Progress towards the revision of the SI

Estefanía de Mirandés
CCU executive secretary
BIPM
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 $N_A$

**Short Communication**

**The CODATA 2017 values of $h$, $e$, $k$, and $N_A$ for the revision of the SI**


**Data and analysis for the CODATA 2017 special fundamental constants adjustment**

Peter J Mohr, David B Newell, Barry N Taylor and Eite Tiesinga
2017 Key input data for the determination of $h$, $e$, $k$ and $N_A$

<table>
<thead>
<tr>
<th>Source</th>
<th>Identification</th>
<th>Quantity</th>
<th>Value</th>
<th>Rel. stand uncert $u_r$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Schlamminger et al. (2015)</td>
<td>NIST-15</td>
<td>$h$</td>
<td>$6.626 069 36(38) \times 10^{-24}$ J s</td>
<td>$5.7 \times 10^{-8}$</td>
</tr>
<tr>
<td>Wood et al. (2017)</td>
<td>NRC-17</td>
<td>$h$</td>
<td>$6.626 070 13(60) \times 10^{-24}$ J s</td>
<td>$9.1 \times 10^{-9}$</td>
</tr>
<tr>
<td>Haddad et al. (2017)</td>
<td>NIST-17</td>
<td>$h$</td>
<td>$6.626 069 934(88) \times 10^{-24}$ J s</td>
<td>$1.3 \times 10^{-8}$</td>
</tr>
<tr>
<td>Thomas et al. (2017)</td>
<td>LNE-17</td>
<td>$h$</td>
<td>$6.626 070 40(38) \times 10^{-24}$ J s</td>
<td>$5.7 \times 10^{-8}$</td>
</tr>
<tr>
<td>Azuma et al. (2015)</td>
<td>IAC-11</td>
<td>$N_A$</td>
<td>$6.022 140 95(18) \times 10^{23}$ mol$^{-1}$</td>
<td>$3.0 \times 10^{-8}$</td>
</tr>
<tr>
<td>Azuma et al. (2015)</td>
<td>IAC-15</td>
<td>$N_A$</td>
<td>$6.022 140 70(12) \times 10^{23}$ mol$^{-1}$</td>
<td>$2.0 \times 10^{-8}$</td>
</tr>
<tr>
<td>Bartl et al. (2017)</td>
<td>IAC-17</td>
<td>$N_A$</td>
<td>$6.022 140 526(70) \times 10^{23}$ mol$^{-1}$</td>
<td>$1.2 \times 10^{-8}$</td>
</tr>
<tr>
<td>Kuramoto et al. (2017)</td>
<td>NMIJ-17</td>
<td>$N_A$</td>
<td>$6.022 140 78(15) \times 10^{22}$ mol$^{-1}$</td>
<td>$2.4 \times 10^{-8}$</td>
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<tr>
<td>Meldover et al. (1988)</td>
<td>NIST-88</td>
<td>$R$</td>
<td>$8.314 740(15) \text{ J mol}^{-1} \text{ K}^{-1}$</td>
<td>$1.8 \times 10^{-5}$</td>
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<tr>
<td>Pitre et al. (2009)</td>
<td>LNE-09</td>
<td>$R$</td>
<td>$8.314 467(23) \text{ J mol}^{-1} \text{ K}^{-1}$</td>
<td>$2.7 \times 10^{-6}$</td>
</tr>
<tr>
<td>Sutton et al. (2010)</td>
<td>NPL-10</td>
<td>$R$</td>
<td>$8.314 468(26) \text{ J mol}^{-1} \text{ K}^{-1}$</td>
<td>$3.2 \times 10^{-6}$</td>
</tr>
<tr>
<td>Pitre et al. (2011)</td>
<td>LNE-11</td>
<td>$R$</td>
<td>$8.314 455(12) \text{ J mol}^{-1} \text{ K}^{-1}$</td>
<td>$1.4 \times 10^{-6}$</td>
</tr>
<tr>
<td>Pitre et al. (2015)</td>
<td>LNE-15</td>
<td>$R$</td>
<td>$8.314 4615(84) \text{ J mol}^{-1} \text{ K}^{-1}$</td>
<td>$1.0 \times 10^{-5}$</td>
</tr>
<tr>
<td>Giovoso et al. (2015)</td>
<td>INRIM-15</td>
<td>$R$</td>
<td>$8.314 4743(88) \text{ J mol}^{-1} \text{ K}^{-1}$</td>
<td>$1.1 \times 10^{-5}$</td>
</tr>
<tr>
<td>Pitre et al. (2017)</td>
<td>LNE-17</td>
<td>$R$</td>
<td>$8.314 4614(50) \text{ J mol}^{-1} \text{ K}^{-1}$</td>
<td>$6.0 \times 10^{-7}$</td>
</tr>
<tr>
<td>de Podesta et al. (2017)</td>
<td>NPL-17</td>
<td>$R$</td>
<td>$8.314 4603(58) \text{ J mol}^{-1} \text{ K}^{-1}$</td>
<td>$7.0 \times 10^{-7}$</td>
</tr>
<tr>
<td>Feng et al. (2017)</td>
<td>NIM-17</td>
<td>$R$</td>
<td>$8.314 459(17) \text{ J mol}^{-1} \text{ K}^{-1}$</td>
<td>$2.0 \times 10^{-6}$</td>
</tr>
<tr>
<td>Gaiser et al. (2017)</td>
<td>PTB-17</td>
<td>$\frac{A_e(\text{He})}{R}$</td>
<td>$6.221 140(12) \times 10^{-8} \text{ m}^3 \text{ K}^{-1}$</td>
<td>$1.9 \times 10^{-5}$</td>
</tr>
<tr>
<td>Qu et al. (2017)</td>
<td>NIM/NIST-17</td>
<td>$k/h$</td>
<td>$2.083 6630(56) \times 10^{10} \text{ Hz} \text{ K}^{-1}$</td>
<td>$2.7 \times 10^{-6}$</td>
</tr>
</tbody>
</table>
Green band: $\pm 2 \times 10^{-8}$
Grey band: $\pm 5 \times 10^{-8}$

$\chi^2$: 8.7
DOF: 7
Prob. $\chi^2$: 27%
$R_B$: 1.12
Max. reduced residuals:
-1.4, 1.9
The Planck constant

- **Consistent**

Expansion factor of 1.7

\[ \frac{h}{(10^{-34} \text{ J s})} - 6.6260 \times 10^5 \]
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

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.
2017 Boltzmann constant

- Dielectric Constant
- Johnson Noise
- Acoustic Gas

\[ k = \frac{1.380 \times 10^{-23}}{J/K} \times 10^4 \]

\[ \chi^2: 2.90 \]
\[ \text{DOF: } 10 \]
\[ \text{Prob. } \chi^2: 98.4\% \]
\[ R_B: 0.53 \]
\[ \text{Max. reduced residuals: } -0.66, 1.31 \]
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

considering
(...)
- that the determination of $k$ is based now on three fundamentally different methods, of which at least one result for each has a relative standard uncertainty less than 3 parts in $10^6$,
- that all requirements of CCT for the new definition of the kelvin have been fulfilled,

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,
Final agreed values of the four fundamental constants to be fixed

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

<table>
<thead>
<tr>
<th>Quantity</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>$h$</td>
<td>$6.626,070,15 \times 10^{-34}$ J s</td>
</tr>
<tr>
<td>$e$</td>
<td>$1.602,176,634 \times 10^{-19}$ C</td>
</tr>
<tr>
<td>$k$</td>
<td>$1.380,649 \times 10^{-23}$ J K$^{-1}$</td>
</tr>
<tr>
<td>$N_A$</td>
<td>$6.022,140,76 \times 10^{23}$ mol$^{-1}$</td>
</tr>
</tbody>
</table>
Consistency from present SI to revised SI

A requirement by the CGPM (2011) is that the revised SI be consistent with the present SI

- **Resolution 1 of the 24th CGPM (2011)**
  - The values of \( m(K) \), \( \mu_0 \), \( T_{\text{TPW}} \), and \( M^{(12}) \) 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 \( m(K) \), \( \mu_0 \), and \( M^{(12}) \) remain consistent within their relative standard uncertainties.
  - The exact value of \( k \) is chosen such that \( T_{\text{TPW}} \) remains consistent at the level it can be presently realized
Consistency from present SI to revised SI

- **International prototype of the kilogram:**
  \[ m(K) / 1 \text{ kg} = 1.000 \ 000 \ 000(10) \]

- **Permeability of vacuum:**
  \[ \mu_0 / 4\pi \times 10^{-7} \text{ H m}^{-1} = 1.000 \ 000 \ 000 \ 20(23) \]

- **Triple point of water:**
  \[ T_{\text{TPW}} / 273.16 \text{ K} = 1.000 \ 000 \ 002(37) \]

- **Molar mass of the carbon 12 atom:**
  \[ M(^{12}\text{C}) / 0.012 \text{ kg mol}^{-1} = 1.000 \ 000 \ 000 \ 37(45) \]
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.
The International Committee for Weights and Measures (CIPM) welcomed recommendations regarding the redefinition of the SI from its Consultative Committees.

The CIPM noted that the agreed conditions for the redefinition are now met and decided to submit draft Resolution A to the 26th meeting of the General Conference on Weights and Measures (CGPM) and to undertake all other necessary steps to proceed with the planned redefinition of the kilogram, ampere, kelvin and mole.

https://www.bipm.org/en/committees/cipm/meeting/106.html
On the revision of the International System of Units (SI)

The General Conference on Weights and Measures (CGPM), at its 26th meeting,

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 proposed in Resolution 1 adopted unanimously by the CGPM at its 24th meeting (2011) 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 CGPM at its 24th meeting (2011), confirmed at its 25th meeting (2014), before such a revised SI could be adopted have now been met.

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, \( \Delta \nu \text{Cs} \), 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 \( \times \) 10\(^{12} \) Hz, \( K_{\text{cd}} \), 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\(^{-1}\) A, C = A s, lm = cd m\(^2\) s\(^{-1}\) = cd sr, and W = m\(^2\) kg s\(^{-2}\).
Draft Resolution A

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 $\Delta v_\text{Cs}$ 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 $540 \times 10^{12}$ 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 $Hz = s^{-1}$, $J = m^2 \text{ kg s}^{-2}$, $C = A \text{ s}$, $\text{lm} = \text{cd m}^2 \text{ m}^{-2} = \text{cd sr}$, and $W = m^3 \text{ kg s}^{-3}$.
invites the Internationa Committee for Weights and Measures (CIPM) to produce a new edition of its Brochure entitled “The International System of Units” in which a full description of the revised SI will be given.

Appendix 1. Abrogation of former definitions of the base units

It follows from the new definition of the SI described above that, effective from 20 May 2019:

- 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 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 CIPM (1988, Recommendations 1 and 2) at the request of the CGPM (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 described above, and from the recommended values of the 2017 special adjustment of the Committee on Data for Science and Technology (CODATA) on which the values of the defining constants are based, that effective from 20 May 2019:

- the mass of the international prototype of the kilogram \( m(K) \) 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 \( 1.0 \times 10^{-8} \) and that in the future its value will be determined experimentally,

- the vacuum magnetic permeability \( \mu_0 \) 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 \( \alpha \) at the time this Resolution was adopted, namely \( 2.3 \times 10^{-10} \) and that in the future its value will be determined experimentally,

- the thermodynamic temperature of the triple point of water \( T_{TPW} \) 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 \( 3.7 \times 10^{-7} \), and that in the future its value will be determined experimentally,

- the molar mass of carbon 12, \( M^{(12)}_\text{C} \), is equal to 0.012 kg mol\(^{-1}\) within a relative standard uncertainty equal to that of the recommended value of \( N_A \) at the time this Resolution was adopted, namely \( 4.5 \times 10^{-10} \), and that in the future its value will be determined experimentally.
Appendix 3. The base units of the SI

Starting from the new definition of the SI described 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, effective from 20 May 2019:

- **The second**, symbol s, is the SI unit of time. It is defined by taking the fixed numerical value of the caesium frequency \( \Delta \nu \) of 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 \( \Delta \nu \).

- **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 \( \Delta \nu \).

- **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 \( \Delta \nu \).

- **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 \( c \), \( h \) and \( \Delta \nu \).

- **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 \( \times 10^{12} \) Hz, \( \varepsilon_0 \), 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\(^{-2}\), where the kilogram, metre and second are defined in terms of \( h \), \( c \) and \( \Delta \nu \).
SI Brochure

- The draft of the 9th Edition of the SI Brochure is in its final stage

- Minor editorial improvements pending
- French translation is ongoing.
- 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.
- Concise Summary in its final version. Translation to French completed.
CCU documents now available in the BIPM open webpages

https://www.bipm.org/en/measurement-units/rev-si/
CIPM Task group for the promotion of the SI

Chair: J. Ullrich
(representing CIPM and CCU)
Executive Secretary: Estefanía de Mirandes

Members:
BIPM, CENAM, CCEM, CCM, CCQM, CCT, CCU, INMETRO, KRISS, LNE, NIM, NIST, NMII, NMISA, NPL, PTB, VNIIM

Observers:
ILAC, ISO, OIML, IEC, CIE

... and guest participants from RMO’s
Official campaign for the promotion of the revision of the SI

20 May 2018

- World metrology day

20 May 2018

- BIPM awareness webpage
- Brand Book
- Press pack
- Speaker’s notes
- Key messages
- FAQs
- CC’s joint statement
- NMI’s promotional material

20 May 2019

- World metrology day

Redefinitions come into force
BIPM public webpage containing all the promotional material developed by the Task Group

https://www.bipm.org/en/si-download-area/
Brand Book updated in April 2018 and sent to NMIs


Future Revision of the SI

Brand Book V2

April 2018
Press pack updated in May 2018 and sent to NMIs for the launching of the campaign

Questions addressed:

- What is the SI?
- Who is involved in agreeing the SI?
- What is wrong with the old system?
- What are the aims of the redefinition of the SI?
- What will future-proofing enable?
- What is the impact of the changes

Each question is fully answered and a key message per question is provided.
Joint CC statement now translated to French, Spanish and German and widely distributed within the NMIs.
26th meeting of the General Conference: 13-16 November 2018 in Versailles