPL’s Watt Balance project (http://www.npl.co.uk/content/conMediaFile/1083)

NIST: This particular Rueprecht Balance (http://museum.nist.gov/object.asp?ObjID=51), an Austrian-made precision balance, was used by the NIST from 1945 until 1960

BIPM: The FB‑2 flexure-strip balance (http://www.bipm.org/en/scientific/mass/research_mass/flexure-strip.html), the BIPM’s modern precision balance featuring a standard deviation of one ten-billionth of a kilogram (0.1 µg)

BIPM: Mettler HK1000 balance (http://www.bipm.org/en/scientific/mass/pictures_mass/mettler.html), featuring 1 µg resolution and a 4 kg maximum mass. Also used by NIST and Sandia National Laboratories’ Primary Standards Laboratory

Micro-g LaCoste: FG‑5 absolute gravimeter, (http://www.microglacoste.com/images/FG5.small.jpg) (diagram (http://www.microglacoste.com/images/fg5schem.jpg)), used in national laboratories to measure gravity to 2 µGal accuracy

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