# The Meter Convention and the future of the International System of Units (SI)

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Bureau International des Poids et Mesures

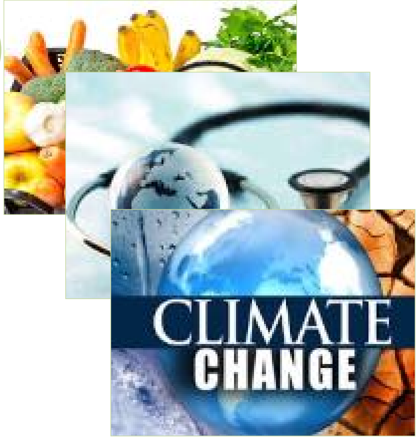
# Outline

# Demands for better measurements

Metrology influences, drives and underpins much of what we do and experience in our everyday lives.

## INDUSTRY & TRADE

## QUALITY of LIFE




## SCIENCE & INNOVATION


…all rely on metrology

# Why was the Metric system of so much interest?

The Metric System was first introduced after the French Revolution:

to allow fair trade by weight and length.

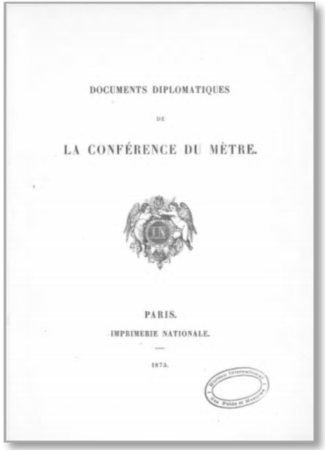
The definitions were:

- **The metre** = one ten millionth of the meridian of the earth (through Paris).
- **The kilogram**= the mass of $1dm^3$ of water (at its temperature of maximum density).

# Why was the Metric system of so much interest?

And
**there were new demands for more accurate measurements.**

Provost, Exposition universelle de 1855, vue de la grande nef du Palais de l'Industrie, 1855, Lithographie en couleurs, musée d'Orsay



DOCUMENTS DIPLOMATIQUES

DE

LA CONFÉRENCE DU MÈTRE.

PARIS.

IMPRIMERIE NATIONALE.

1875.

**20 May 1875**

The Metre Convention was signed in Paris

by 17 nations

# The BIPM – an international organisation

**"the intergovernmental organization through which Member States act together on matters related to measurement science and measurement standards"**

**Established in 1875 when 17 States signed the Metre Convention.**

**CGPM – Conférence Générale des Poids et Mesures**

*Official representatives of Member States.*

**CIPM – Comité International des Poids et Mesures**

*Eighteen individuals of different nationalities elected by the CGPM.*

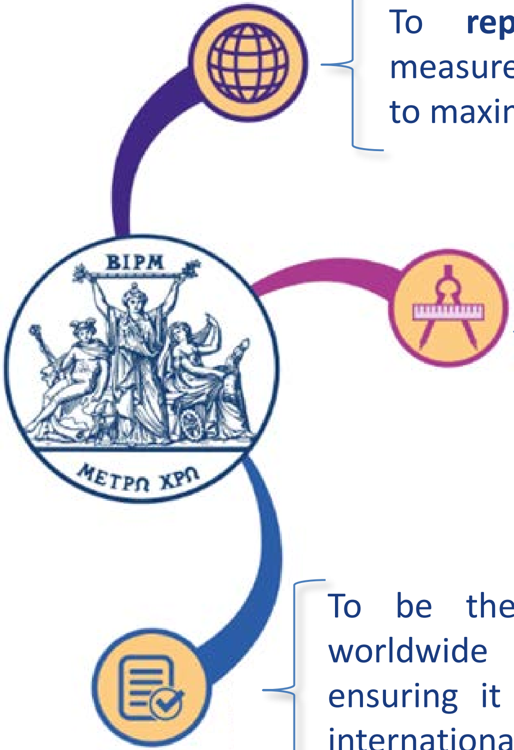
**BIPM – Bureau International des Poids and Mesures**

- *International coordination and liaison*
- *Technical coordination – laboratories*
- *Capacity building*

Consultative Committees (CCs)

*CCAUV – Acoustics, US & Vibration*
*CCEM – Electricity & Magnetism*
*CCL – Length*
*CCM – Mass and related*
*CCPR – Photometry & Radiometry*
*CCQM – Amount of substance*
*CCRI – Ionizing Radiation*
*CCT – Thermometry*
*CCTF – Time & Frequency*
*CCU - Units*

# The objectives of the BIPM




To **represent** the worldwide measurement community aiming to maximise its uptake and impact

To be a **centre for scientific and technical** collaboration between Member States providing capabilities for international measurement comparisons on a shared-cost basis.

To be the **coordinator** of the worldwide measurement system ensuring it gives comparable and internationally-accepted measurement results

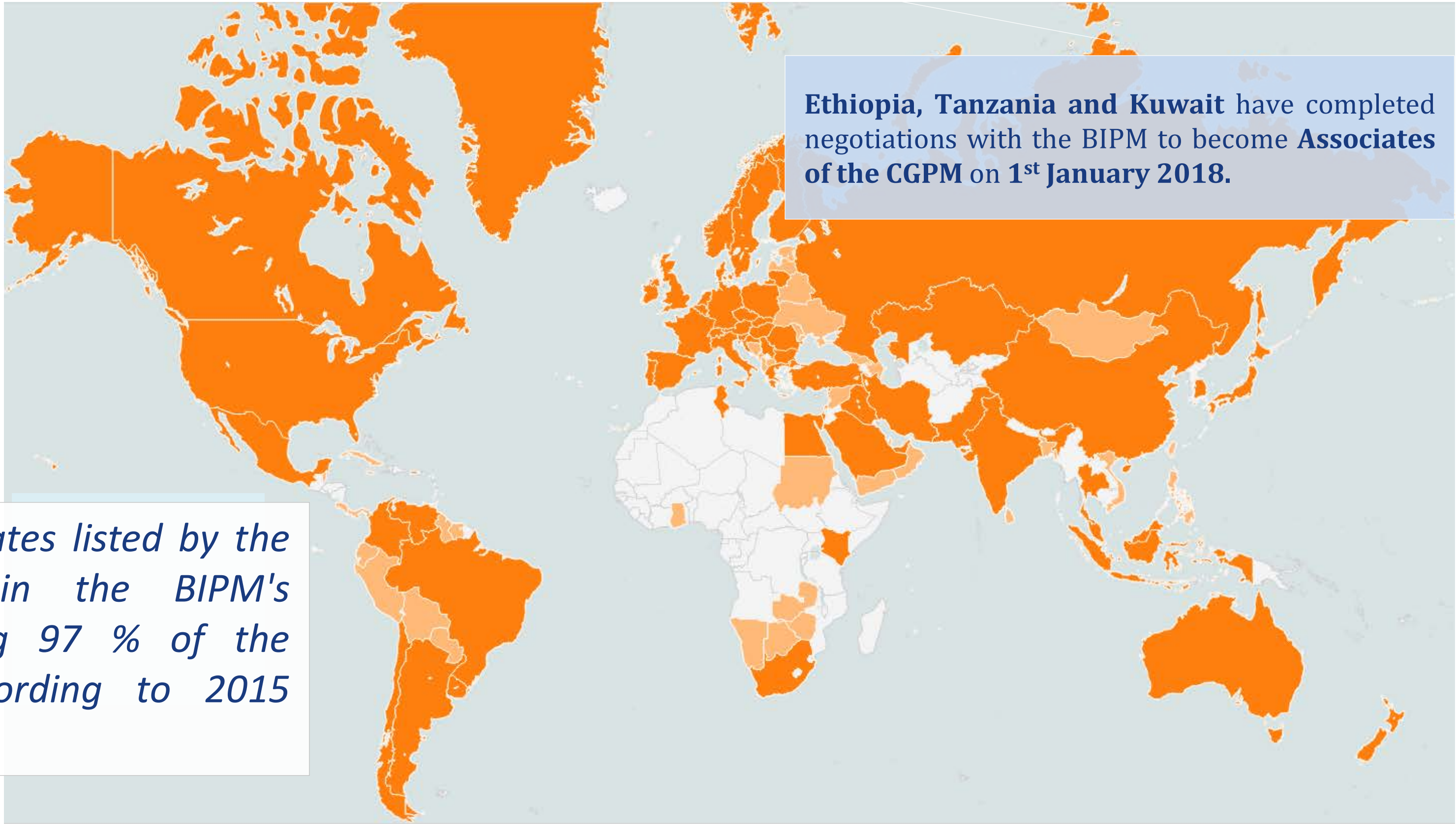

***Fulfilling our mission and objectives is underpinned by our work in:***

- ***capacity building**, which aims to achieve a global balance between the metrology capabilities in Member States.*
- ***knowledge transfer,** which ensures that our work has the greatest impact.*

# Member States and Associates

**As of today, there are:**

- **58 Member States**
- **41 Associates** (States and Economies) of the CGPM



*107 of the 193 states listed by the UN participate in the BIPM's activities, covering 97 % of the world's GDP according to 2015 World Bank data.*

**Ethiopia, Tanzania and Kuwait** have completed negotiations with the BIPM to become **Associates of the CGPM** on **1st January 2018.**

# Outline



Bureau International des Poids et Mesures

# The International System of Units (SI)

## Prefixes

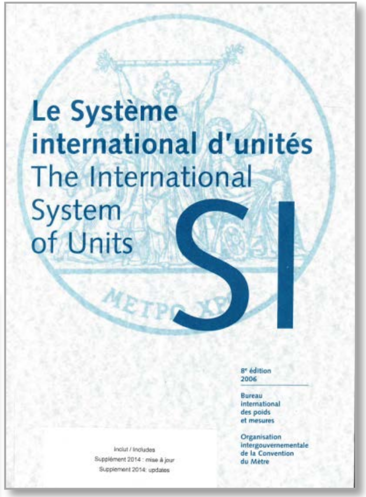
**Table 5. SI prefixes**

| Factor | Name | Symbol | Factor | Name | Symbol |
|---|---|---|---|---|---|
| $10^1$ | deca | da | $10^{-1}$ | deci | d |
| $10^2$ | hecto | h | $10^{-2}$ | centi | c |
| $10^3$ | kilo | k | $10^{-3}$ | milli | m |
| $10^6$ | mega | M | $10^{-6}$ | micro | µ |
| $10^9$ | giga | G | $10^{-9}$ | nano | n |
| $10^{12}$ | tera | T | $10^{-12}$ | pico | p |
| $10^{15}$ | peta | P | $10^{-15}$ | femto | f |
| $10^{18}$ | exa | E | $10^{-18}$ | atto | a |
| $10^{21}$ | zetta | Z | $10^{-21}$ | zepto | z |
| $10^{24}$ | yotta | Y | $10^{-24}$ | yocto | y |

## Base units

**Table 1. SI base units**

| Base quantity | | SI base unit | |
|---|---|---|---|
| Name | Symbol | Name | Symbol |
| length | $l, x, r$, etc. | metre | m |
| mass | $m$ | kilogram | kg |
| time, duration | $t$ | second | s |
| electric current | $I, i$ | ampere | A |
| thermodynamic temperature | $T$ | kelvin | K |
| amount of substance | $n$ | mole | mol |
| luminous intensity | $I_v$ | candela | cd |



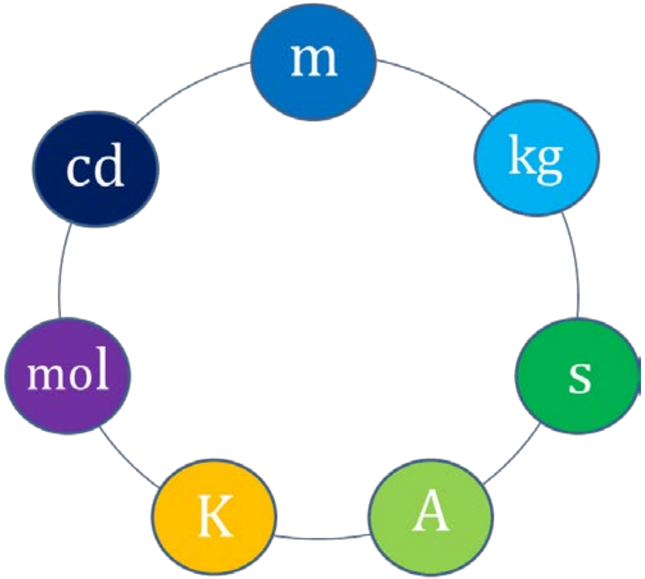

## Derived units

**Table 3. Coherent derived units in the SI with special names and symbols**

| | SI coherent derived unit [a] | | | |
|---|---|---|---|---|
| Derived quantity | Name | Symbol | Expressed in terms of other SI units | Expressed in terms of SI base units |
| plane angle | radian [b] | rad | 1 [b] | m/m |
| solid angle | steradian [b] | sr [c] | 1 [b] | $m^2/m^2$ |
| frequency | hertz [d] | Hz | | $s^{-1}$ |
| force | newton | N | | $m\ kg\ s^{-2}$ |
| pressure, stress | pascal | Pa | $N/m^2$ | $m^{-1}\ kg\ s^{-2}$ |
| energy, work, amount of heat | joule | J | N m | $m^2\ kg\ s^{-2}$ |
| power, radiant flux | watt | W | J/s | $m^2\ kg\ s^{-3}$ |
| electric charge, amount of electricity | coulomb | C | | s A |
| electric potential difference, electromotive force | volt | V | W/A | $m^2\ kg\ s^{-3}\ A^{-1}$ |
| capacitance | farad | F | C/V | $m^{-2}\ kg^{-1}\ s^4\ A^2$ |
| electric resistance | ohm | Ω | V/A | $m^2\ kg\ s^{-3}\ A^{-2}$ |
| electric conductance | siemens | S | A/V | $m^{-2}\ kg^{-1}\ s^3\ A^2$ |
| magnetic flux | weber | Wb | V s | $m^2\ kg\ s^{-2}\ A^{-1}$ |
| magnetic flux density | tesla | T | $Wb/m^2$ | $kg\ s^{-2}\ A^{-1}$ |
| inductance | henry | H | Wb/A | $m^2\ kg\ s^{-2}\ A^{-2}$ |
| Celsius temperature | degree Celsius [e] | °C | | K |
| luminous flux | lumen | lm | cd sr [c] | cd |
| illuminance | lux | lx | $lm/m^2$ | $m^{-2}\ cd$ |
| activity referred to a radionuclide [f] | becquerel [d] | Bq | | $s^{-1}$ |
| absorbed dose, specific energy (imparted), kerma | gray | Gy | J/kg | $m^2\ s^{-2}$ |
| dose equivalent, ambient dose equivalent, directional dose equivalent, personal dose equivalent | sievert [g] | Sv | J/kg | $m^2\ s^{-2}$ |
| catalytic activity | katal | kat | | $s^{-1}\ mol$ |

The 8th edition of the SI Brochure is available from the BIPM website.

# The International System of Units (SI)




## *Système International d'Unités (SI)*

The name adopted by the 11th CGPM in 1960
for the system with 6 base units.

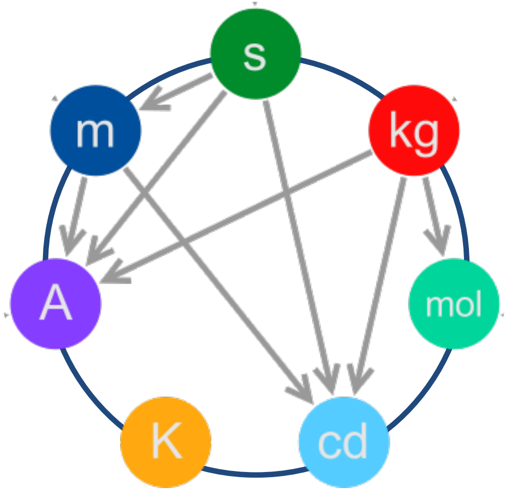
kilogram, second, metre,
ampere, kelvin and candela.

Six important changes since 1960:

| | |
|---|---|
| 1967 | the second was redefined – the atomic second |
| 1972 | the mole was introduced – to provide a unit for chemistry |
| 1983 | the meter was redefined – the first fundamental constant. |
| 1990 | conventions for the volt and the ohm adopted. |
| 1990 | the International Temperature Scale (ITS90) was adopted. |
| 1979 | the candela was defined - as monochromatic radiation |

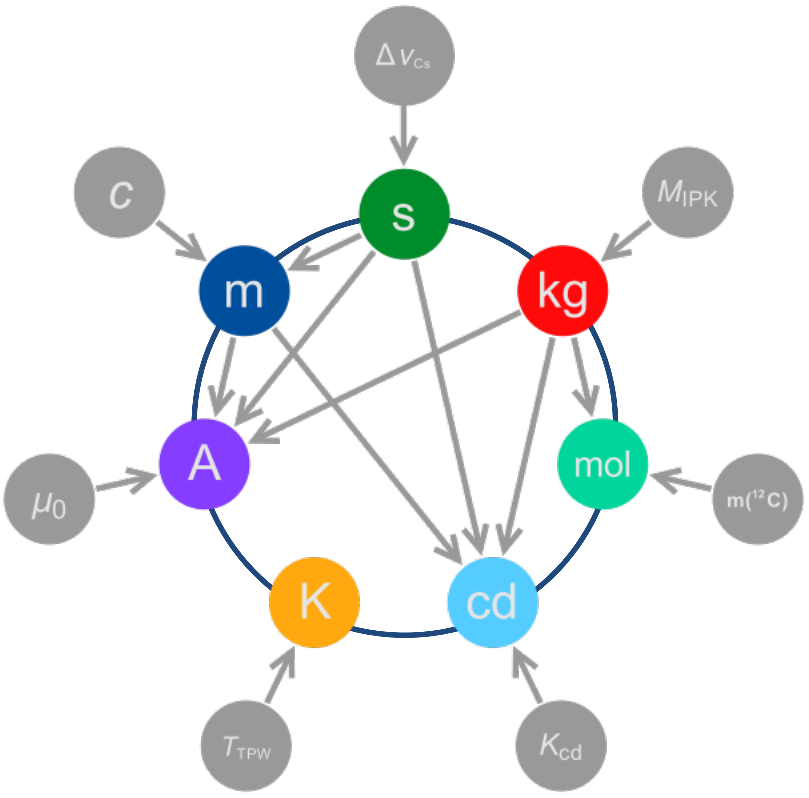
and many smaller changes too, except to the kg!!

# The re-definition in diagrams



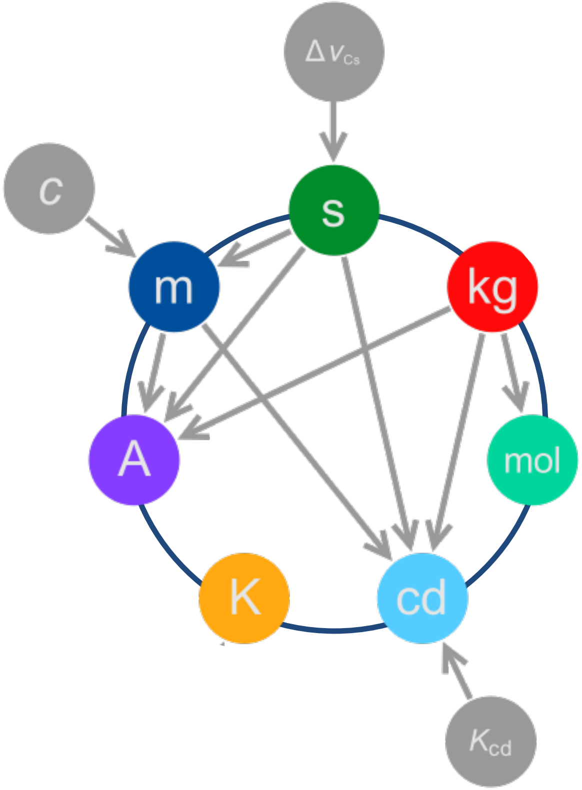

Seven base units –that are linked together.

# The re-definition in diagrams




and each has a
« defining constant ».

# The re-definition in diagrams

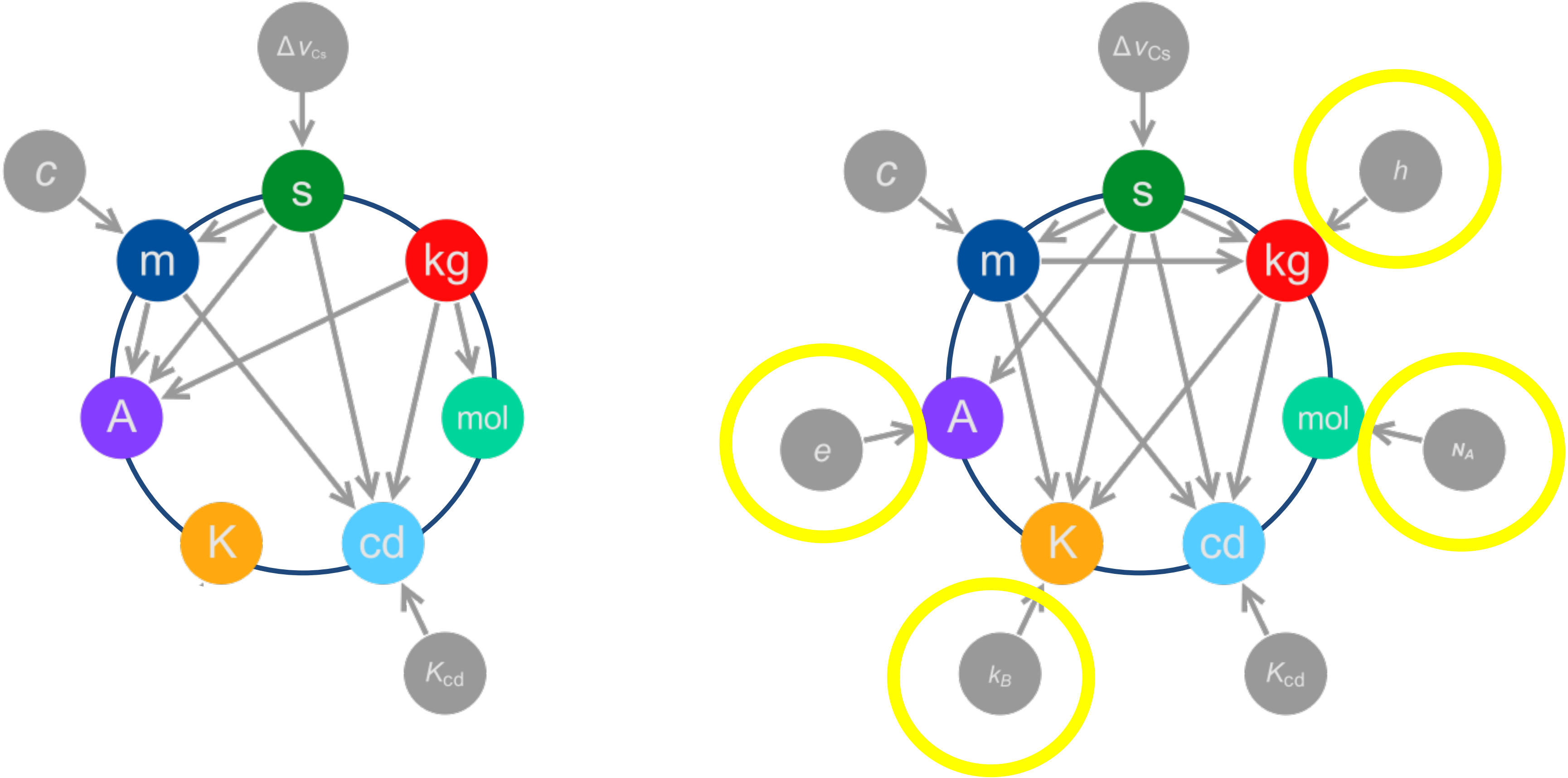



and each has a
« defining constant ».

We propose to change
four of them.

- the kilogram
- the ampere
- the kelvin
- the mole

# The re-definition in diagrams



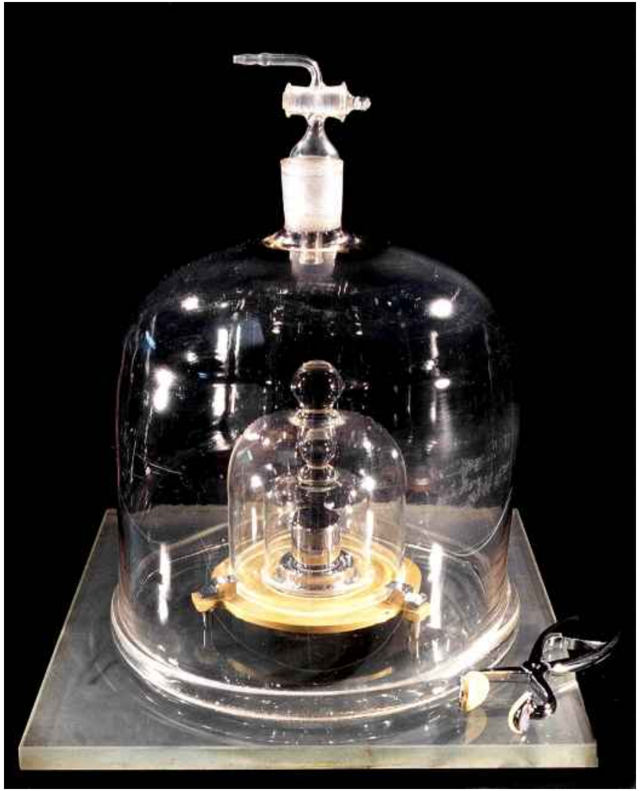

**Introducing 4 new definitions.**

# The definition of the kilogram in the SI

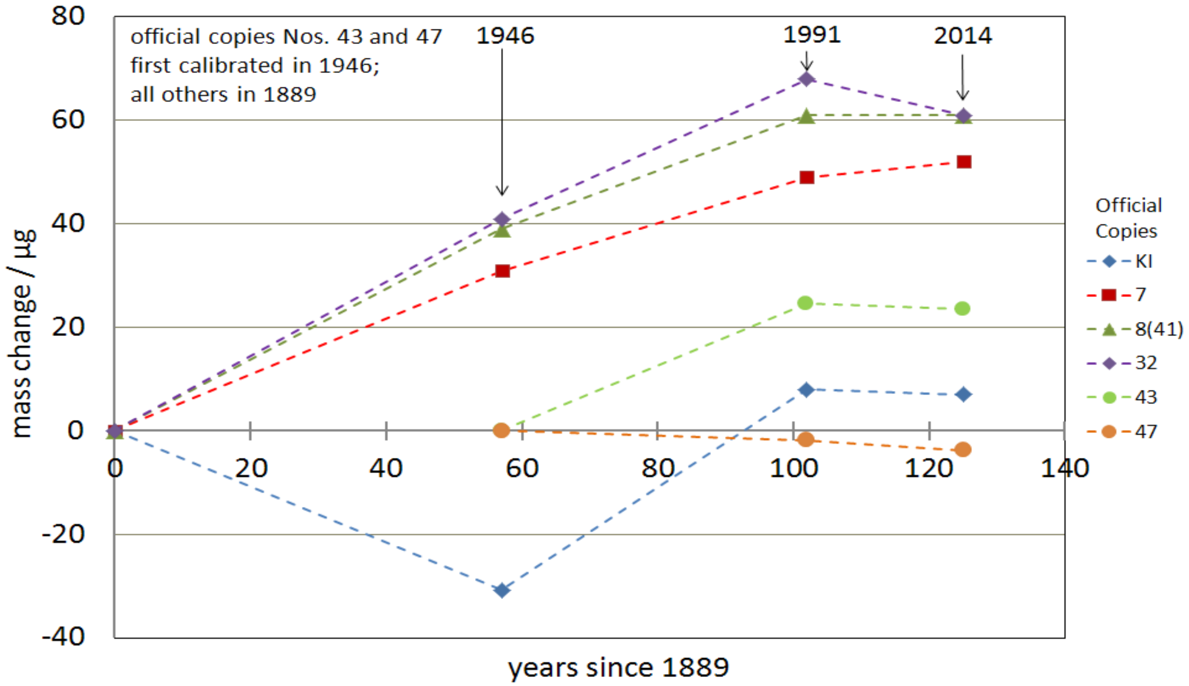
**The kilogram is the unit of mass - it is equal to the mass of the international prototype of the kilogram.**

- manufactured around 1880 and ratified in 1889
- represents the mass of 1 $dm^3$ of $H_2O$ at its maximum density (4 °C)
- alloy of 90% Pt and 10% Ir
- cylindrical shape, *Ø* = *h* ~ 39 mm
- kept at the BIPM in ambient air

The kilogram is the last SI base unit defined by a material artefact.



# Why make the change ? – the International Prototype kg




standard deviation: 3 µg

The IPK and the six official copies form a very consistent set of mass standards

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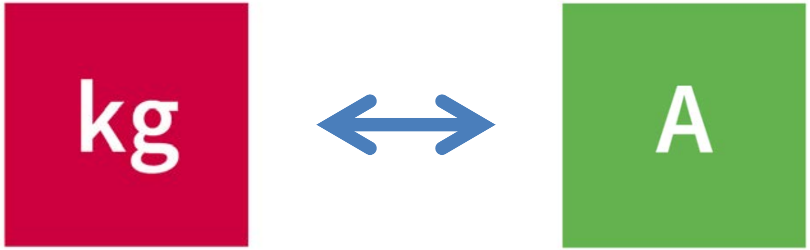
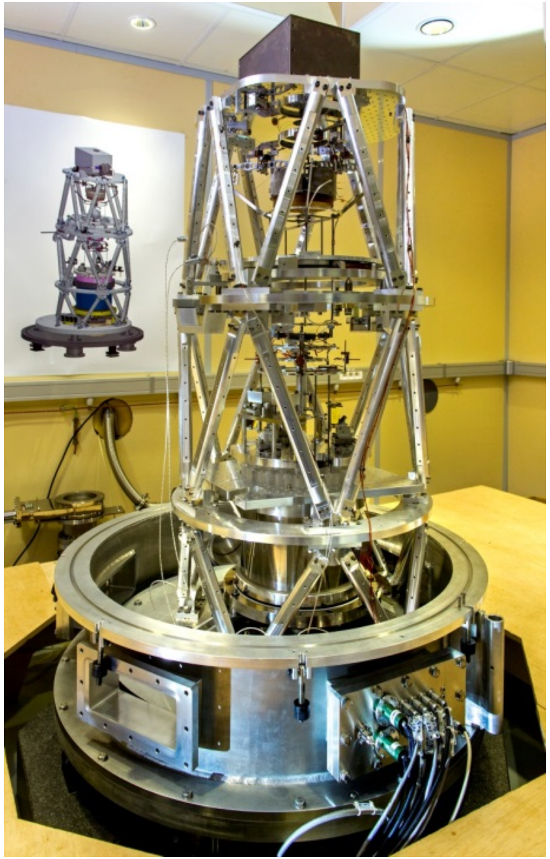
# A new way to link electrical units to mechanical units

- An experiment that links electrical power to mechanical power.




- The « moving coil watt balance »
- Now called the Kibble Balance.



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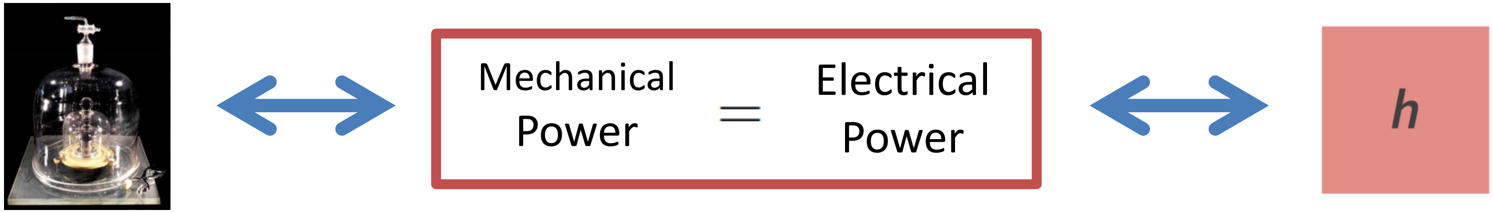
# A new way to link electrical units to mechanical units

- The Kibble balance can set

↔ Mechanical Power = Electrical Power ↔ $h$

# A new way to link electrical units to mechanical units

- The Kibble balance can set



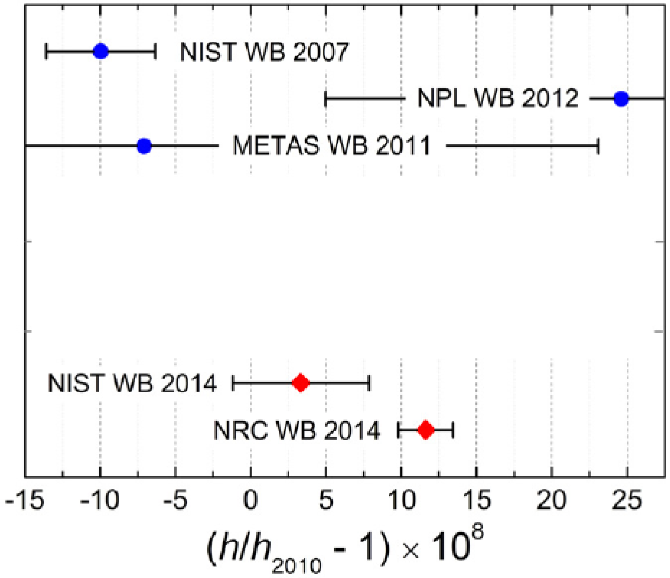

- If we can measure *h* with an uncertainty of some parts in $10^8$.

- Then the Kibble Balance can define the kilogram to some part in $10^8$ - if we fix the Planck Constant.

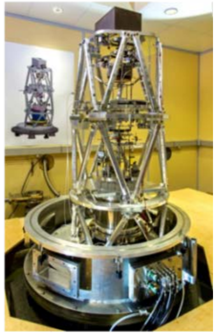
**Why did'nt we agree to implement this many years ago?**

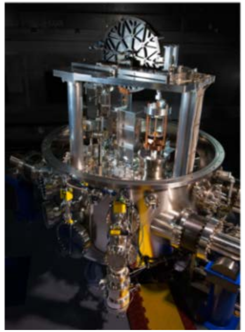
# It has not been easy to agree on the best value of the Planck constant

Metrologia 51 (2014) R21




Many Kibble balances have been commissioned to resolve the discrepancy – and hence to realise the kg.





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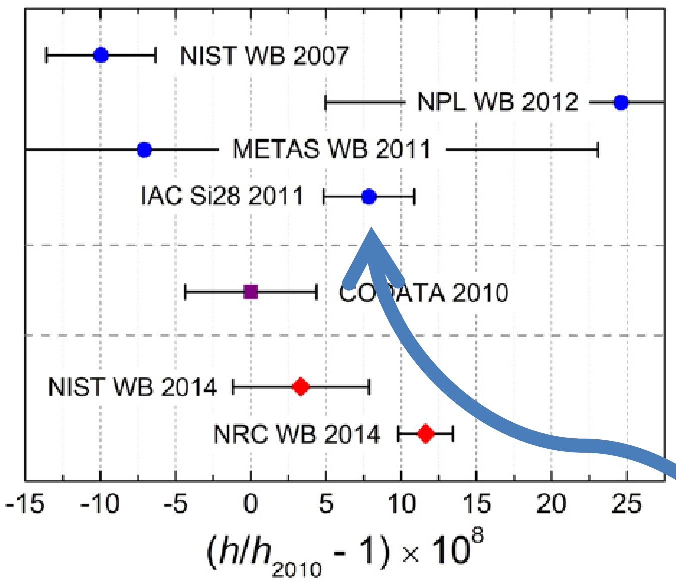


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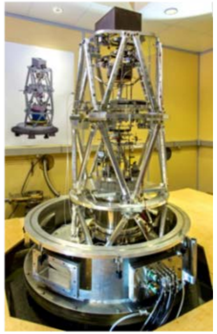

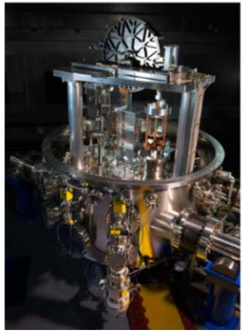

Values for *h* are available from other methods, including one that can be used to realised the kg.

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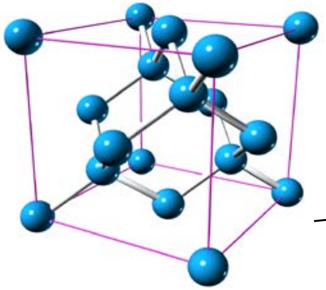
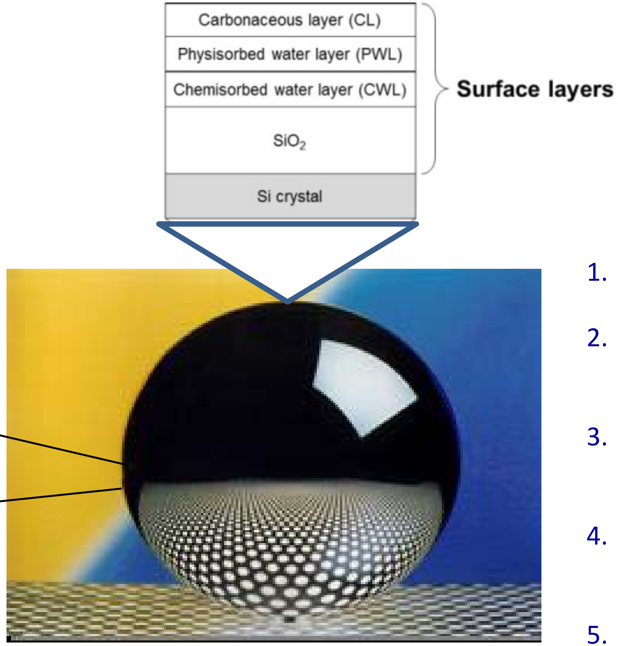
# The X-ray crystal density (XRCD) method

$$m_{\text{sphere}} = m_{\text{core}} + m_{\text{SL}}$$



**8 atoms per unit cell**



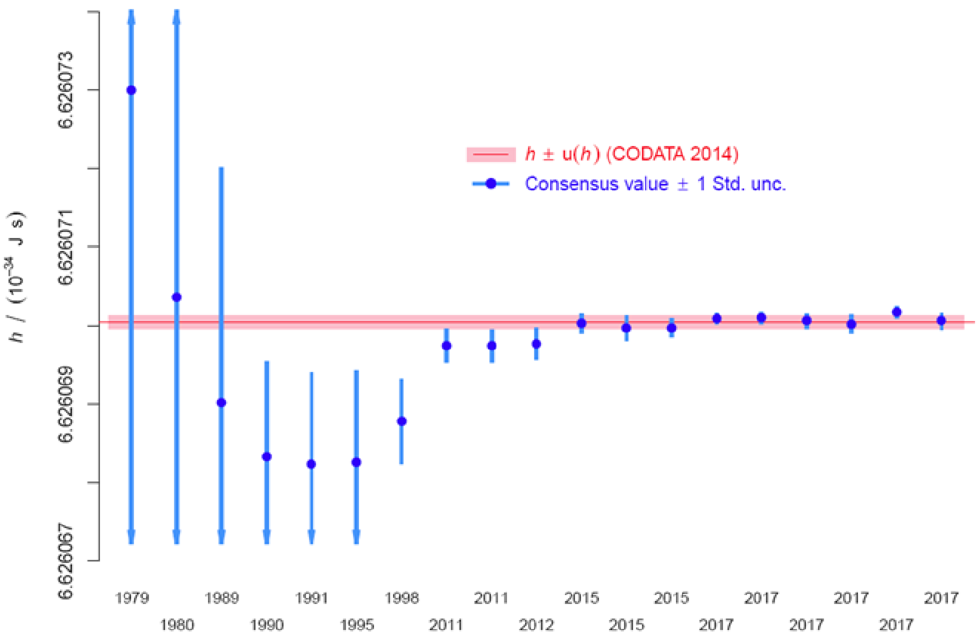

$N_A$ can be converted to a measurement of $h$ because of our knowledge of the Bohr atom.

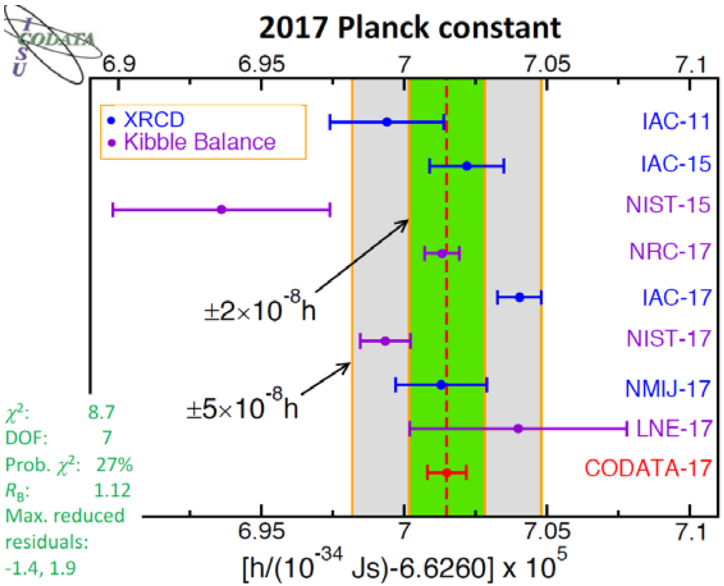
## Five sets of measurements

1. Lattice spacing measurement at INRIM (Italy)
2. Volume measurement at PTB (Germany) and **NMIJ (Japan)**
3. Surface measurement at PTB (Germany) and **NMIJ (Japan)**
4. Molar mass measurement at PTB (Germany) and **NMIJ (Japan)** with NIST (USA)
5. Mass measurement at PTB (Germany) and **NMIJ (Japan)**

**All must be more accurate than 2 parts in $10^8$**

# Progress with the measurement of the Planck constant




$$h = 6.626\,070\,150(69) \times 10^{-34}\ \mathrm{J\ s} \qquad 1.0 \times 10^{-8}$$

Data from CODATA 2017

# Outline



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# Writing the new definitions eg **the ampere**

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

**How does this work in practice?**

**Since *h* is fixed by the definition of the kilogram and *e* by the definition of the ampere:**

- **The quantum Hall effect defines an impedence in terms of $h/e^2$**
- **The Josephson effects defines a voltage in terms of $2e/h$**

**Note –there will be very small changes to the volt and the ohm**

$K_J$ will be smaller than $K_{J\text{-}90}$ by the fractional amount $18.8 \times 10^{-9}$.

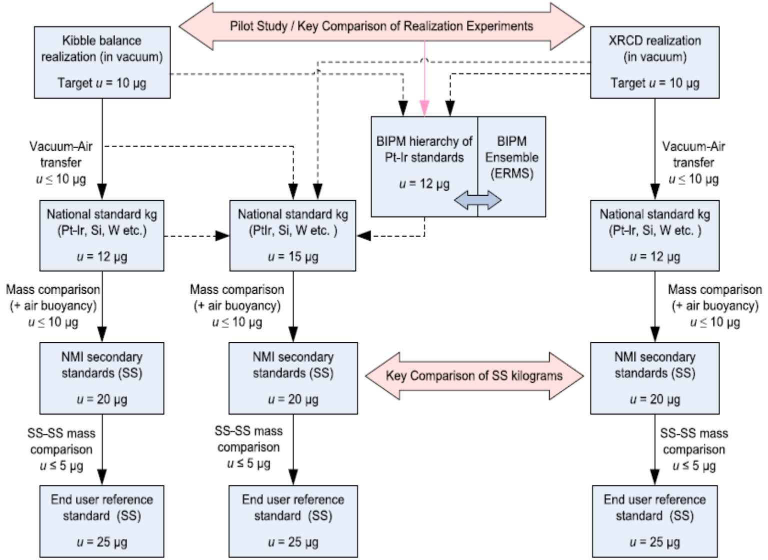
$R_K$ will be larger than $R_{K\text{-}90}$ by the fractional amount $21.6 \times 10^{-9}$.

# Writing the new definitions eg **the kilogram**

"The kilogram … is defined by taking the fixed numerical value of the Planck constant $h$ to be 6.626 070 15 × $10^{-34}$ 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 $\Delta\nu_{Cs}$".

## How does this work in practice?

- **The Kibble balance or the Si-XRCD method can be used to realise the kilogram.**
- **A protocol will be in place to ensure there is no change in the value of the kg.**



# Writing the new definitions eg **the kelvin**

"The kelvin … 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 $\Delta\nu_{Cs}$".

**How does this work in practice?**

- **Primary thermometers can be used to make measurements in kelvin.**
- **The ITS-90 will remain in use.**

# The International System of Units

By stating the fixed values of the 7 constants, the whole system is defined.

**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 × $10^{-34}$ J s,
- the elementary charge $e$ is 1.602 176 634 × $10^{-19}$ C,
- the Boltzmann constant $k$ is 1.380 649 × $10^{-23}$ J/K,
- the Avogadro constant $N_A$ is 6.022 140 76 × $10^{23}$ $mol^{-1}$,
- the luminous efficacy of monochromatic radiation of frequency 540 × $10^{12}$ hertz $K_{cd}$ 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 $s^{-3}$.

The numerical values of the seven defining constants have no uncertainty.

# How can we justify the new definitions?

- **The new definitions will "facilitate universality of access to the agreed basis for worldwide measurements".**
  - This has been an ambition for the "metric system" that goes back more than 200 years. The 2018 definitions will make it possible for the first time.
- **The changes will underpin future requirements for increases in accuracy**
  - As science and technology advances, the demands for the accuracy of measurements will continue to increase accuracy. The 2018 definitions will provide for these needs for many years to come.

# Summary

**The new definitions use “the rules of nature to create the rules of measurement”.**

- They will tie measurements at the atomic (and quantum) scales to those at the macroscopic level.

**The new definitions will provide long-term stability**

- The realisation of units will be possible using new methods.

**The challenge in the future will be to maintain comparability of “primary realisations”**

- The challenge is the same as we have with other measurement units.
- Coordination will become an even greater challenge.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Capacity Building & Knowledge Transfer

# *Thank you*


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