Report from the Consultative Committee for Units (CCU)

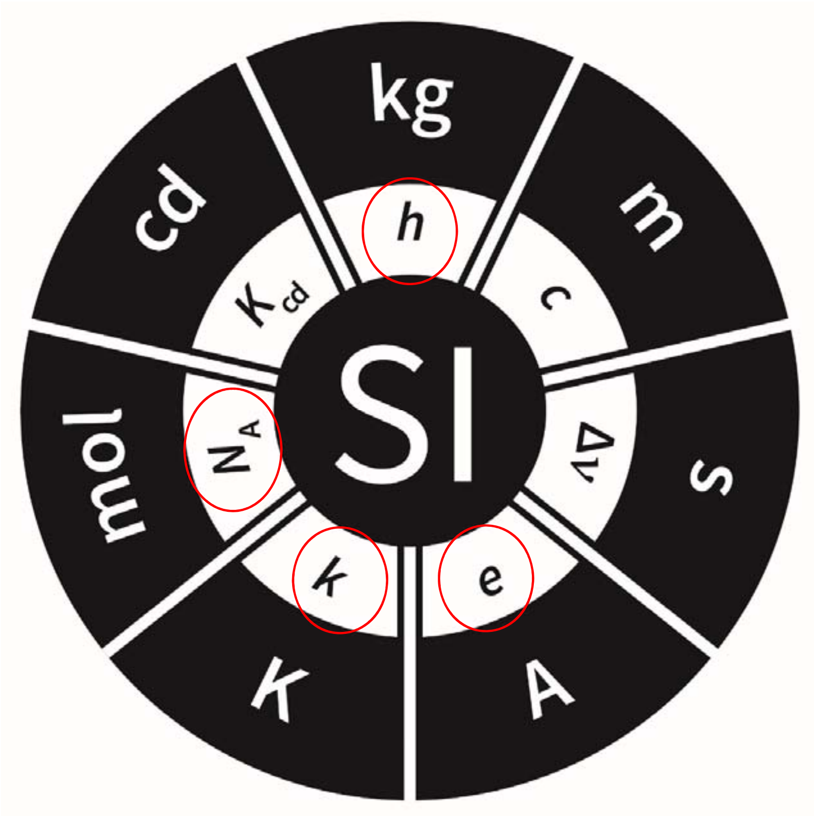
Estefanía de Mirandés

CCU executive secretary

On behalf of Prof. Joachim Ullrich, CCU President

23rd meeting of the CCU held the 5 and 6 September 2017

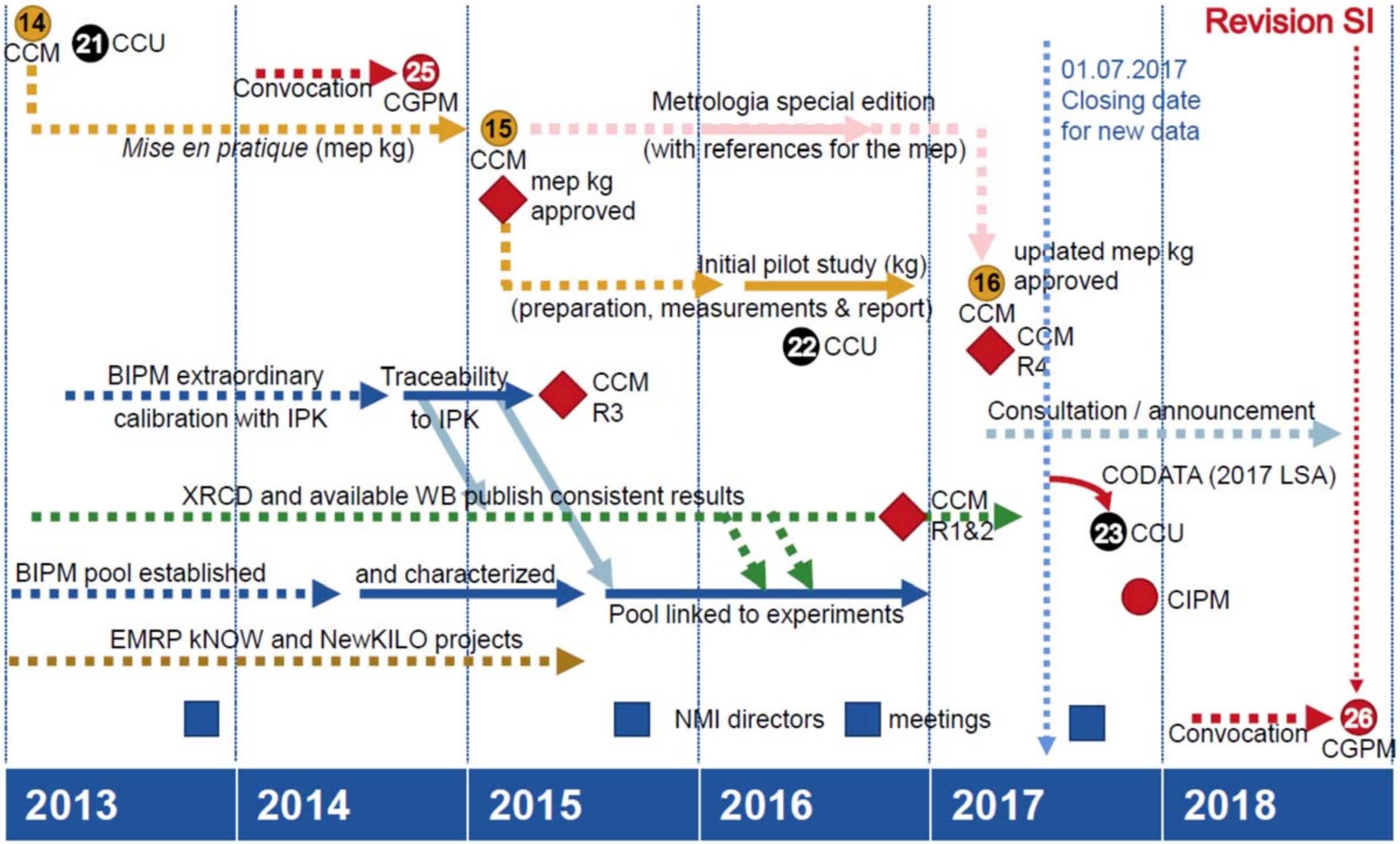
Proposed revision of the SI



In the revised SI all units would be defined in terms of a set of seven reference constants, to be known as the "defining constants of the SI", namely the caesium hyperfine splitting frequency, the speed of light in vacuum, the Planck constant, the elementary charge (i.e. the charge on a proton), the Boltzmann constant, the Avogadro constant, and the luminous efficacy of a specified monochromatic source.

This would result in a simpler and more fundamental definition of the entire SI, and would dispense with the last of the definitions based on a material artefact – the international prototype of the kilogram.

Joint CCM and CCU roadmap for the new SI



Conditions from CCM Recommendation G1 (2013)

Special 2017 CODATA adjustment of h, e, k and N_A

- **Resolution 1 of the 24th CGPM (2011) :**

  The General Conference on Weights and Measures

  invites

  - CODATA to continue to provide adjusted values of the fundamental physical constants based on all relevant information available and to make the results known to the International Committee through its Consultative Committee for Units since these CODATA values and uncertainties will be those used for the revised SI,

- **Decision CIPM/104-9 (2015)**: The CIPM revised its Decision CIPM/103-30 and decided that experimental results to be used by the CODATA Task Group on Fundamental Constants in the evaluation of the fundamental constants leading to the fixed values for the defining constants of the new SI should be accepted for publication by **1 July 2017**

Special 2017 CODATA adjustment of *h*, *e*, *k* and N_A

The CODATA 2017 Values of h, e, k, and $N_{\rm A}$

D. B. Newell[*], F. Cabiati, J. Fischer, K. Fujii, S. G. Karshenboim, H. S. Margolis, E. de Mirandés, P. J. Mohr, F. Nez, K. Pachucki, T. J. Quinn, B. N. Taylor, M. Wang, B. M. Wood, and Z. Zhang

Committee on Data for Science and Technology (CODATA) Task Group on Fundamental Constants (TGFC)

(Dated: August 25, 2017)

Data and Analysis for the CODATA 2017 Special Fundamental Constants Adjustment[*]

Peter J. Mohr[†], David B. Newell[‡], Barry N. Taylor[§] and Eite Tiesinga[¶]

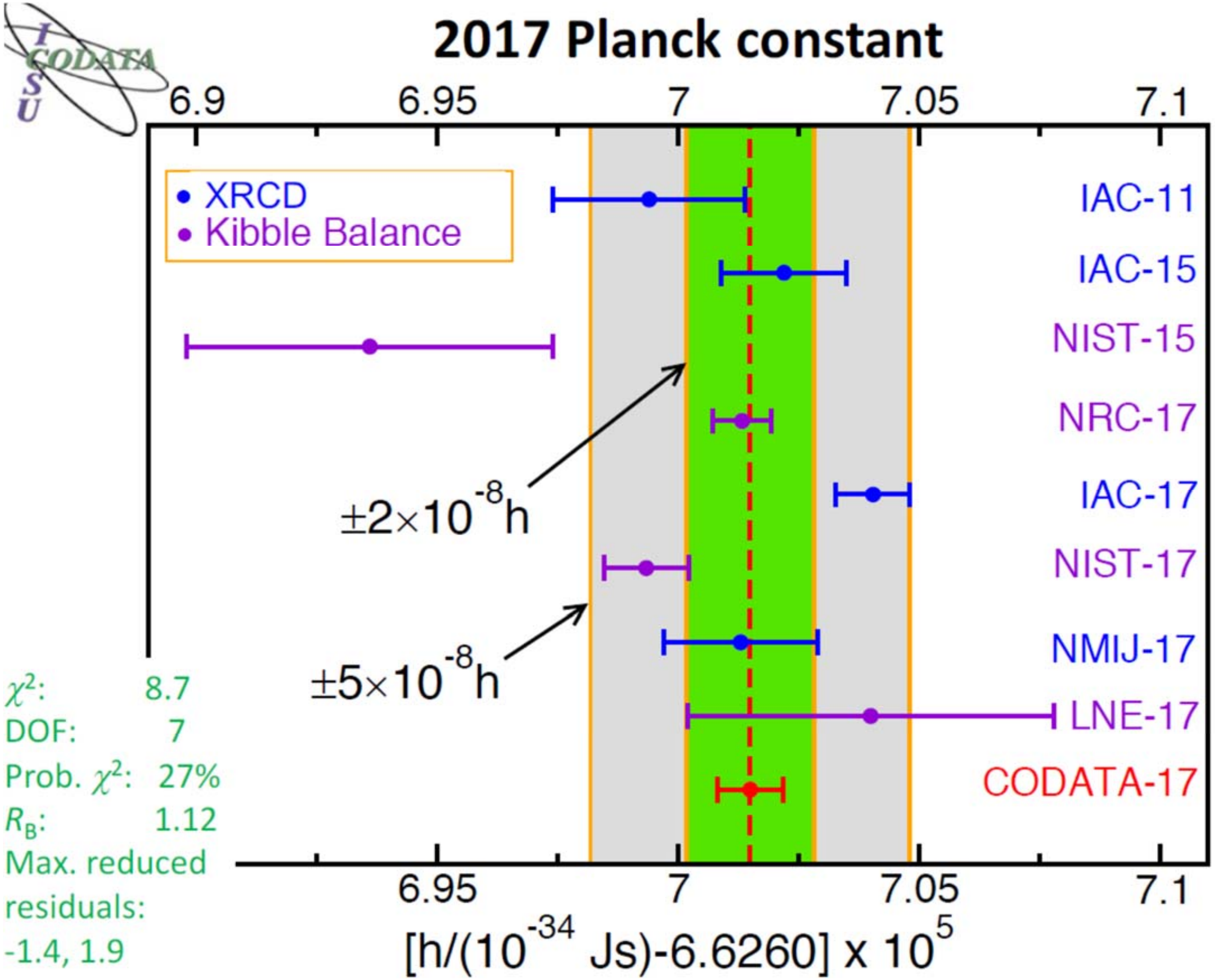
National Institute of Standards and Technology, Gaithersburg, Maryland 20899-8420, USA

(Dated: August 25, 2017)

2017 Key Input data for the determination of h, e, k, and N_A

TABLE I Key data for the determination of h, e, k, and N_A in the CODATA 2017 Special Adjustment. See Mohr *et al.* (2017) for a complete list of input data.

Source	Identification[a]	Quantity[b]	Value	Rel. stand. uncert u_r
Schlamminger *et al.* (2015)	NIST-15	h	$6.626\,069\,36(38) \times 10^{-34}$ J s	5.7×10^{-8}
Wood *et al.* (2017)	NRC-17	h	$6.626\,070\,133(60) \times 10^{-34}$ J s	9.1×10^{-9}
Haddad *et al.* (2017)	NIST-17	h	$6.626\,069\,934(88) \times 10^{-34}$ J s	1.3×10^{-8}
Thomas *et al.* (2017)	LNE-17	h	$6.626\,070\,40(38) \times 10^{-34}$ J s	5.7×10^{-8}
Azuma *et al.* (2015)	IAC-11	N_A	$6.022\,140\,95(18) \times 10^{23}$ mol^{-1}	3.0×10^{-8}
Azuma *et al.* (2015)	IAC-15	N_A	$6.022\,140\,70(12) \times 10^{23}$ mol^{-1}	2.0×10^{-8}
Bartl *et al.* (2017)	IAC-17	N_A	$6.022\,140\,526(70) \times 10^{23}$ mol^{-1}	1.2×10^{-8}
Kuramoto *et al.* (2017)	NMIJ-17	N_A	$6.022\,140\,78(15) \times 10^{23}$ mol^{-1}	2.4×10^{-8}
Moldover *et al.* (1988)	NIST-88	R	$8.314\,470(15)$ J mol^{-1} K^{-1}	1.8×10^{-6}
Pitre *et al.* (2009)	LNE-09	R	$8.314\,467(23)$ J mol^{-1} K^{-1}	2.7×10^{-6}
Sutton *et al.* (2010)	NPL-10	R	$8.314\,468(26)$ J mol^{-1} K^{-1}	3.2×10^{-6}
Pitre *et al.* (2011)	LNE-11	R	$8.314\,455(12)$ J mol^{-1} K^{-1}	1.4×10^{-6}
Pitre *et al.* (2015)	LNE-15	R	$8.314\,4615(84)$ J mol^{-1} K^{-1}	1.0×10^{-6}
Gavioso *et al.* (2015)	INRIM-15	R	$8.314\,4743(88)$ J mol^{-1} K^{-1}	1.1×10^{-6}
Pitre *et al.* (2017)	LNE-17	R	$8.314\,4614(50)$ J mol^{-1} K^{-1}	6.0×10^{-7}
de Podesta *et al.* (2017)	NPL-17	R	$8.314\,4603(58)$ J mol^{-1} K^{-1}	7.0×10^{-7}
Feng *et al.* (2017)	NIM-17	R	$8.314\,459(17)$ J mol^{-1} K^{-1}	2.0×10^{-6}
Gaiser *et al.* (2017)	PTB-17	$A_\epsilon(^4\mathrm{He})/R$	$6.221\,140(12) \times 10^{-8}$ m^3 K J^{-1}	1.9×10^{-6}
Qu *et al.* (2017)	NIM/NIST-17	k/h	$2.083\,6630(56) \times 10^{10}$ Hz K^{-1}	2.7×10^{-6}



CCM conditions for redefinition of the kilogram

- at least three independent experiments, including work from Kibble balance and XRCD experiments, yield consistent values of the Planck constant with relative standard uncertainties not larger than 5×10^{-8} ,
- at least one of these results should have a relative standard uncertainty not larger than 2×10^{-8}

Slide from CODATA

RECOMMENDATION OF THE CONSULTATIVE COMMITTEE FOR MASS AND RELATED QUANTITIES SUBMITTED TO THE INTERNATIONAL COMMITTEE FOR WEIGHTS AND MEASURES

RECOMMENDATION G 1 (2017)
For a new definition of the kilogram in 2018 (publicly available in the CCM webpage)

noting that the CCM will conduct an on-going key comparison of primary realizations of the kilogram that will capture and maintain a table of the experimental degrees of equivalence, which can be used to create a formal procedure for applying corrections relative to the consensus value,

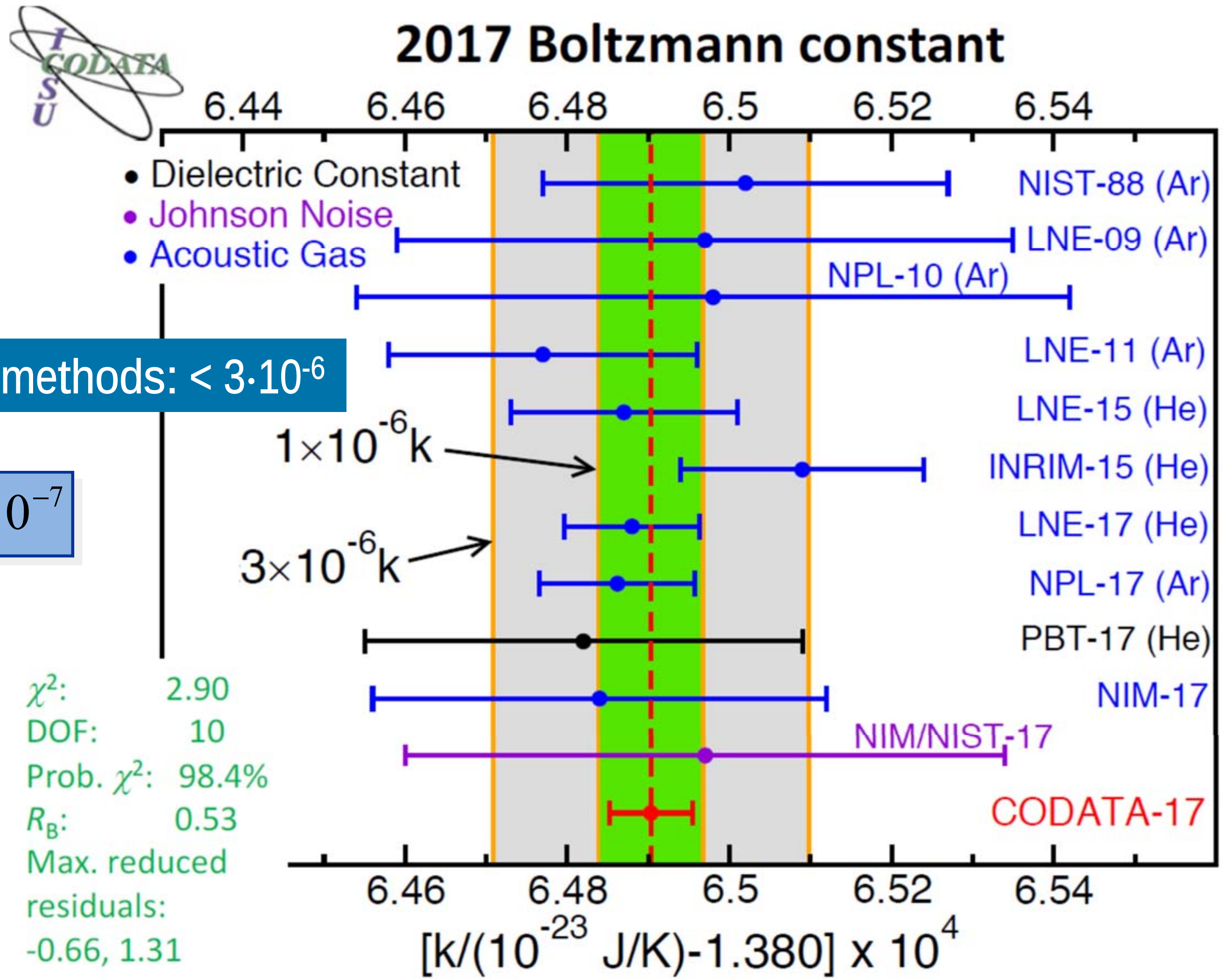
requests those National Metrology Institutes having a realization of the kilogram to avail themselves of the consensus value (as determined from the ongoing comparison) when disseminating the unit of mass according to the new definition, until the dispersion in values becomes compatible with the individual realization uncertainties, thus preserving the international equivalence of calibration certificates and in accordance with the principles and agreed protocols of the CIPM Mutual Recognition Arrangement,

recommends that the CIPM undertakes the necessary steps to proceed with the planned redefinition of the SI at the next meeting of the CGPM, acknowledging the measures to be taken by the CCM to ensure integrity and continuity in the dissemination of the kilogram.

Consistent

2 independent methods: $< 3 \cdot 10^{-6}$

$$u_{rel}(k) = 3.7 \cdot 10^{-7}$$



Slide from CODATA

Reccomendation from the CCT

RECOMMENDATIONS OF THE
CONSULTATIVE COMMITTEE FOR THERMOMETRY
SUBMITTED TO THE INTERNATIONAL COMMITTEE FOR WEIGHTS AND MEASURES

RECOMMENDATION T 1 (2017)

For a new definition of the kelvin in 2018

The Consultative Committee for Thermometry (CCT), at its 28th meeting in 2017,

recommends

- that the CIPM finalises the unit redefinitions through agreeing to fix the values of the fundamental physical constants, from which a fixed numerical value of the Boltzmann constant with 8 digits will be adopted for the redefinition of the kelvin,
- that member state NMIs take full advantage of the opportunities for the realisation and dissemination of thermodynamic temperature afforded by the kelvin redefinition and the *mise en pratique* for the definition of the kelvin.

Final agreed values of the four fundamental constants to be fixed

The CODATA 2017 Values of h, e, k, and N_A

Quantity	Value
h	$6.626\,070\,15 \times 10^{-34}$ J s
e	$1.602\,176\,634 \times 10^{-19}$ C
k	$1.380\,649 \times 10^{-23}$ J K^{-1}
N_A	$6.022\,140\,76 \times 10^{23}$ mol^{-1}

Determining the Exact Values of h, e, k, and N_A for the Revised SI

- **Resolution 1 of the 24th CGPM (2011)**
  - The values of $m(\mathcal{K})$, μ_0, T_{TPW}, and $M(^{12}C)$ remain consistent with their exact values in present SI

- **Decision CIPM/105-15 of the 105th CIPM (2016)**
  - The exact values of h, e, and N_A are chosen such that $m(\mathcal{K})$, μ_0, and $M(^{12}C)$ remain consistent within their relative standard uncertainties.
  - The exact value of k is chosen such that T_{TPW} remains consistent at the level it can be presently realized

Consistency from present SI to revised SI

- **International prototype of the kilogram:**

  $m(\mathcal{K})/1\ \text{kg} = 1.000\ 000\ 000(10)$

- **Permeability of vacuum:**

  $\mu_0/4\pi \times 10^{-7}\ \text{H m}^{-1} = 1.000\ 000\ 000\ 20(23)$

- **Triple point of water:**

  $T_{\text{TPW}}/273.16\ \text{K} = 1.000\ 000\ 02(37)$

- **Molar mass of the carbon 12 atom:**

  $M(^{12}\text{C})/0.012\ \text{kg mol}^{-1} = 1.000\ 000\ 000\ 37(45)$

CCU Recommendation U1 (2017)

RECOMMENDATION OF THE CONSULTATIVE COMMITTEE FOR UNITS TO BE SUBMITTED TO THE INTERNATIONAL COMMITTEE FOR WEIGHTS AND MEASURES

considering

- the general agreement on the importance, value and expected benefits of a revision of the SI based on a redefinition of the kilogram, ampere, kelvin and mole in terms of defining constants,
- that the revised SI will provide world-wide harmonization and long-term stability for the realization of these units,
- recommendation G1 (2017) from the Consultative Committee for Mass and Related Quantities (CCM) and recommendation T1 (2017) from the Consultative Committee for Thermometry (CCT) each of which recommends that the CIPM should undertake the necessary steps to proceed with the planned redefinition of the SI at the 26th CGPM,
- that work on the preparation of the *mises-en-pratique* for the new definitions of the kilogram, ampere, kelvin and mole is close to completion,
- that work on the preparation of the 9th edition of the SI Brochure, which will present the revised SI, is also close to completion,

CCU Recommendation U1 (2017)

RECOMMENDATION OF THE CONSULTATIVE COMMITTEE FOR UNITS TO BE SUBMITTED TO THE INTERNATIONAL COMMITTEE FOR WEIGHTS AND MEASURES

notes

- that work is under way in NMIs to understand the cause for the dispersion of the experimental determinations of the Planck and Avogadro constants,
- that the number of NMIs involved in the development of a primary realization of the redefined kilogram and kelvin has been increasing, and that new efforts are expected,

concludes

- that numerical values and uncertainties for the Planck constant, the elementary charge, the Boltzmann constant and the Avogadro constant provided by the CODATA Task Group on Fundamental Constants in their special Least Squares Adjustment of the experimental data provide a sufficient foundation to support the redefinition,

CCU Recommendation U1 (2017)

RECOMMENDATION OF THE CONSULTATIVE COMMITTEE FOR UNITS TO BE SUBMITTED TO THE INTERNATIONAL COMMITTEE FOR WEIGHTS AND MEASURES

RECOMMENDATION U1 (2017)

On the possible redefinition of the kilogram, ampere, kelvin and mole in 2018

The Consultative Committee for Units (CCU), at its 23rd meeting in 2017,

recommends

- that the CIPM undertakes the necessary steps to proceed with the planned redefinition of the kilogram, ampere, kelvin and mole at the 26th CGPM in 2018.

CIPM decision

The CIPM welcomes Recommendation U1 (2017) by the CCU and decides to undertake all necessary steps to proceed with the planned redefinition of the kilogram, ampere, kelvin and mole at the CGPM in 2018.

SI Brochure

- The draft of the 9th Edition of the SI Brochure is close to final
  - The CCU accepts the edited draft 9th Brochure and some modifications proposed by the editing team.
  - The CCU has accepted to include a side note including the **var** and the **gal** in the 9th SI Brochure
  - The CCU has decided to reject all requests to include further non-SI units in the 9th SI Brochure
  - A new wording of the definition of the mole in the revised SI has been agreed with the CCQM and IUPAC
  - Appendix 1 (the list of decisions of the CGPM and the CIPM) will be kept both in printed form in the 9th Brochure and as an online appendix.
  - Appendix 3 (Units for photochemical and photobiological quantities) has been updated by the CCPR and will be kept as an online appendix in the 9th Brochure.
  - Other minor changes proposed by the CCPR were discussed and agreed

New wording for the revised definition of the mole

CCU decision

Agreed by the CIPM

The mole, symbol mol, is the SI unit of amount of substance. One mole contains exactly 6.022 140 8Y × 10^{23} elementary entities. This number is the fixed numerical value of the Avogadro constant, N_A, when expressed in the unit mol^{-1} and is called the Avogadro number.

The amount of substance, symbol *n*, of a system is a measure of the number of specified elementary entities. An elementary entity may be an atom, a molecule, an ion, an electron, any other particle or specified group of particles.

Previous wording, as in the *Draft of the 9th SI Brochure dated 10 November 2016:*

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 to be 6.022 140 8Y ×10^{23} when expressed in the unit mol^{-1}.

Draft Resolution A to be presented to the 26th CGPM 2018

The International System of Units (SI)

The 26th General Conference,

considering

- the essential requirement for an International System of Units (SI) that is uniform and accessible world-wide for international trade, high-technology manufacturing, human health and safety, protection of the environment, global climate studies and the basic science that underpins all these,
- that the SI units must be stable in the long term, internally self-consistent and practically realizable being based on the present theoretical description of nature at the highest level,
- that a revision of the SI to meet these requirements was described in Resolution 1 of the 24th General Conference in 2011, adopted unanimously, that laid out in detail a new way of defining the SI based on a set of seven defining constants, drawn from the fundamental constants of physics and other constants of nature, from which the definitions of the seven base units are deduced,
- that the conditions set by the 24th General Conference, confirmed by the 25th General Conference, before such a revised SI could be adopted have now been met,

Draft Resolution A to be presented to the 26th CGPM 2018

The International System of Units (SI)

The 26th General Conference,

decides

that, effective from 20 May 2019, the International System of Units, the SI, is the system of units in which

- the unperturbed ground state hyperfine transition frequency of the caesium 133 atom $\Delta \nu_{Cs}$ is 9 192 631 770 Hz,
- the speed of light in vacuum c is 299 792 458 m/s,
- the Planck constant h is $6.626\,070\,15 \times 10^{-34}$ J s,
- the elementary charge e is $1.602\,176\,634 \times 10^{-19}$ C,
- the Boltzmann constant k is $1.380\,649 \times 10^{-23}$ J/K,
- the Avogadro constant N_A is $6.022\,140\,76 \times 10^{23}$ mol^{-1},
- the luminous efficacy of monochromatic radiation of frequency 540×10^{12} Hz, K_{cd}, is 683 lm/W,

where the hertz, joule, coulomb, lumen, and watt, with unit symbols Hz, J, C, lm, and W, respectively, are related to the units second, metre, kilogram, ampere, kelvin, mole, and candela, with unit symbols s, m, kg, A, K, mol, and cd, respectively, according to $Hz = s^{-1}$, $J = m^2\ kg\ s^{-2}$, $C = A\ s$, $lm = cd\ m^2\ m^{-2} = cd\ sr$, and $W = m^2\ kg\ s^{-3}$,

Appendix 1. Abrogation of former definitions of the base units:

It follows from the new definition of the SI adopted above that

- the definition of the second in force since 1967/68 (13th meeting of the CGPM, Resolution 1) is abrogated,
- the definition of the metre in force since 1983 (17th meeting of the CGPM, Resolution 1), is abrogated,
- the definition of the kilogram in force since 1889 (1st meeting of the CGPM, 1889, 3rd meeting of the CGPM, 1901) based upon the mass of the international prototype of the kilogram is abrogated,
- the definition of the ampere in force since 1948 (9th meeting of the CGPM) based upon the definition proposed by the International Committee (CIPM, 1946, Resolution 2) is abrogated,
- the definition of the kelvin in force since 1967/68 (13th meeting of the CGPM, Resolution 4) is abrogated,
- the definition of the mole in force since 1971 (14th meeting of the CGPM, Resolution 3) is abrogated,
- the definition of the candela in force since 1979 (16th meeting of the CGPM, Resolution 3) is abrogated,
- the decision to adopt the conventional values of the Josephson constant K_{J-90} and of the von Klitzing constant R_{K-90} taken by the International Committee (CIPM, 1988, Recommendations 1 and 2) at the request of the General Conference (18th meeting of the CGPM, 1987, Resolution 6) for the establishment of representations of the volt and the ohm using the Josephson and quantum Hall effects, respectively, is abrogated.

Appendix 2. Status of constants previously used in the former definitions:

It follows from the new definition of the SI adopted above, and from the recommended values of the 2017 special CODATA adjustment on which the values of the defining constants are based, that at the time this Resolution was adopted

- the mass of the international prototype of the kilogram $m(\mathcal{K})$ is equal to 1 kg within a relative standard uncertainty equal to that of the recommended value of h at the time this Resolution was adopted, namely 1.0×10^{-8} and that in the future its value will be determined experimentally,

- the vacuum magnetic permeability μ_0 is equal to $4\pi \times 10^{-7}$ H m^{-1} within a relative standard uncertainty equal to that of the recommended value of the fine-structure constant α at the time this Resolution was adopted, namely 2.3×10^{-10} and that in the future its value will be determined experimentally,

- the thermodynamic temperature of the triple point of water $T_{\rm TPW}$ is equal to 273.16 K within a relative standard uncertainty closely equal to that of the recommended value of k at the time this Resolution was adopted, namely 3.7×10^{-7}, and that in the future its value will be determined experimentally,

- the molar mass of carbon 12, $M(^{12}\mathrm{C})$, is equal to 0.012 kg mol^{-1} within a relative standard uncertainty equal to that of the recommended value of $N_{\rm A}h$ at the time this Resolution was adopted, namely 4.5×10^{-10}, and that in the future its value will be determined experimentally.

Appendix 3. The base units of the SI

Starting from the definition of the SI adopted above in terms of fixed numerical values of the defining constants, definitions of each of the seven base units are deduced by taking, as appropriate, one or more of these defining constants to give the following set of definitions:

- 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 unperturbed ground-state hyperfine transition frequency of the caesium 133 atom, to be 9 192 631 770 when expressed in the unit Hz, which is equal to s^{-1}.

- 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 $\Delta\nu_{Cs}$.

- 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 $6.626\ 070\ 15 \times 10^{-34}$ when expressed in the unit J s, which is equal to kg $m^2\ s^{-1}$, where the metre and the second are defined in terms of c and $\Delta\nu_{Cs}$.

- 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 $1.602\ 176\ 634 \times 10^{-19}$ when expressed in the unit C, which is equal to A s, where the second is defined in terms of $\Delta\nu_{Cs}$.

- 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 $1.380\ 649 \times 10^{-23}$ 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 $\Delta\nu_{Cs}$.

- The mole, symbol mol, is the SI unit of amount of substance. One mole contains exactly $6.022\ 140\ 76 \times 10^{23}$ elementary entities. This number is the fixed numerical value

  of the Avogadro constant, N_A, when expressed in the unit mol^{-1} and is called the Avogadro number.

  The amount of substance, symbol n, of a system is a measure of the number of specified elementary entities. An elementary entity may be an atom, a molecule, an ion, an electron, any other particle or specified group of particles.

- The candela, symbol cd, is the SI unit of luminous intensity in a given direction. It is defined by taking the fixed numerical value of the luminous efficacy of monochromatic radiation of frequency 540×10^{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 $\Delta\nu_{Cs}$.

Symposium at the end of the CCU meeting

https://www.bipm.org/en/conference-centre/bipm-workshops/fundamental-constants/

Symposium on

The fundamental constants of physics: what are they and what is their role in redefining the SI

Venue: Pavillon du Mail, BIPM, Sèvres, France

Concise summary of 9th Broschure

S I

A concise summary of the International System of Units, SI

Metrology is the science of measurement, embracing all measurements, made at a known level of uncertainty, in any field of human activity.

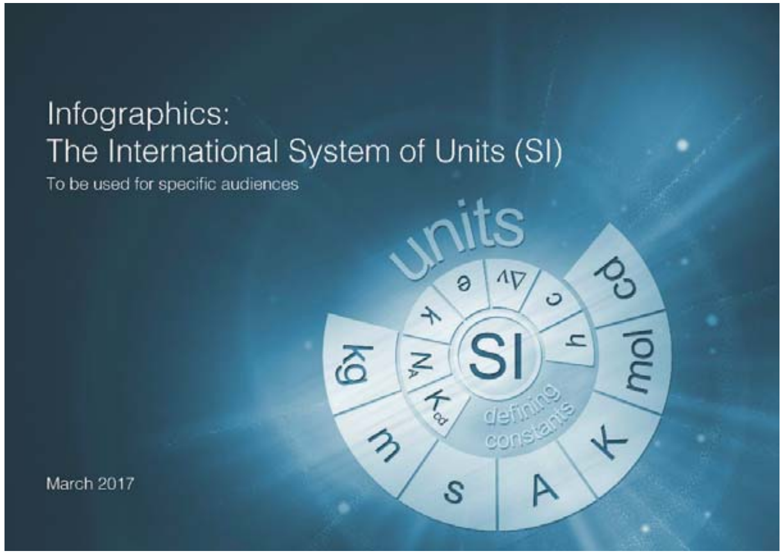
The International Bureau of Weights and Measures (BIPM) was established by Article 1 of the Metre Convention, which was signed on 20 May 1875. It is charged with providing the basis for a single, coherent system of measurements to be used throughout the world. The decimal metric system, dating from the time of the French Revolution, was based in 1799 on the metre and the kilogram. Under the terms of the Metre Convention, new international prototypes of the metre and kilogram were manufactured and formally adopted by the first General Conference on Weights and Measures (CGPM) in 1889. In 1960 the 11th CGPM formally defined and established the International System of Units (SI). Since then the SI has been periodically updated to take account of advances in science and the need for measurements in new domains. The last major revision was adopted by the 26th CGPM (2018), which decided that henceforth the SI would be based on the fixed numerical values of a set of seven **defining constants** from which the definitions of the seven base units of the SI would be deduced. This document is a summary of the **SI Brochure**, a publication produced by the BIPM, which gives a detailed explanation of the current status of the SI.

Thank you for your attention

10. Promotion of the revised SI

All the different graphics files are available in the SI download area.

SI illustration and SI infographics



SI download area

Promotional files prepared by the Task Group

SI download area

Files shared by NMIs

The **SI illustration** developed by the PR group is endorsed by the Task group. Its basic concept consists in the word “SI” surrounded by two circles, one depicting the base units and the other depicting the fixed constants.

The **SI infographics** previously developed by Ian Mills, Terry Quinn and Joachim Ullrich approved by the CCU and CIPM is endorsed to be used for specific audiences.