Guide to the Consensus Value of the kilogram

CCM -TGPfD-kg*

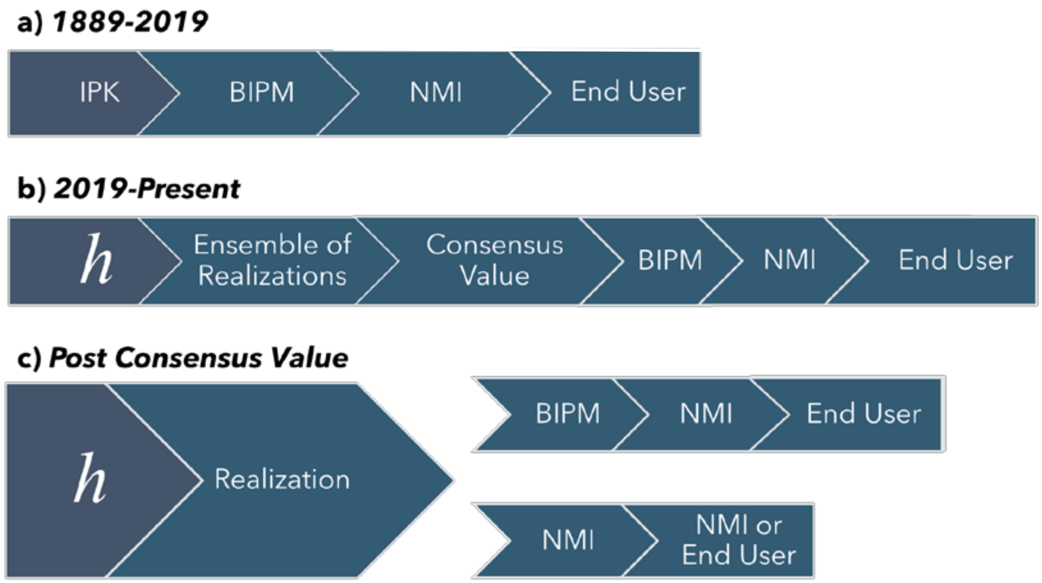

Figure 1. The dissemination paths of the kilogram from its definition 1889-2019 (a) and since the 2019 redefinition of the kilogram based on the Planck constant (b). Since 2021 the kilogram has been disseminated through the Consensus Value of the kilogram. In the future (c) the kilogram may be realized directly from independent experiments.

The **Consensus Value of the kilogram** (CV-kg) is the one-kilogram reference for the SI mass unit based on the fixed value of the Planck constant. It is represented by an aggregate of measurements performed by experiments at the **Bureau International des Poids et Mesures** and **National Metrology Institutes** (NMIs) from around the world that can **realize** the kilogram directly from the **Planck constant**. It can be considered as the global **realization** of the kilogram within the International System of Units (SI).

The Consensus Value was conceived when **comparisons of realization experiments** showed disagreement between their results.[1] A disagreement of sufficient magnitude that the mass unit would vary depending on the NMI that realized it. Consequently, the international metrology community agreed that to ensure world-wide consistency, dissemination of the kilogram would proceed through an average of measurements from the set of global realization experiments rather than from any one individually, which is the future goal (Figure 1c). The CV-kg is represented by this average and is effectively the world's best estimate of the SI kg and as such is set to be equal to one kilogram by definition. It has been assigned a standard uncertainty of 20 μg, reflecting the typical uncertainty of a mature realization experiment and

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of sufficient magnitude to bring the highest accuracy realization experiments into agreement.

The global set or **ensemble of realization experiments** that underlies the CV-kg is not static and can evolve with technological improvements and the integration of new experiments. Such changes are tracked and periodically instituted as a correction to the global mass scale, that is, in the calibrated mass value of all objects traceable to the SI. The periodic correction, called the **Consensus Adjustment of the kilogram** (CA-kg) is accounted for by NMIs and disseminated globally through their laboratories. As of early 2025 the total adjustment since the redefinition in 2019 has been small with a reduction of about 7 μg/kg and therefore insignificant for most end users. It is recalculated approximately every two to four years after a new Key Comparison of realization experiments has been completed. A Consensus Value of the kilogram will no longer be necessary once individual realization experiments have reached sufficient agreement that they may disseminate mass independently while ensuring global consistency. [2]

Historical Development

Prior to revision of the International System of Units (SI) on the 20th of May 2019, the unit kilogram was defined with zero uncertainty as the mass of the **International Prototype of the kilogram** (IPK), a cylindrical mass standard made of platinum-iridium alloy. The IPK, being a physical object, could be directly compared to other mass standards to determine their value by measuring only the mass difference between them. Such comparisons could be repeated from one standard to the next and used to disseminate the unit kilogram from the IPK to end users through an unbroken chain of calibrations (Figure 1a). With the redefinition of 2019,[3] the kilogram is now defined by the fixed value of the Planck constant. Planck's constant, a fundamental constant of nature, like the speed of light in vacuum, cannot be compared directly to a physical artefact, therefore realization experiments must be used to link it to physical mass standards through which the kilogram can be disseminated. The realization experiments (current precision methods are described in the **'mise en pratique' of the kilogram**[4]) are complex, instead of measuring small differences between similar objects, they rely on a large number of high accuracy absolute measurements that are combined into a single experiment.

In preparation for the 2019 revision of the SI, the consistency in results from available realization experiments was tested,[1] and it was found that some experiments did not agree within their assigned uncertainties. Therefore, rather than using individual experiments to disseminate the mass unit, the Consensus Value of the kilogram was conceived as a method to conserve global consistency by disseminating mass from an average result of global realization experiments (Figure 1b). The consistency is now rechecked periodically through international Key Comparisons, which track both how individual realization experiments evolve in time, as well as any changes to the global average their results contribute to. When these **ongoing Key**

Comparisons of realization experiments demonstrate sufficient agreement amongst participant experiments, independent realizations will be used to disseminate the mass unit.

Implementation

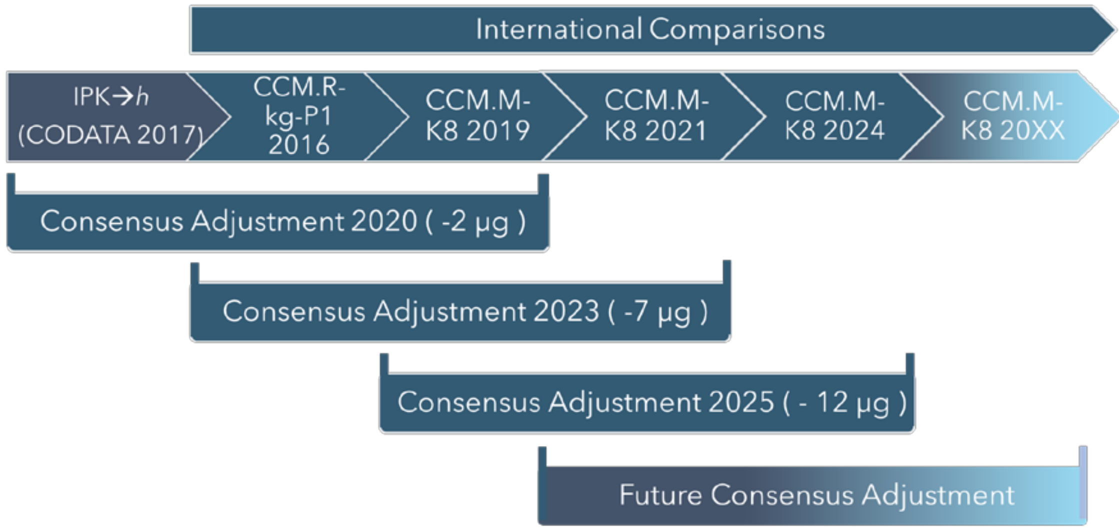

Figure 2. The Consensus Adjustment of the kilogram is based on the result of the three most recent key comparisons of realization experiments. The Consensus Adjustment of 2025 results in the global mass scale getting lighter by -12 µg/kg since the redefinition of 2019.

The BIPM organises the ongoing Key Comparison approximately every two to four years for participant NMIs that operate mass realization experiments meeting a threshold for accuracy. These experiments make up the global ensemble of mass realization experiments and rely generally on one of two techniques to calibrate a physical mass from the Planck constant:

1. The **X-ray crystal density method** uses the Planck constant to determine the mass of a silicon atom in order to determine the mass of a near perfect sphere of isotopically-enriched monocrystalline silicon by summing the mass of all atoms it contains.

2. The **Kibble balance** compares the gravitational weight of a physical mass to a known electromagnetic force that is dependent on the Planck constant through quantum electrical standards.

During the Key Comparison, mass artefacts are calibrated by each participant traceable to their realization experiment and brought to the BIPM to be compared with each other and with standards of the BIPM. The BIPM working standards used in the comparison have then effectively been calibrated by each participating NMI's realization experiment and the value assigned for that comparison is simply the average of the NMI's results weighted by their uncertainty. The BIPM carefully maintains their working standards so that any physical change due to contamination or wear is accounted for with low uncertainty and any deviation from one iteration of the Key Comparison to the next can be attributed solely to changes in the ensemble of realization experiments. Furthermore, since the BIPM standards had been compared with the IPK before redefinition, the difference in their values based on the IPK and those based on the ensemble of realizations can be determined. Changes in the running average of this difference for three successive key comparisons yields the Consensus Adjustment of the kilogram (Figure 2). It is recalculated after each key comparison has been completed to capture the evolution of the global ensemble of realization experiments that underlies the Consensus Value of the kilogram and the global mass scale. While the Consensus adjustment is calculated as the change in the running average of Key comparisons, it is expressed as a cumulative change since redefinition of the kilogram in 2019.

Present status and outlook

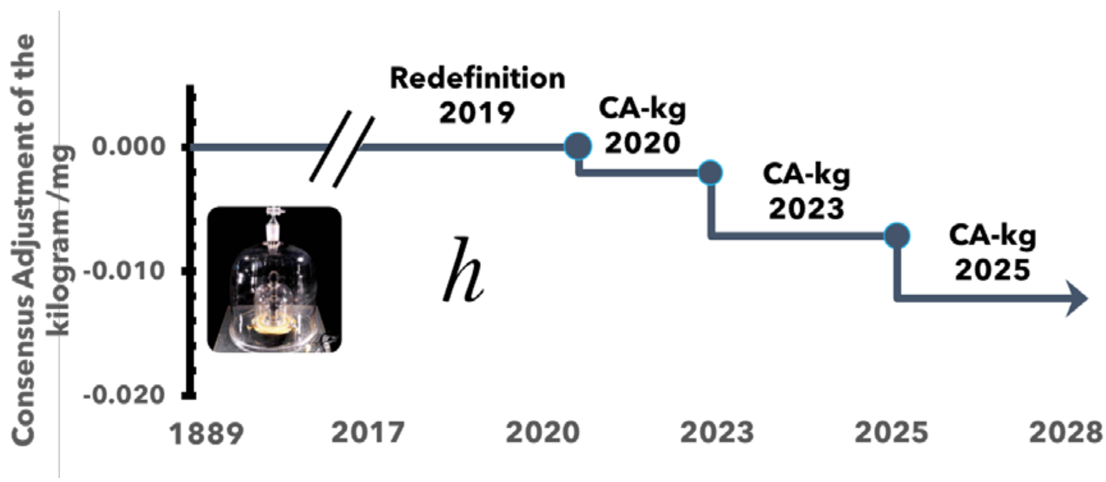

Figure 3. Changes in the global mass scale as represented by the Consensus Adjustment of the kilogram. It arises due to the evolution of realization experiments that underlie the Consensus Value of the kilogram. The line represents the adjustments applied by year relative to the value of the kg upon redefinition of the SI.

The *Consensus Adjustment of the kilogram*, a term sometimes used interchangeably with *Consensus Value of the kilogram*, has been determined twice since the redefinition of the SI in 2019. Figure 3 illustrates those adjustments up to 2025. An adjustment in 2020[5] yielded a change of -2 µg, with another in 2023[6] yielding a cumulative adjustment of -7 µg since the redefinition of 2019. The measurements of the 2024 key comparison are complete. There was a significant change in the results between the first comparison (2016) and subsequent Key Comparisons (2019, 2021, 2024). As a result, the Consensus Adjustment in 2025 is expected change by -5 µg for a cumulative adjustment of -12 µg since redefinition. This remains below the uncertainty in the Consensus Value of the kilogram and while it may be observable to some laboratories, it will not have significant impact. Physical drift of masses in time can still be tracked by removing changes in the CA-kg between their calibrations.

Laboratories with realization experiments have been making a concerted effort to identify the source of disagreement in their results in order to accelerate the transition to dissemination from independent realizations by NMIs or the BIPM.

References and Further Reading

[1] D. B. Newell *et al.*, "The CODATA 2017 values of h, e, k, and NA for the revision of the SI," *Metrologia*, vol. 55, no. 1, p. L13, Jan. 2018, doi: 10.1088/1681-7575/aa950a.

[2] S. Davidson and M. Stock, "Beginning of a new phase of the dissemination of the kilogram," *Metrologia*, vol. 58, no. 3, p. 033002, Apr. 2021, doi: 10.1088/1681-7575/abef9f.

[3] M. Stock, R. Davis, E. Mirandés, and M. Milton, "The revision of the SI - the result of three decades of progress in metrology," *Metrologia*, vol. 56, Feb. 2019, doi: 10.1088/1681-7575/ab0013.

[4] Consultative Committee for Mass and Related Quantities, "Mise en pratique for the definition of the kilogram in the SI," SI Brochure- 9th edition- Appendix 2, Jul. 2021. Available online from www.bipm.org.

[5] M. Stock and S. Davidson, "Report on the Calculation of the CCM Consensus Value for the Kilogram 2020," Dec. 2020. Available online from www.bipm.org.

[6] M. Stock and S. Davidson, "Report on the calculation of the CCM Consensus Value 2023". Available online from www.bipm.org.

Glossary of Terms

Bureau International des Poids et Mesures (BIPM): An intergovernmental metrology organization whose mandate is to support the global coherence of the SI system of units.

Consensus Adjustment of the kilogram (CA-kg): An adjustment to the global mass scale implemented periodically in response to changes in measurements from the global ensemble of realization experiments. It is calculated as a change in the average result of the last three key comparisons, but expressed as a cumulative change since the previous definition of the kilogram.

Consensus Value of the kilogram (CV-kg): Representation of the SI unit kilogram based on an aggregate of measurements from the global ensemble of realization experiments that can determine mass from the Planck constant. It is the global realization of the SI kg.

Global ensemble of mass realization experiments: An evolving set of experiments usually developed by NMIs that can realize mass from the Planck constant. The set includes experiments that meet a certain threshold for accuracy and which participate in the ongoing key comparison of mass realizations.

International Protype of the Kilogram: A physical artefact made of platinum iridium alloy whose mass defined the unit kilogram prior to its redefinition in 2019.

Kibble Balance: A device used to realize the kilogram by balancing the force generated by a mass artefact with an electromagnetic force whose value is directly tied to the Planck constant through quantum electrical standards.

***Mise en Pratique* of the kilogram:** A practical guide for the realization of the kilogram from its definition by the fixed value of the Planck constant.

National Metrology Institute (NMI): A sovereign nations officially designated Metrology organization whose responsibility is to support globally consistent measurement capability and measurement standards.

(Ongoing) key comparisons of mass realizations: A comparison of global mass realization experiments run periodically by the BIPM. Standards whose masses have been determined by participant's realization experiments are sent to the BIPM where they are compared with each other and with BIPM standards to track evolution in the Global ensemble of mass realization experiments.

Planck Constant: A fundamental constant of nature ubiquitous in physics that, for example, relates the energy of a photon to its frequency.

Realization experiment (realize): An experiment that links the definition of a unit in the SI to a physical artefact or device that can be used practically to disseminate that unit.

X-ray crystal density method: A method to realize the kilogram traceably to the Planck constant. In this method the mass of a manufactured, near perfect, sphere of isotopically-enriched single-crystal silicon is determined by summing the mass of the silicon atoms contained within its known volume.

Document History

Version	Date	Approval	Remarks
1.0	15 Dec 2024		Draft document produced by CCM WGM Chair and Vice-Chair
1.1	March 24th, 2025		Updated in response to early comments
1.2	May 8th, 2025		Updated with aggregated comments/edits from CCM -TGPfD-kg
1.3	May 20th, 2025		Updated with edits based on aggregated suggestions from colleagues of TG members.
1.4	June 23rd		Updated after WGM comments and TGPfD-kg meeting.
1.5	June 24th		Updated based on comments during WGM meeting.
1.6	July 15th		Final update from TG. Version for publication without document history.
1.7	July 16th		Updated title to “Guide to the Consensus Value of the kilogram”