Revising the International System (SI) of Units of Measurement

Dr Barry Inglis
President, International Committee for Weights and Measures

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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
4. Key conditions to be met before revision
5. Where are we now?
6. Proposed date of change
7. Conclusion

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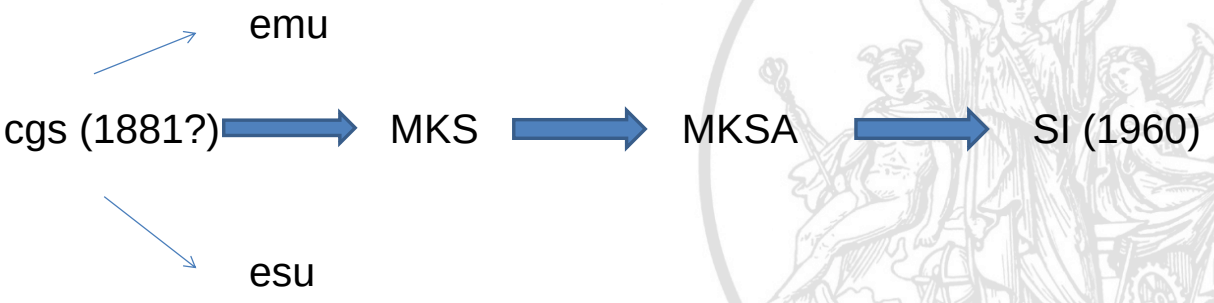
Evolution of the SI



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Essential requirements for an SI

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

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A Brief History of Changes in the SI

1948 Decision of 9th CGPM to establish a practical system of units
1954 Decision of 10th CGPM on the six base units to be used
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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Why the need to revise, redefine

- Long-term stability
- The kilogram – last physical artefact standard, drifting
- The electrical units – currently maintained outside of SI
- International concern – revision under discussion for many years, Resolutions adopted by last four CGPMs, since 1995
- A system based on invariant constants of nature fully meets essential requirements
- Constants are now known experimentally with sufficient accuracy

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Current Definitions

metre, m – in terms of speed of light 'c'

second, s – in terms of radiation from a hyperfine transition in Cs '$\Delta\nu_{Cs}$'

candela, cd – in terms of radiated power W or kg, m, s

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Current Definitions (ctd)

kilogram, kg – mass of prototype material standard, drifting

ampere, A – in terms of force between two infinitely long conductors, difficult to realise, maintained in terms of two quantum mechanical constants Kj and Rk

kelvin, K – in terms of triple point of water

mole, mol – in terms of numbers of atoms in 0.012 kg of carbon 12

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Proposed revision

- SI base units: kilogram, kelvin, ampere, mole, second, metre, candela retained **the same SI not a new system**
- Base Units: kilogram, kelvin, ampere, mole to be re-defined
- Base Units: second, metre, candela to be restated in same format for consistency
- All definitions to be in “explicit-constant” format based on seven defining constants

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Seven Defining Fundamental Constants

- Hyperfine splitting frequency of the caesium 133 atom $\Delta\nu_{Cs}$
- Speed of light c
- Planck constant *h*
- Elementary charge *e*
- Boltzmann constant *k*
- Avogadro constant N_A
- Luminous efficacy *Kcd*

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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.

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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 Δv_{Cs}.

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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 Δv_{Cs}.

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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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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.

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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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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, cd sr kg^{-1} m^{-2} s^3, where the kilogram, metre and second are defined in terms of *h, c*, and $\Delta\nu_{Cs}$.

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Proposed Definitions - Conceptually

metre, m – the distance that light travels in a certain fraction of a second
- speed of light 'c'

second, s – a specified number of periods of radiation from a hyperfine transition '$\Delta\nu_{Cs}$'

candela, cd – a specified amount of radiated power per steradian

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Proposed Definitions - Conceptually (ctd)

kilogram, kg – defined in terms of the mass equivalent of the energy of a photon at the Cs hyperfine frequency ?

ampere, A – flow rate of a certain number of elementary charges per second

kelvin, K – change in temperature corresponding to a specified change in thermal energy

mole, mol – a specified number of particular entities of substance

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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 to have an uncertainty not greater than 2×10^{-8} and agreement within 5×10^{-8}
- Uncertainty of Boltzmann constant *k* to be $< 1 \times 10^{-6}$ with agreement between two different methods of primary thermometry to $< 3 \times 10^{-6}$
- 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
- 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

encouraged

- 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, 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.

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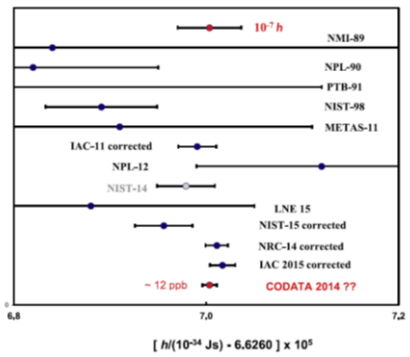
Results published for *h* and *k* during 2015



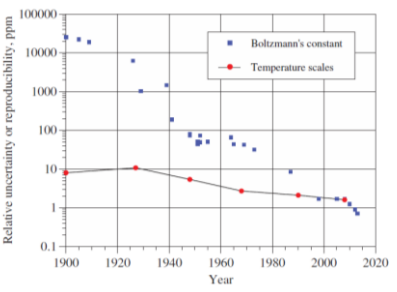
from **Advances in Determination of Fundamental Constants** Karshenboim, Mohr and Newell, J. Phys. Chem. Ref. Data 44, 031101 (2015);

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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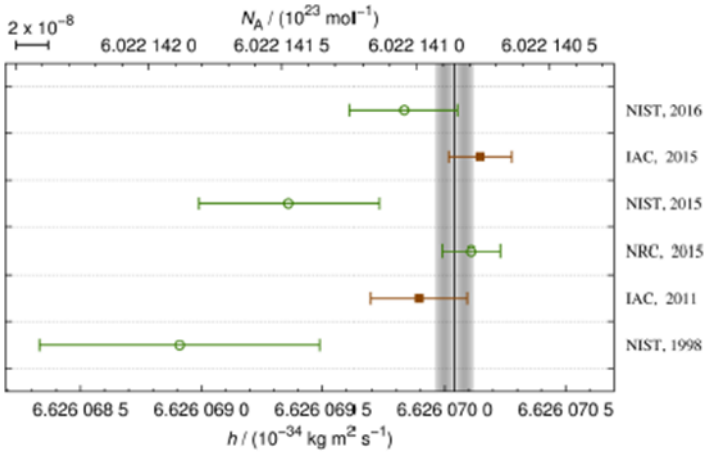
Results published for *h* 2016

- from Realization, maintenance and dissemination of the kilogram in the revised SI, Schlamminger and Bettin , Metrologia 53, 2016



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Deadline for new data

- Experiments in the NMIs are continuing to provide new data for inclusion in the final evaluation of the Constants before revision.
- CIPM has decided on 31 July 2017 as the deadline for new data

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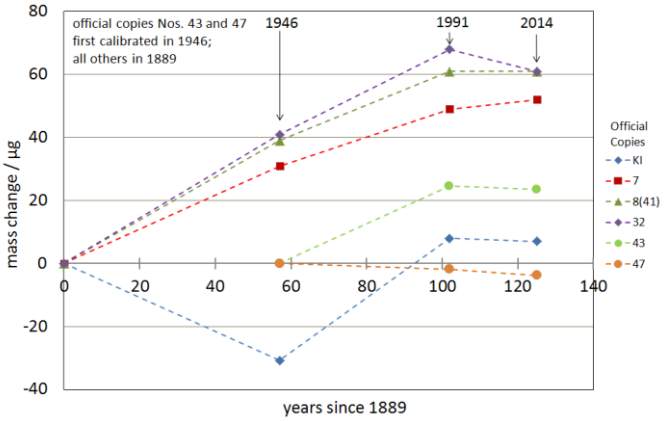
"Extraordinary Calibrations" with the International Prototype of the Kilogram and official copies



- Results published in Metrologia


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

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

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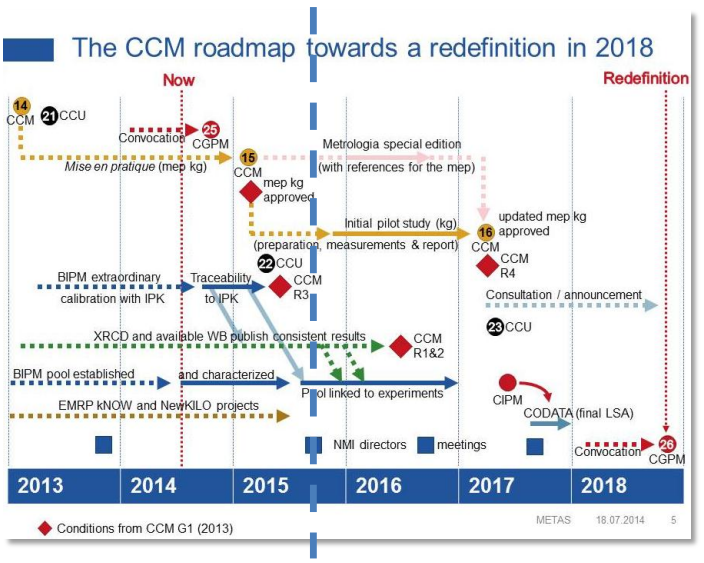
The CCM roadmap



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Mises en pratique

Mises en pratique, or practical methods for realising the units under the proposed revised definitions, have been prepared by the relevant Consultative Committees and are in place or undergoing final revision.

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Awareness Campaign

- CIPM, CCs, NMIs have been very active - papers/ presentations have been delivered at NCSLI, CPEM, scientific institution conferences/meetings, ISO CASCO plenary, meetings of CIML, OIML, meetings of RMOs, seminars, others ….
- CIPM has established an Awareness Task Group – including a number of professional communicators, videos are being produced
- 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*

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Date of Effect

- *Date of acceptance by CGPM in 2018?*
- 1 January 2019?

- **World Metrology Day 20 May 2019!!!!**

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Conclusion

- The proposed re-definitions **do not** constitute a 'new' system (SI)
- All conditions for re-definition have been met or are well advanced
- Road map for continuity of the kg is on target
- Experiments for the determination of values of Constants, are continuing, deadline 31 July 2017
- On target to present a Resolution for change to the 26th CGPM in 2018 (26th CGPM to be held at the *Palais des Congrès de Versailles* on 13 – 16 November 2018)
- Proposed date of effect 20 May 2019 (World Metrology Day 2019!)

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Thank you

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