Towards a Revised International System (SI) of Units of Measurement

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Outline

1. Background
   - evolution of the International System SI
   - brief history of changes in the SI
   - essential requirements for an SI
2. Why the need to revise the SI
3. Proposed definitions
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5. Where are we now?
6. Conclusion

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Evolution of the SI

emu

cgs (1881?) → MKS → MKSA → SI (1960)

esu

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A Brief History of Changes in the SI

1960 SI adopted by the 11th CGPM – kg, m, s, A, K, cd

1960 metre redefined in terms of Kr 86 radiation 11th CGPM

1967 second redefined in terms Cs transition 13th CGPM.

1971 mole defined as base unit (14th CGPM)

1983 metre redefined based on fixed value of c (17th CGPM)

1990 Electrical units based on conventional values for $2e/h$ and h/e^2, K_J and R_K

2018 kg, A, K, mole, redefined; definitions of m, s, cd re-stated (26th CGPM)???

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Essential requirements for an SI

- Long-term stability,
- Internally self consistent ,
- Practically realizable
- Uniform and accessable world-wide

Why the need to revise, redefine

- A long standing objective to have a system based on invariant constants of nature to fully meet essential requirements
- The kilogram – last physical artefact standard, drifting
- The electrical units – maintained outside of SI
- International support for revision - under discussion for many years, Resolutions adopted by last four CGPMs, since 1995

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Proposed revision

- SI base units: kilogram, kelvin, ampere, mole, second, metre, candela retained
- Definitions to be in “explicit-constant” format based on seven defining constants
- Base Units: kilogram, kelvin, ampere, mole to be re-defined
- Base Units: second, metre, candela to be restated in same format for consistency

Seven Defining Fundamental Constants

- Hyperfine splitting frequency of the caesium 133 atom v
- Speed of light c
- Planck constant h
- Elementary charge e
- Boltzmann constant k
- Avogadro constant N_A
- Luminous efficacy K_{cd}

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Proposed new definition – the ampere

The **ampere**, symbol A, is the SI unit of electric current. It is defined by taking the fixed numerical value of the elementary charge e to be 1.602 176 620 8X x 10 $^{-19}$ when expressed in the unit C, which is equal to A s , where the second is defined in terms of $\Delta\nu_{Cs}$.

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Conceptually: The flow rate of a certain number of electrons per second.

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Proposed new definitions – the kilogram

The **kilogram**, symbol *kg*, is the SI unit of mass. It is defined by taking the fixed numerical value of the Planck constant *h* to be 6.626 070 040 X x 10 $^{-34}$ when expressed in the unit J s, which is equal to kg m^2 s^{-1} , where the metre and second are defined in terms of the speed of light and the hyperfine splitting frequency of caesium 133.

Conceptually: A multiple of the mass equivalent of the energy of a photon at the Cs hyperfine frequency. In practice to be realised in terms of electromagnetic force or in terms of the mass of an atom.

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Proposed new definition – the kelvin

The **kelvin**, symbol K, is the SI unit of thermodynamic temperature. It is defined by taking the fixed numerical value of the Boltzmann constant *k* to be 1.380 648 52X x 10^{-23} when expressed in the unit J K^{-1}, which is equal to kg m^2 s^{-2} K^{-1}, where the kilogram, metre and second are defined in terms of h, c, and $\Delta\nu_{Cs}$.

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Conceptually: The change in temperature corresponding to a specified change in thermal energy.

Proposed new definition – the ampere

The **ampere**, symbol A, is the SI unit of electric current. It is defined by taking the fixed numerical value of the elementary charge e to be 1.602 176 620 8X x 10 $^{-19}$ when expressed in the unit C, which is equal to A s , where the second is defined in terms of $\Delta\nu_{Cs}$.

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Conceptually: The flow rate of a certain number of electrons per second.

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Proposed new definition – the mole

The **mole**, symbol mol, is the SI unit of amount of substance of a specified elementary entity, which may be an atom, molecule, ion, electron, any other particle or a specified group of such particles. It is defined by taking the fixed numerical value of the Avogadro constant N_A be 6.022 140 857 X x 10^{23} when expressed in the unit mol^{-1}.

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Conceptually: A number of specified entities of substance.

Proposed restated definition – the second

The **second**, symbol s, is the SI unit of time. It is defined by taking the fixed numerical value of the caesium frequency $\Delta\nu_{Cs}$, the hyperfine splitting frequency of the caesium 133 atom, to be

9 192 631 770 when expressed in the unit Hz, which is equal to s^{-1} for periodic phenomena.

Conceptually: A specified number of periods (cycles) of radiation from the Cs133 hyperfine splitting transition.

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Proposed restated definition – the metre

The **metre**, symbol m, is the SI unit of length. It is defined by taking the fixed numerical value of the speed of light in vacuum c to be 299 792 458 when expressed in the unit m/s, where the second is defined in terms of the caesium frequency $\Delta\nu_{Cs}$,.

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Conceptually: the distance that light travels in a certain fraction of a second.

Proposed restated definition – the candela

The **candela**, symbol cd, is the SI unit of luminous intensity. It is defined by taking the fixed numerical value of the luminous efficacy of monochromatic radiation of frequency 540x10 ^{12} Hz, K_{cd} to be 683 when expressed in the unit Lm W^{-1} , which is equal to cd sr W^{-1} or, kg^{-1} m^{-2} s^{3} cd sr, where the kilogram, metre and second are defined in terms of *h, c*, and $\Delta\nu_{Cs}$.

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Conceptually: A specified amount of radiated power per steradian of monochromatic radiation at a specific frequency.

Key Conditions to be met before Redefinition

- Consistent values for *h* from at least 3 independent experiments, including watt-balance and XRCD
- At least one of these to have uncertainty not greater than 2×10^{-8}
- Mass standards used in the experiments to be compared as directly as possible with the international prototype
- Procedures for future realization and dissemination of kg validated
- Uncertainty of Boltzmann constant *k* to be of order of 1×10^{-6} based on different methods of primary thermometry
- Mises en pratique in place for all new definitions
- Initiate awareness campaigns to alert user communities

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Where are we now?

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Resolution 1. 25th CGPM 2014: On the future revision of the International System of Units, the SI

encourages

- continued effort in the NMIs, the BIPM, and academic institutions to obtain data relevant to the determination of h, e, k, and N_A with the requisite uncertainties,
- the NMIs to continue acting through the CCs to discuss and review this data,
- the CIPM to continue developing a plan to provide the path via the Consultative Committees and the CCU for implementing Resolution 1 adopted by the CGPM at its 24th meeting (2011), and
- continued effort by the CIPM, together with its Consultative Committees, the NMIs, the BIPM, and other organizations such as the International Organization of Legal Metrology (OIML), to complete all work necessary for the CGPM at its 26th meeting to adopt a resolution that would replace the current SI with the revised SI, provided the amount of data, their uncertainties, and level of consistency are deemed satisfactory.

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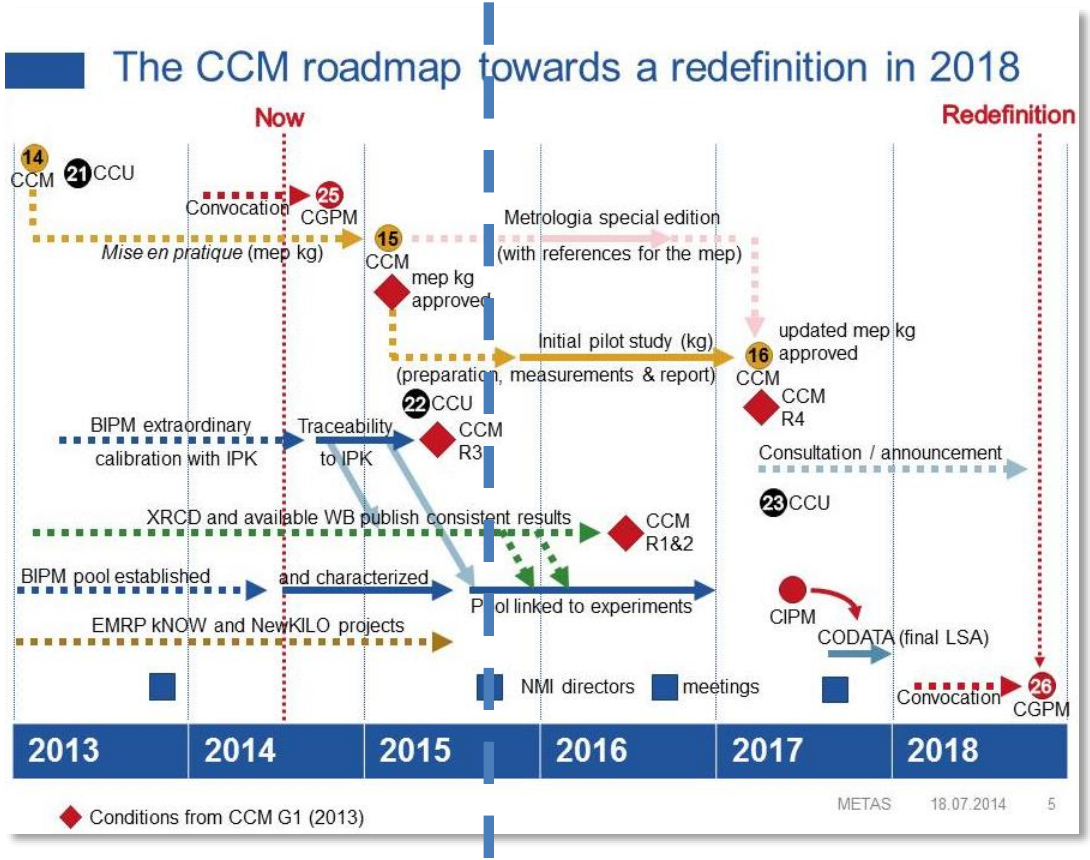
The CCM roadmap



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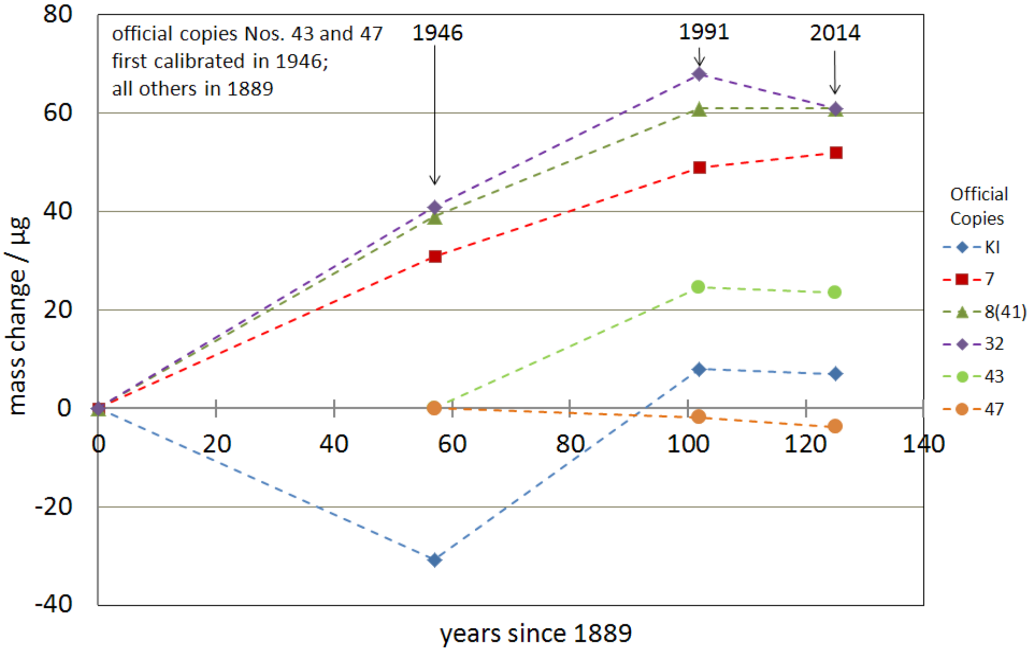
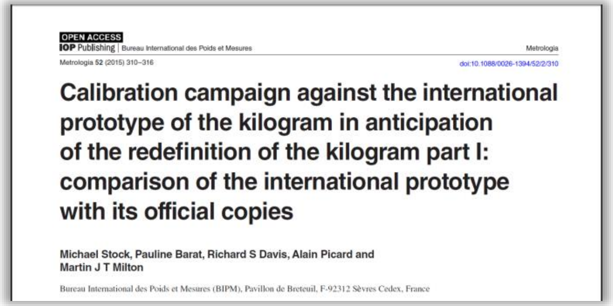
“Extraordinary Calibrations” with the International Prototype of the Kilogram and official copies



- Results published in Metrologia



OPEN ACCESS
IOP Publishing | Bureau International des Poids et Mesures Metrologia
Metrologia 52 (2015) 310–316 doi:10.1088/0026-1394/52/2/310

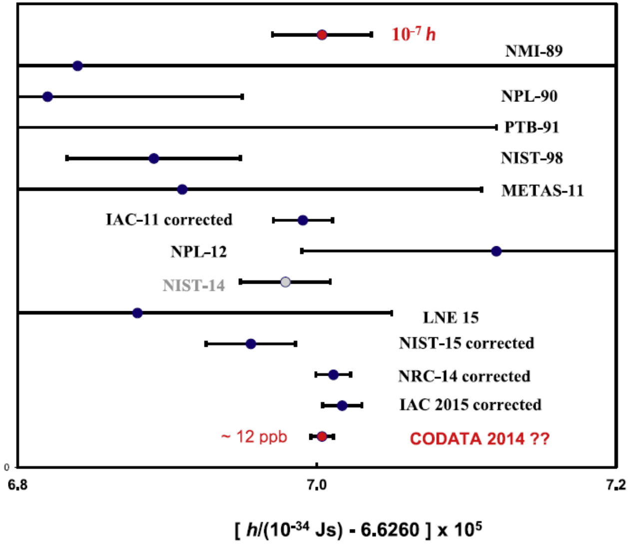
Calibration campaign against the international prototype of the kilogram in anticipation of the redefinition of the kilogram part I: comparison of the international prototype with its official copies

Michael Stock, Pauline Barat, Richard S Davis, Alain Picard and Martin J T Milton

Bureau International des Poids et Mesures (BIPM), Pavillon de Breteuil, F-92312 Sèvres Cedex, France

- Consequences for mass calibration certificates issued by the BIPM have been managed through the CCM.
- All corrected certificates have been issued.

Results published for *h* and *k* during 2015



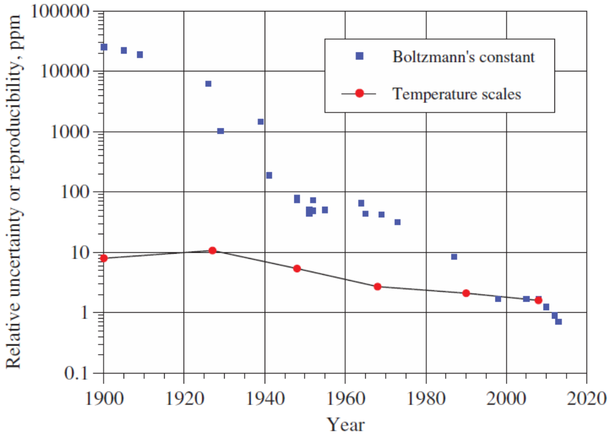
from **Advances in Determination of Fundamental Constants** Karshenboim, Mohr and Newell, J. Phys. Chem. Ref. Data 44, 031101 (2015);

CCM criteria

At least 3 experiments, using 2 different methods with u_r<50 ppb, at least one with u_r<20 ppb.

CCT criteria

Value of k with u_r<1 ppm based on two "fundamentally different" methods with u_r<3 ppm.



from **The Boltzmann constant and the new kelvin** White and Fischer, Metrologia 52 (2015) S213–S216

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Awareness Campaign

- CIPM, CCs, NMIs have been very active

  - papers/ presentations have been delivered at NCSLI, CPEM conferences, ISO CASCO plenary, Meetings of CIML, OIML, others ….
- CIPM has established an Awareness Task Group – including a number of professional communicators
- NMI activities

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Impact on the SI base units after redefinition

- second, candela, metre – no change
- kilogram - takes on uncertainty of *h*
- ampere – negligible uncertainty but a step change of approx. 0.1ppm from the present ‘as maintained’ value
- kelvin – Temperature of triple point of water will take on uncertainty of *k*
- mole will take on uncertainty of $N_A\,h$

Date of Effect

Not yet finalised, possibly

- date of acceptance by CGPM in 2018?
- 1 January 2019?
- World Metrology Day 20 May 2019?

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Conclusion

- All conditions have been met or are well advanced
- Road map for the kg is on target
- Final decision in 2017
- On target to present a Resolution for change to the 26th CGPM in 2018

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Thank you.

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