Capacity
Building &

The re-definition of the base units of the SI:

- using the rules of nature to create the rules of measurement

Dr Martin J.T Milton

Director, BIPM
10th October 2018

Bureau
International des
Poids et
Mesures

Redefinición del Sistema Internacional de Unidades
CENTRO NACIONAL DE METROLOGÍA

SImposio
8 -12 octubre 2018 metrología
Para la innovación tecnológica y el desarrollo sustentable

Outline

01 – The metric system and the Metre Convention

02 - The re-definition of the SI in 2018

03 – The impact of the new definitions

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Mesures

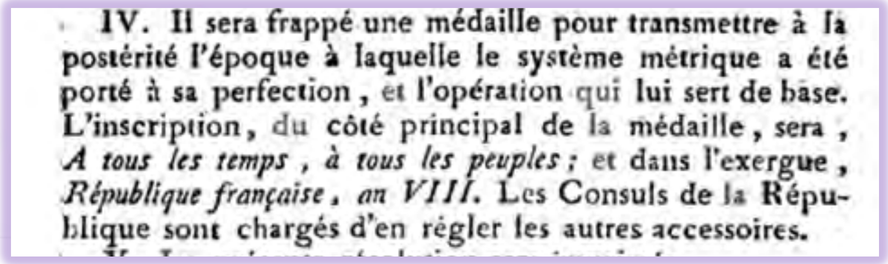
Why was the Metric system of so much interest?

The Metric System was first introduced after the French Revolution:

to allow fair trade by weight and length.

- **The metre** = one ten millionth part of the arc of the meridian between the north pole and the equator (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?



IV. Il sera frappé une médaille pour transmettre à la postérité l'époque à laquelle le système métrique a été porté à sa perfection, et l'opération qui lui sert de base. L'inscription, du côté principal de la médaille, sera, *A tous les temps, à tous les peuples;* et dans l'exergue, *République française, an VIII.* Les Consuls de la République sont chargés d'en régler les autres accessoires.

LOI 3456 DU
19 FRIMAIRE AN VIII
(1799)

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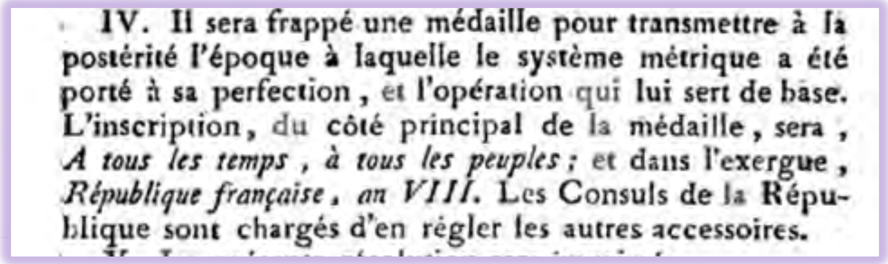
But, in 1812 – Napoleon abandoned the Metric System !

Why was the Metric system of so much interest?



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.... in 1837 it was re-intrduced

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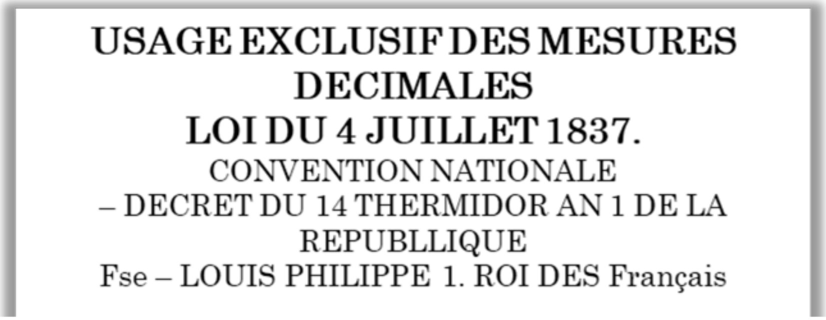
USAGE EXCLUSIF DES MESURES
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LOI DU 4 JUILLET 1837.
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Fse – LOUIS PHILIPPE 1. ROI DES Français

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International des
Poids et
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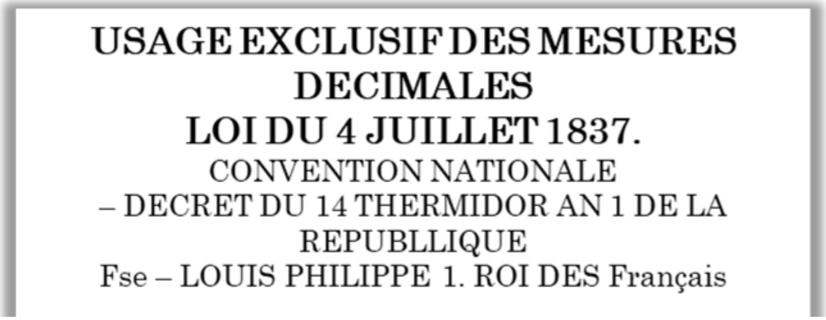
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But confusion developed about the definitions of the metre and the kilogram. Were they:

- the old revolutionary standards? or
- the artefact standards held in the National Archives?

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.

DOCUMENTS DIPLOMATIQUES

DE

LA CONFÉRENCE DU MÈTRE.

PARIS.

IMPRIMERIE NATIONALE.

1874.

20 May 1875

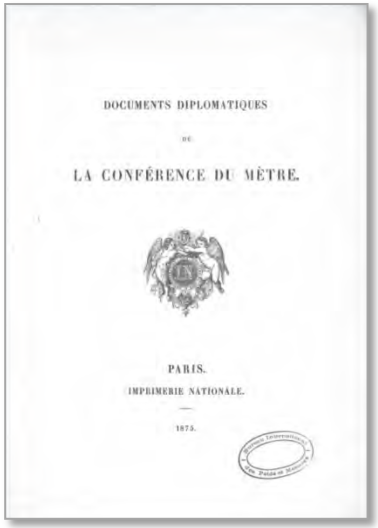
The Metre Convention was signed in Paris

by 17 nations

"TO ASSURE THE INTERNATIONAL UNIFICATION AND PERFECTION OF THE METRIC SYSTEM"

the Metre Convention

20 May 1875 - The Metre Convention was signed in Paris by 17 nations



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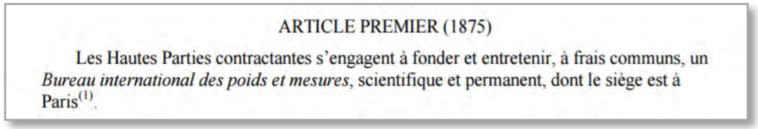
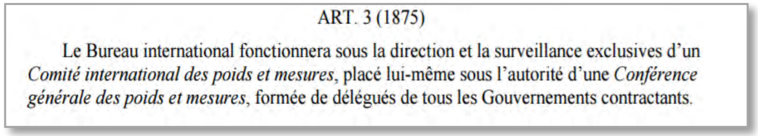


ARTICLE PREMIER (1875)

Les Hautes Parties contractantes s'engagent à fonder et entretenir, à frais communs, un *Bureau international des poids et mesures*, scientifique et permanent, dont le siège est à Paris(1).

Article 1 The High Contracting Parties undertake
To create and maintain, at their common expense, a ***scientific and permanent International Bureau of Weights and Measures*** *with its headquarters in Paris.*



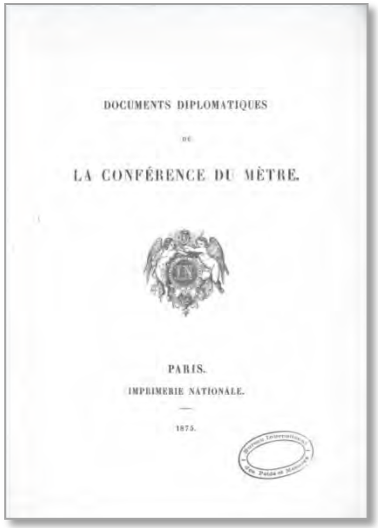
ART. 3 (1875)

Le Bureau international fonctionnera sous la direction et la surveillance exclusives d'un *Comité international des poids et mesures*, placé lui-même sous l'autorité d'une *Conférence générale des poids et mesures*, formée de délégués de tous les Gouvernements contractants.

Article 3 states that
The BIPM shall operate under the authority of the ***General Conference on Weights and Measures (CGPM)*** *and the supervision of the* ***International Committee for Weights and Measures (CIPM)***

the Metre Convention

20 May 1875 - The Metre Convention was signed in Paris by 17 nations



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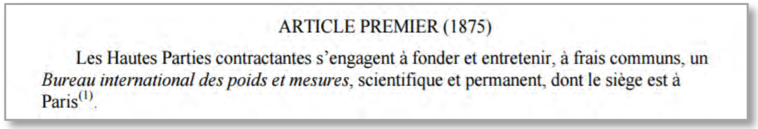

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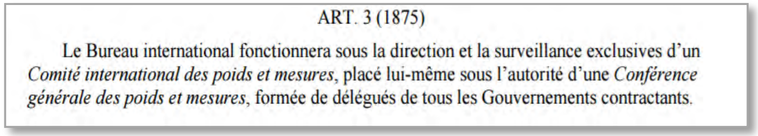

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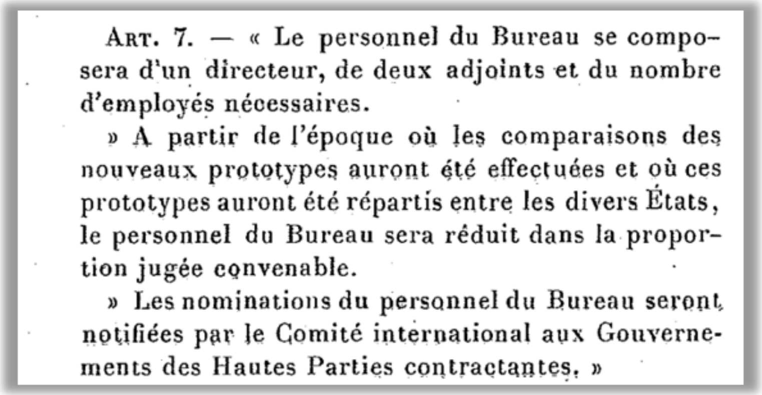


ART. 7. — « Le personnel du Bureau se composera d'un directeur, de deux adjoints et du nombre d'employés nécessaires.

» A partir de l'époque où les comparaisons des nouveaux prototypes auront été effectuées et où ces prototypes auront été répartis entre les divers États, le personnel du Bureau sera réduit dans la proportion jugée convenable.

» Les nominations du personnel du Bureau seront notifiées par le Comité international aux Gouvernements des Hautes Parties contractantes. »

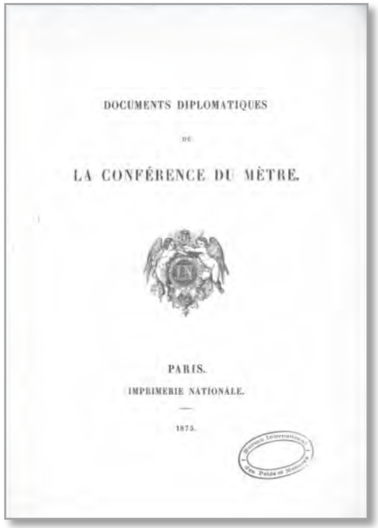
Article 7 states that

The personnel of the Bureau shall be a Director, two assistants and the number of employees necessary.

… and will be reduced when the work on the new prototypes is finished and they are distributed to the States.

the Metre Convention

20 May 1875 - The Metre Convention was signed in Paris by 17 nations



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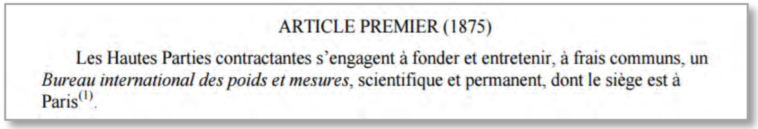

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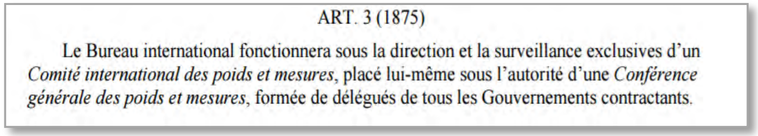

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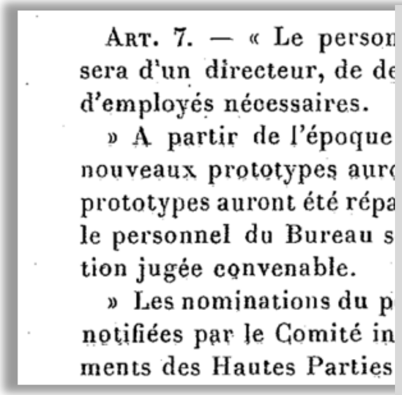

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tion jugée convenable.
» Les nominations du p
notifiées par le Comité in
ments des Hautes Parties

Article 7 revised in 1920 *the Bureau will be charged with*

- *the establishment and the conservation of standards of electrical units ...*
- *determinations related to physical constants for which more accurate knowledge might serve to increase the precision and ensure better uniformity in the fields to which the units mentioned above belong.*
- *the work of coordinating similar determinations made in other institutes.*

The BIPM – an international organisation

Established in 1875 when 17 States signed the Metre Convention, now with 60 Member States.

CGPM – Conférence Générale des Poids et Mesures

Official represntatives of Member States.

CIPM – Comité International des Poids et Mesures

Eighteen individuals of different nationalities elected by the CGPM.

BIPM Staff

- *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

World-famous scientists at **the BIPM**

Dmitri Mendeleev
was a CIPM
Member
(1895-1901)

Charles Édouard Guillaum
BIPM Director,
won the Nobel Prize in 1920

Marie and Pierre Curie
collaborated with the
BIPM

Five CIPM Members have won the Nobel prize including **De Broglie** and **Michelson**

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Mesures

Outline

01 - The need for Measurements and the Meter Convention

02 - A re-definition of the SI in 2018

03 – The impact of the new definitions

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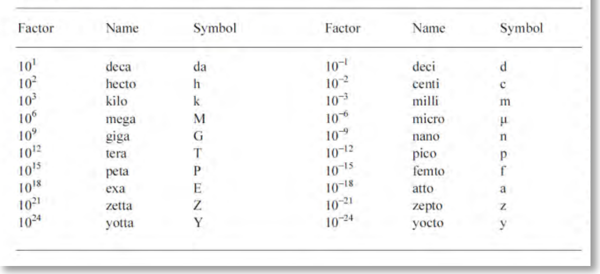
Poids et
Mesures

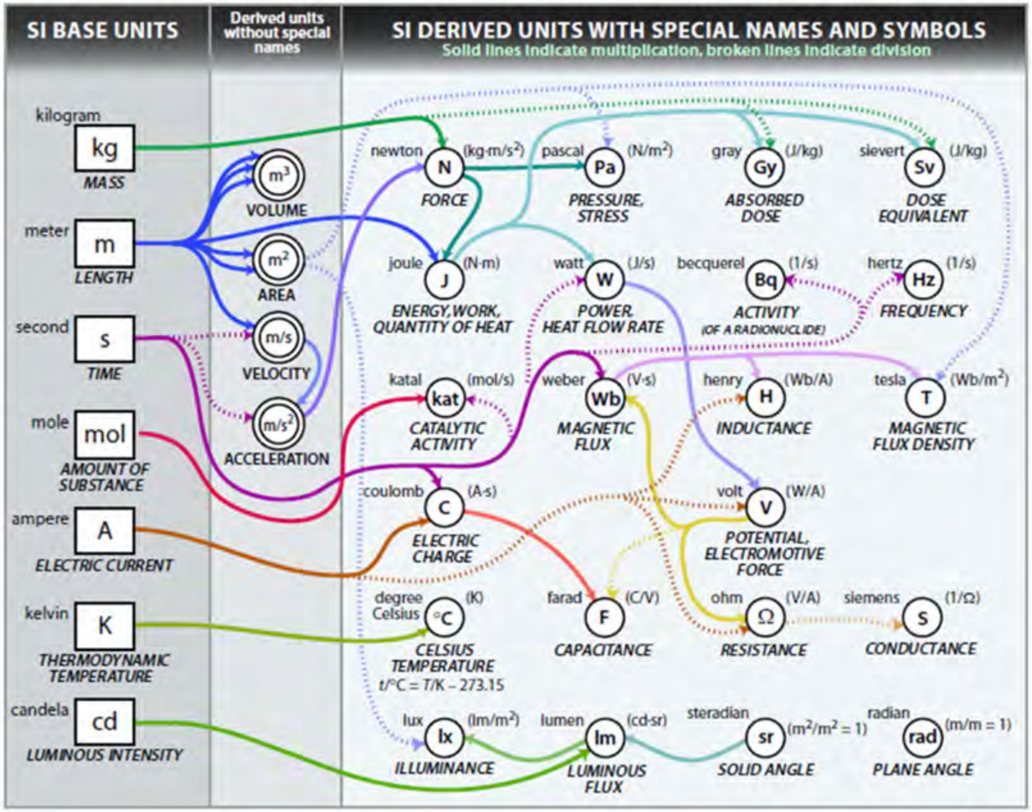
The International System of Units (SI)

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

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



From NIST -http://physics.nist.gov/cuu/Units/SIdiagram.html

Seven base units - *that are linked together*

3 definitions based on fundamental (or conventional) constants:

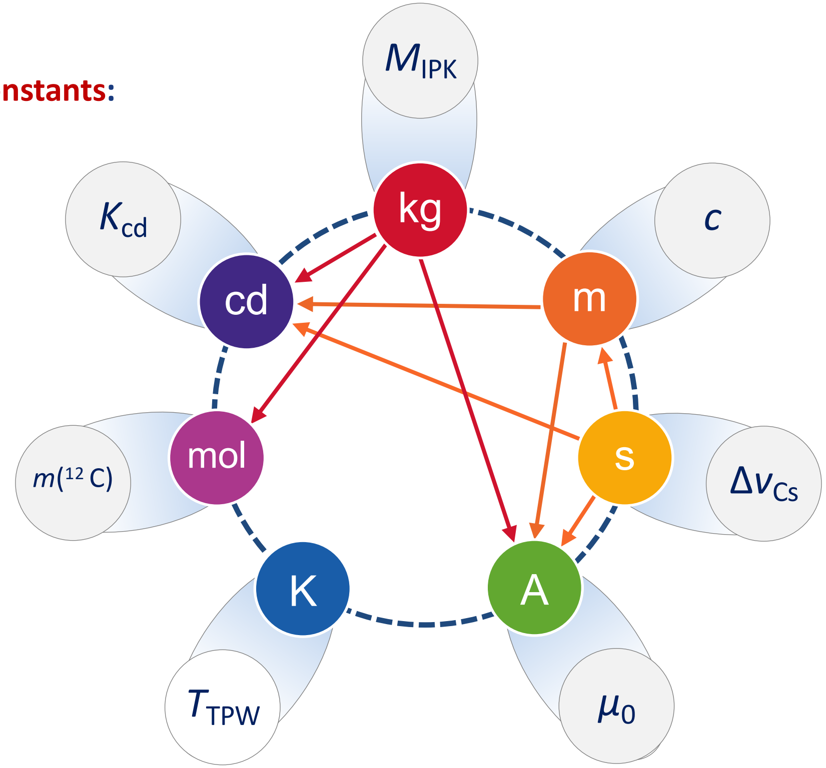
- metre (c)
- ampere (μ_0)
- candela (K_{cd})

3 definitions based on atomic or material properties:

- second ($\Delta\nu_{Cs}$)
- kelvin (T_{TPW})
- mole (m^{12}C)

1 definition based on an artefact:

- kilogram (M_{IPK})



Bureau International des Poids et Mesures

Seven base units

We propose to change the definitions of four of them

3 definitions based on fundamental (or conventional) constants:

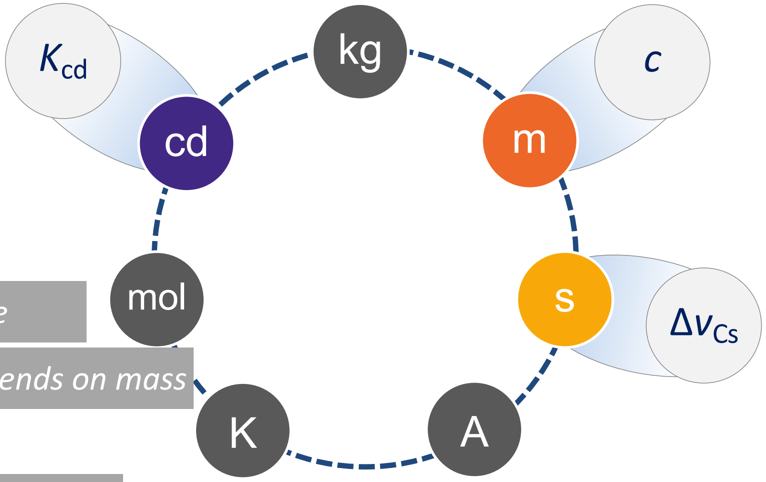
- metre (c)
- ampere (μ_0) *- Superseded by the 1990 convention*
- candela (K_{cd})

3 definitions based on atomic or material properties:

- second ($\Delta\nu_{Cs}$)
- kelvin (T_{TPW}) *- Implemented through the ITS-90 scale*
- mole (m^{12}C) *- definition is often misunderstood – depends on mass*

1 definition based on an artefact:

- kilogram (M_{IPK}) *- artefact – may not be stable ?*



Bureau International des Poids et Mesures

Seven base units

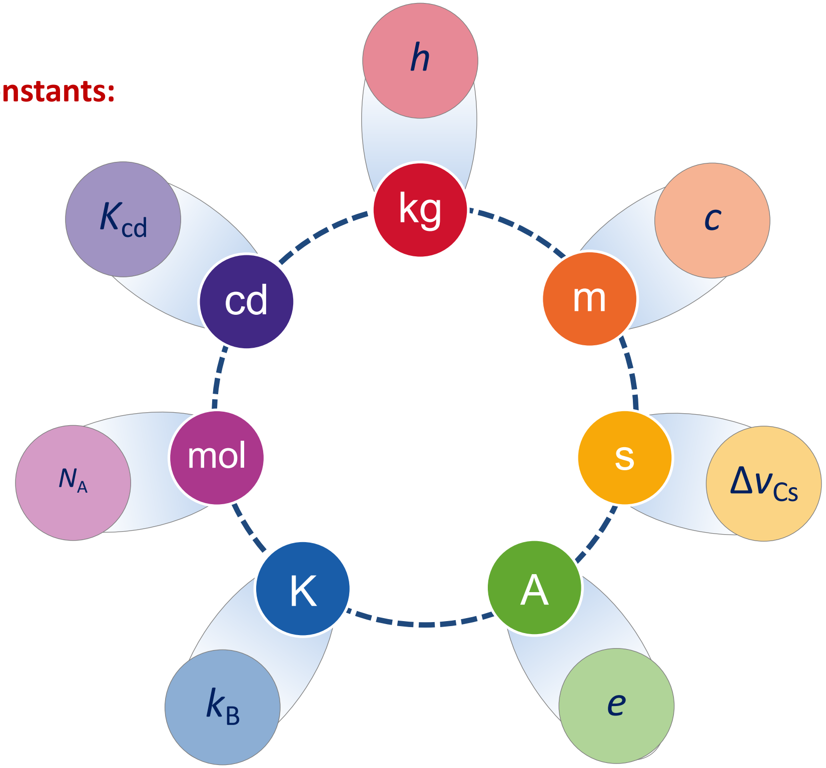
Introducing 4 new definitions

6 definitions based on fundamental (or conventional) constants:

- metre (c)
- candela (K_{cd})
- kilogram (h)
- ampere (e)
- kelvin (k_{B})
- mole (N_{A})

1 definition based on atomic property:

- second ($\Delta\nu_{\text{Cs}}$)



Bureau International des Poids et Mesures

Seven base units

…same base units but different links

6 definitions based on fundamental (or conventional) constants:

- metre (c)
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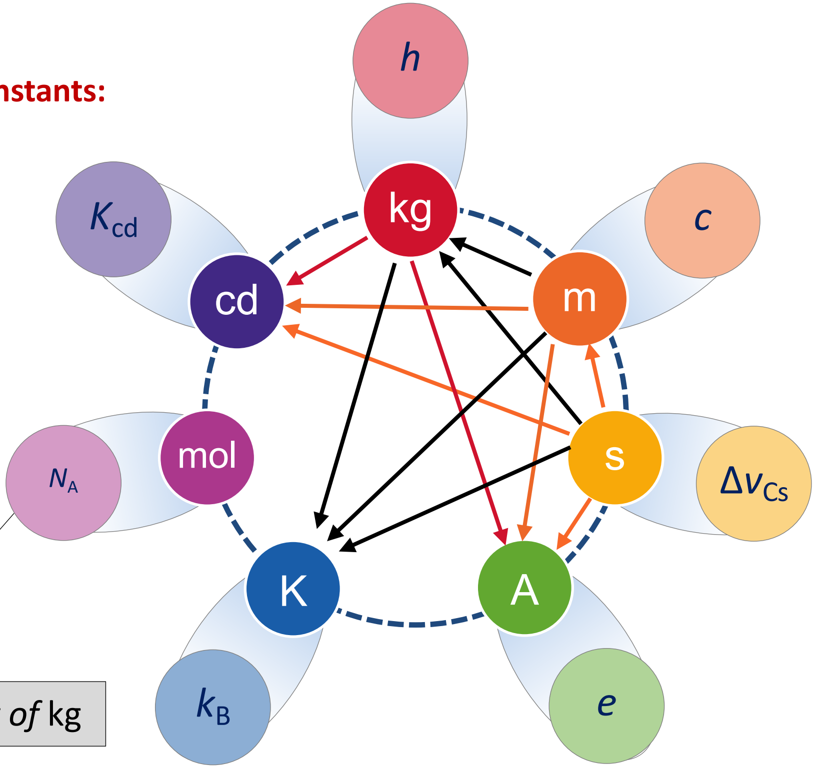


mol *is now independent of* kg

Bureau International des Poids et Mesures

How difficult will it be to achieve?

Is it worth doing ?

Bureau
International des
Poids et
Mesures

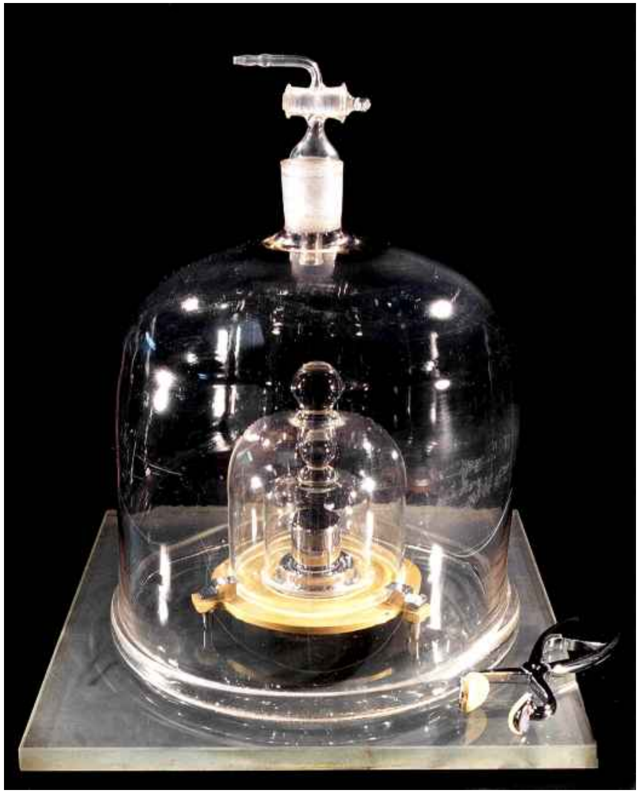

kg

The definition of the kilogram in the SI

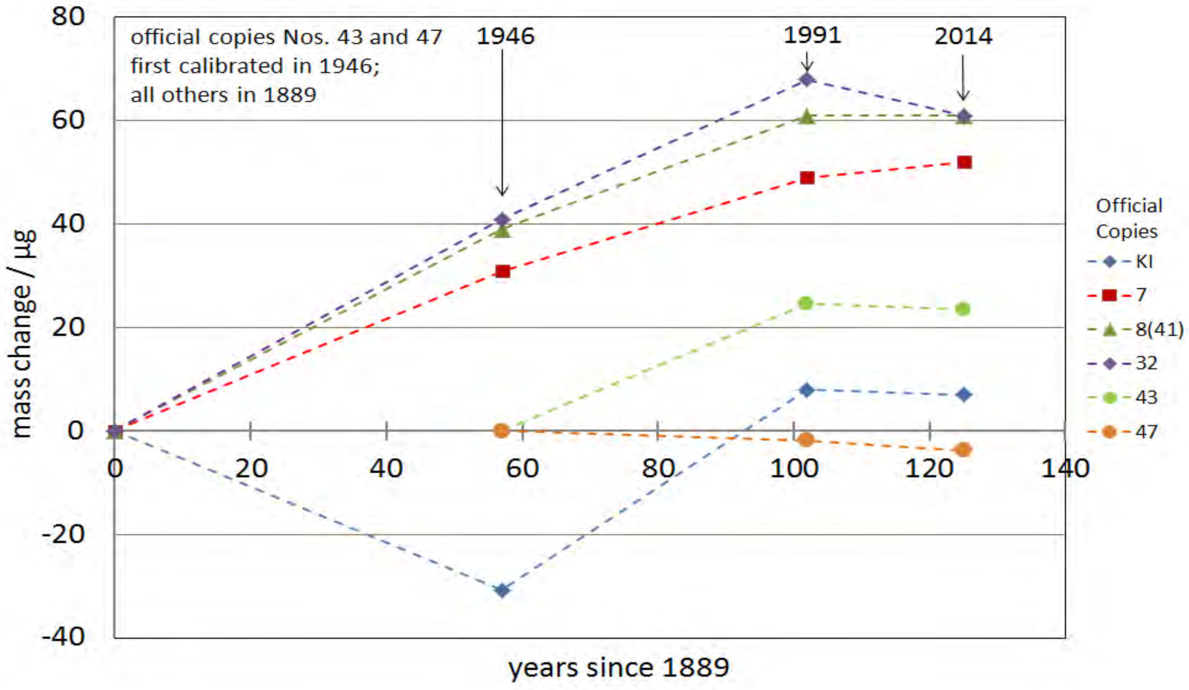
The kilogram is the unit of mass -
it is equal to the mass of the international prototype of the kilogram.

- 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, $Ø = h \sim 39$ mm
- kept in ambient air at the BIPM

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



Why make the change ? – the International Prototype kg



official copies Nos. 43 and 47 first calibrated in 1946; all others in 1889

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

standard deviation of changes between 1991 and 2014 = 3 µg

Why make the change ? – the size of the kg (!)

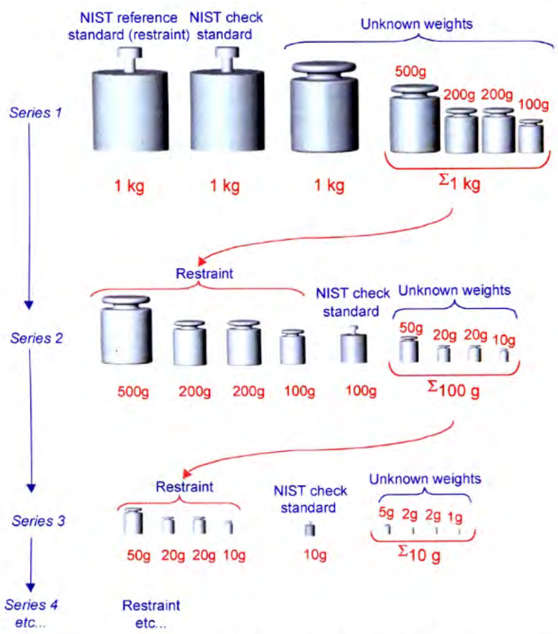


Fig. 3. A schematic description of the weighing designs used in the dissemination to submultiples of the kilogram.

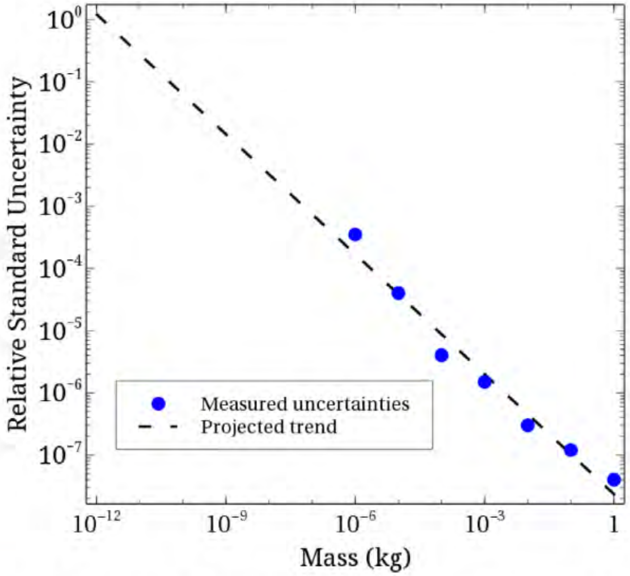


Figure 1. Relative uncertainty in mass as a function of mass value. Dashed line is a linear fit to the data shown.

Z. J. Jabbour and S. L. Yaniv,
J. Res. Natl. Inst. Stand. Technol. 106, 25–46 (2001)]

Gordon A Shaw et al
Metrologia 53 (2016) A86 –A94

A

Why make the change ? – the electrical units.

The ampere is that constant current which, if maintained in two straight parallel conductors of infinite length, of negligible circular cross-section, and placed 1 metre apart in vacuum, would produce between these conductors a force equal to 2 x 10^{-7} *newton per metre of length.*

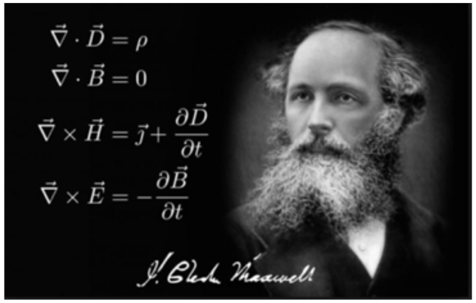
The definition of the ampere gives us:-

- Ampere's law

$$\frac{dF}{dl} = \frac{\mu_0}{2\pi}\frac{II'}{r}$$

- Coulomb's law

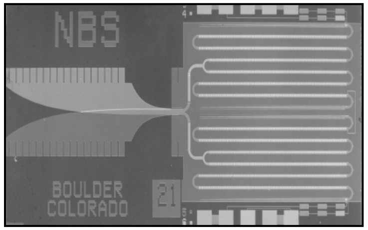
$$F = \frac{1}{4\pi\epsilon_0}\frac{qq'}{r^2}$$

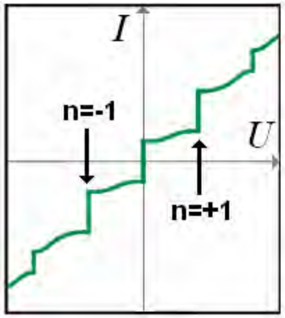


Since 1990, macroscopic quantum effects have been the basis for the reproduction of the electrical units

Josephson effect

Nobel Prize 1973



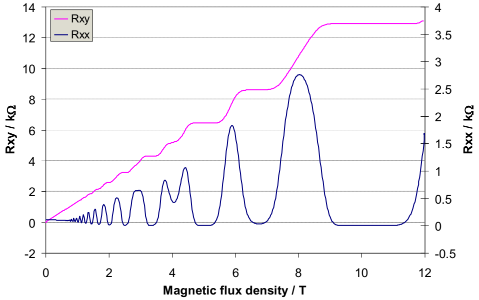


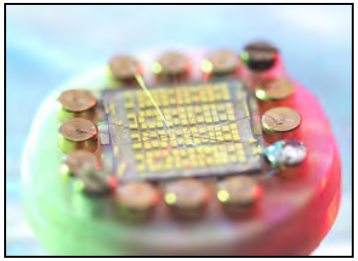
$$U_\mathrm{J} = n\frac{f}{K_\mathrm{J}}, \qquad K_\mathrm{J} = \frac{2e}{h}$$

***$K_{\text{J-90}}$* ≡ 483 597.9 GHz/V**

Quantum-Hall effect

Nobel Prize 1985





$$R_\mathrm{H}(i) = \frac{R_\mathrm{K}}{i}, \qquad R_\mathrm{K} = \frac{h}{e^2}$$

***$R_{\text{K-90}}$* ≡ 25 812.807 Ω**

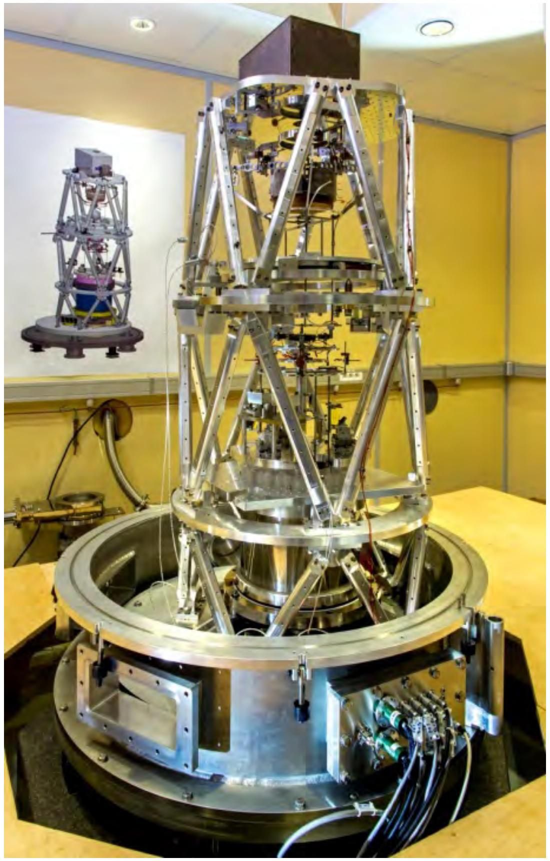
- But: this convention is not within the SI
  (because they may not lead to $\mu_0 \equiv 4\pi \cdot 10^{-7}$ N A^{-2})

A new way to link electrical units to mechanical units

- An experiment that links electrical power to mechanical power.

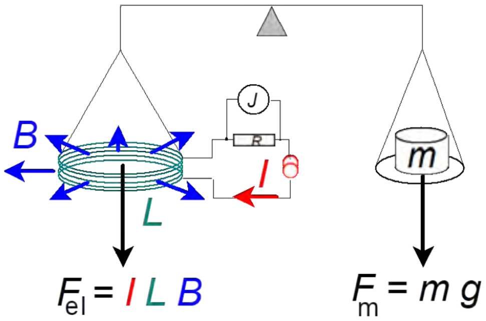
kg ↔ A

- The « moving coil watt balance »
- Now named the Kibble Balance after its inventor.



The Kibble balance – a 2-phase experiment

Phase 1: static experiment
(weighing or force mode)



Ampere's Law

$$\boxed{mg = -I\frac{d\Phi}{dz}}$$

In a radial magnetic field, this can be simplified to

$$\boxed{m\,g = I\,L\,B}$$

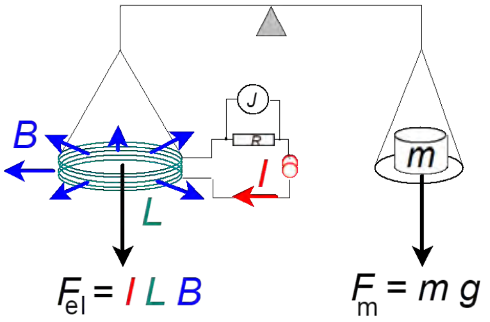
current

wire length

flux density

The Kibble balance – a 2-phase experiment

Phase 1: static experiment (weighing or force mode)



Ampere's Law

$$mg = -I\frac{d\Phi}{dz}$$

In a radial magnetic field, this can be simplified to

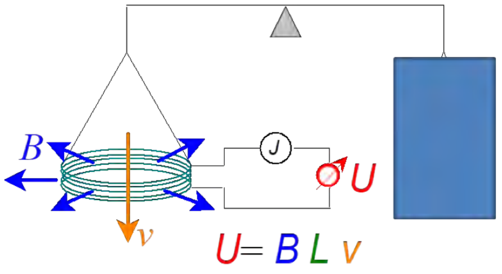
$$m\,g = I\,L\,B$$

current

wire length

flux density

Phase 2: dynamic experiment (velocity mode)



Coil is moved through the magnetic field and a voltage is induced.

Faraday's Law

$$U = -\frac{d\Phi}{dt} = -v\frac{d\Phi}{dz}$$

In a radial magnetic field, this can be simplified to

$$U = B\,L\,v$$

ind. voltage

flux density

wire length

velocity

$$mgv_z = UI$$

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Mesures

The Kibble balance – a 2-phase experiment

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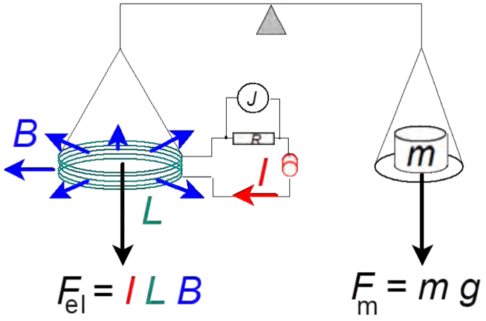

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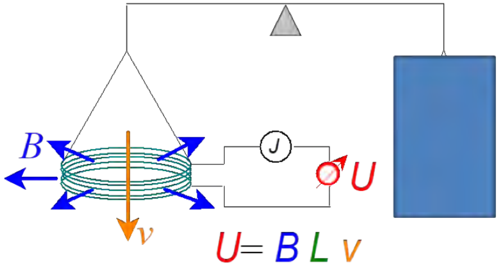

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ind. voltage

flux density

wire length

velocity

$$mgv_z = UI = \frac{h}{4}f_1 f_2 n_1 n_2 p.$$

by use of:

the Josephson effect (twice)

the Quantum Hall effect

A new way to link electrical units to mechanical units

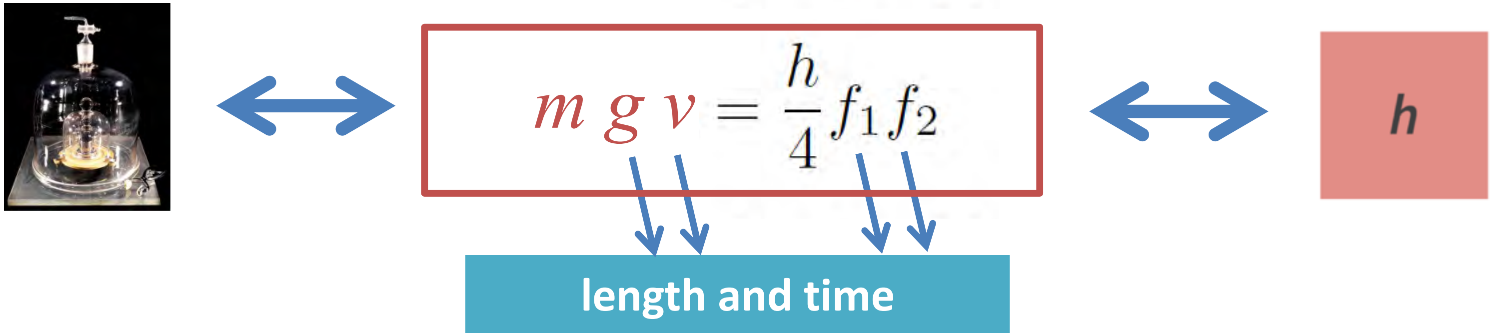
- The Kibble balance can set

Mechanical Power = Electrical Power

$$m\,g\,v$$

A new way to link electrical units to mechanical units

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

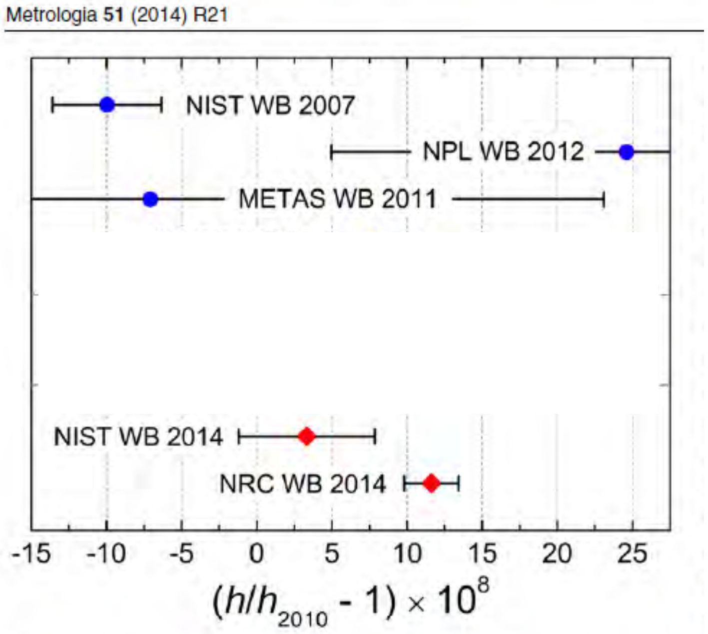


$$m\,g\,v = \frac{h}{4} f_1 f_2$$

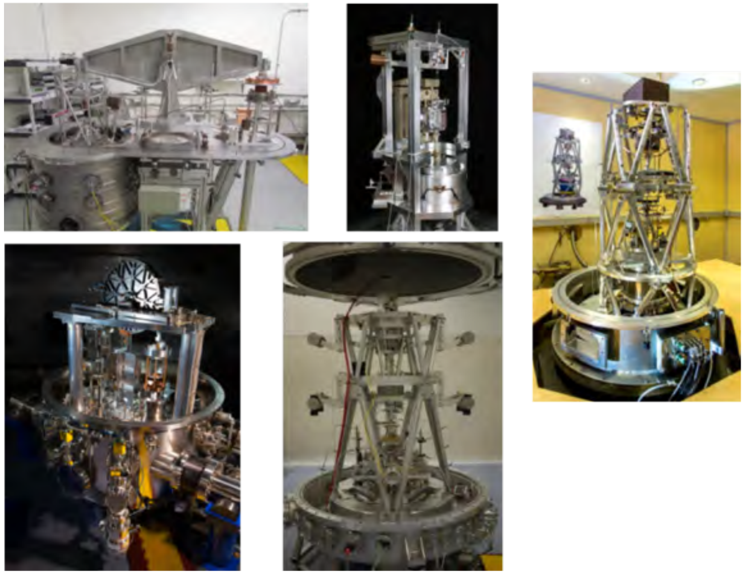
length and time

- 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.**

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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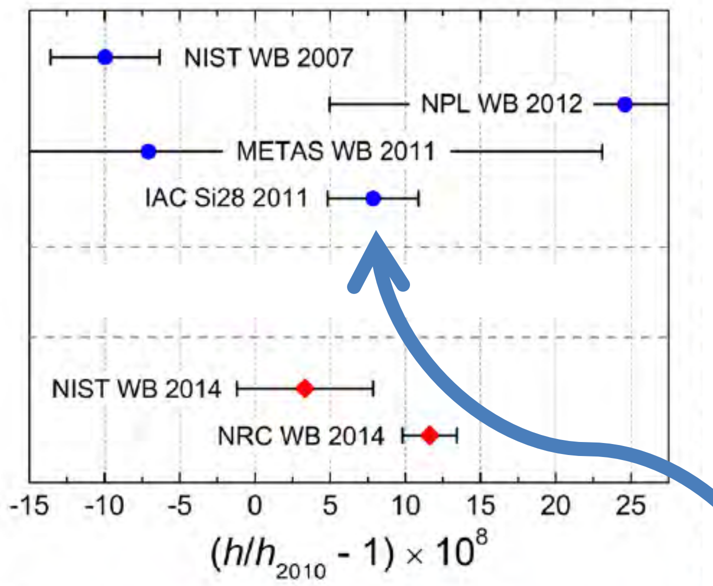
Metrologia **51** (2014) R21



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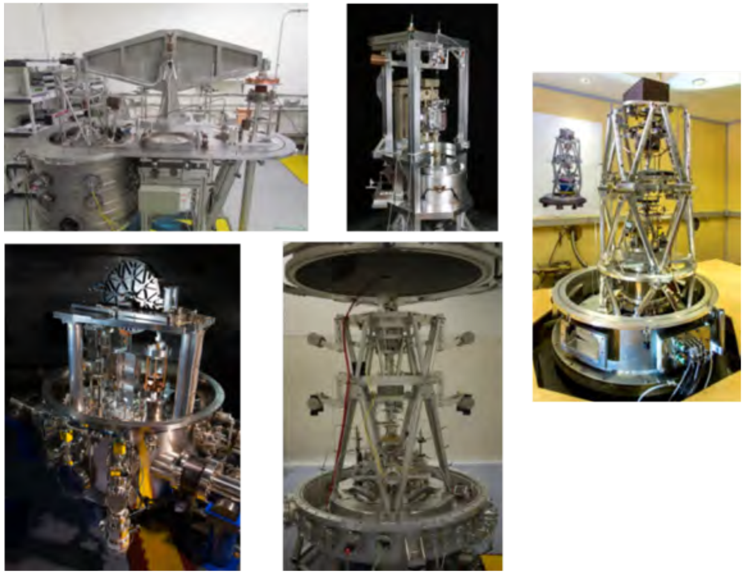
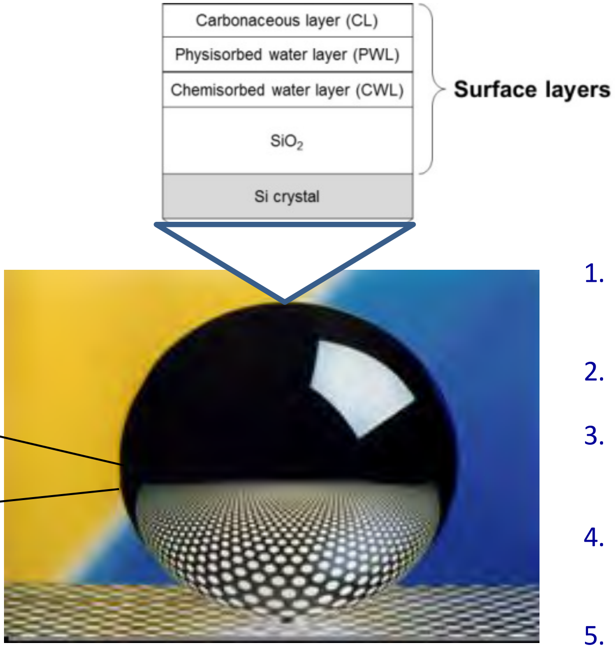
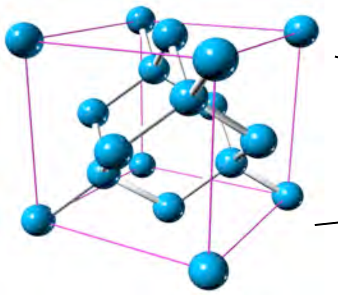


Values for *h* are available from other methods, including one that can be used to realise the kg.

The X-ray crystal density (XRCD) method

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





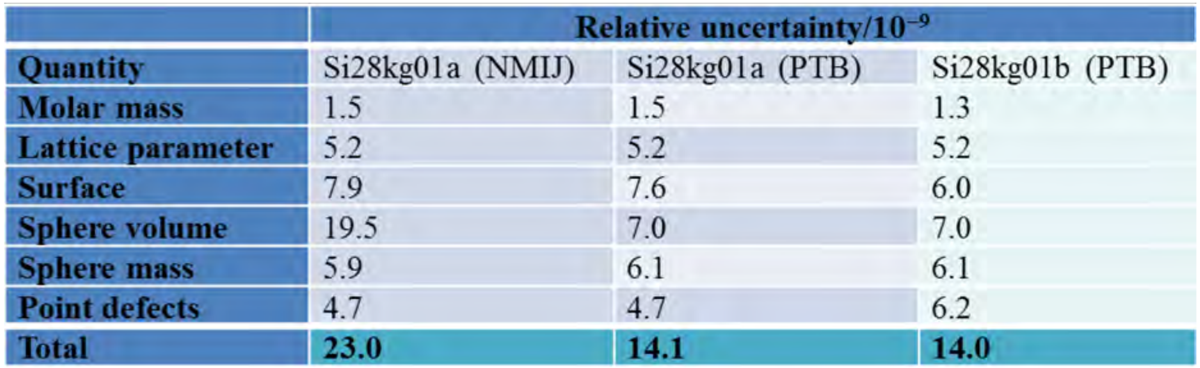
8 atoms per unit cell

Five sets of measurements

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

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

The X-ray crystal density (XRCD) method



	Relative uncertainty/10^{-9}		
Quantity	Si28kg01a (NMIJ)	Si28kg01a (PTB)	Si28kg01b (PTB)
Molar mass	1.5	1.5	1.3
Lattice parameter	5.2	5.2	5.2
Surface	7.9	7.6	6.0
Sphere volume	19.5	7.0	7.0
Sphere mass	5.9	6.1	6.1
Point defects	4.7	4.7	6.2
Total	**23.0**	**14.1**	**14.0**

Five sets of measurements

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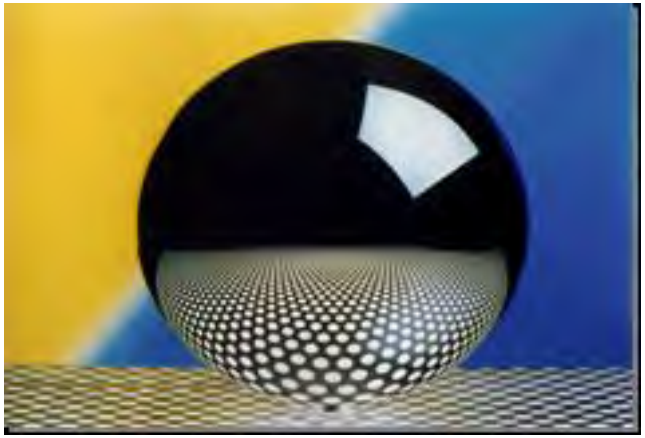
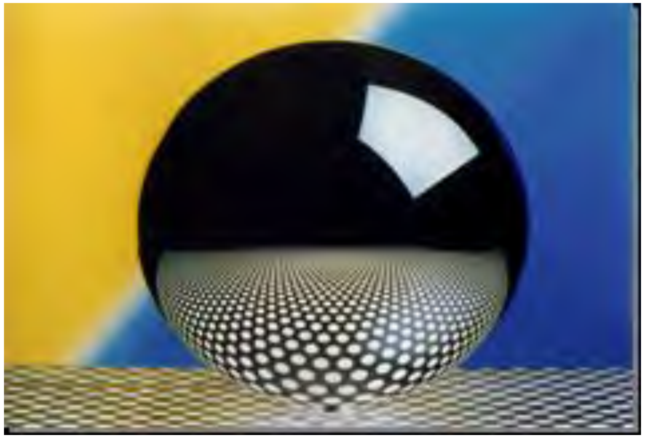


The silicon sphere

1. links macroscopic mass (1kg) to macroscopic mass (m_{Si})

The X-ray crystal density (XRCD) method

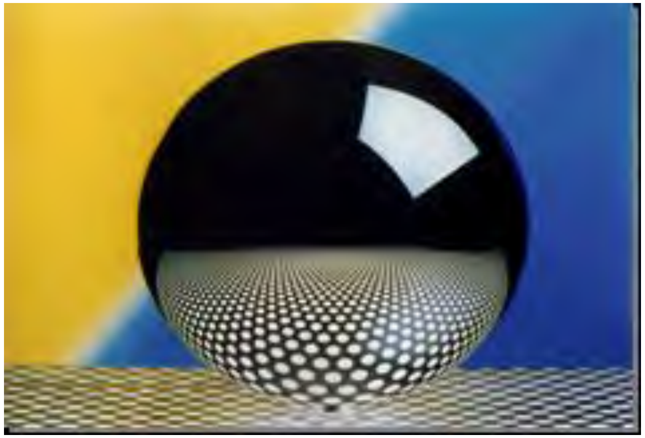


The silicon sphere

1. links macroscopic mass (1kg) to macroscopic mass (m_{Si})
2. uses the Rydberg constant, R_∞ , to link m_{Si} to h

$$m_{Si} = A_r(Si).\frac{2h}{c}.\frac{R_\infty}{A_r(e).\alpha^2}$$

The X-ray crystal density (XRCD) method



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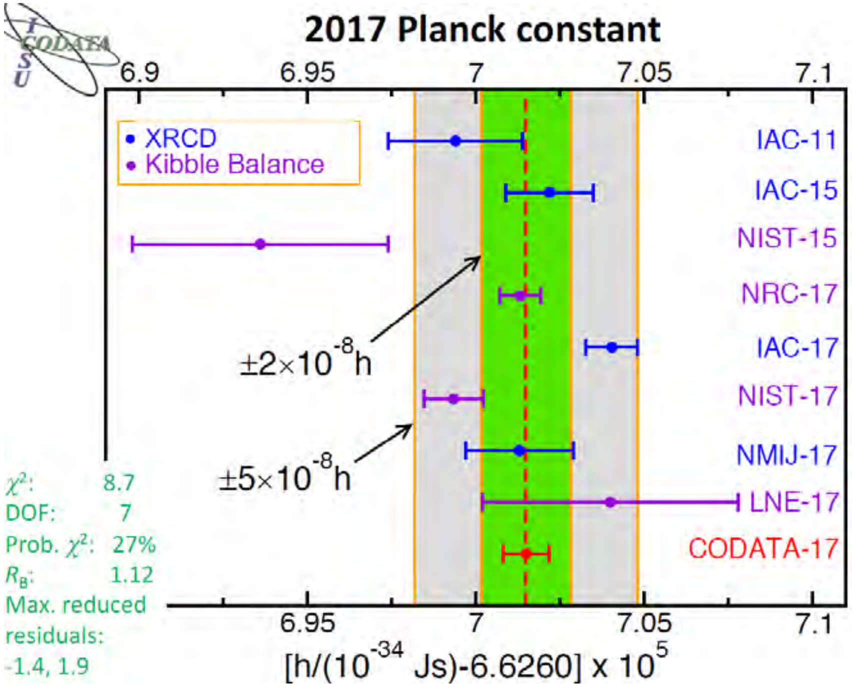
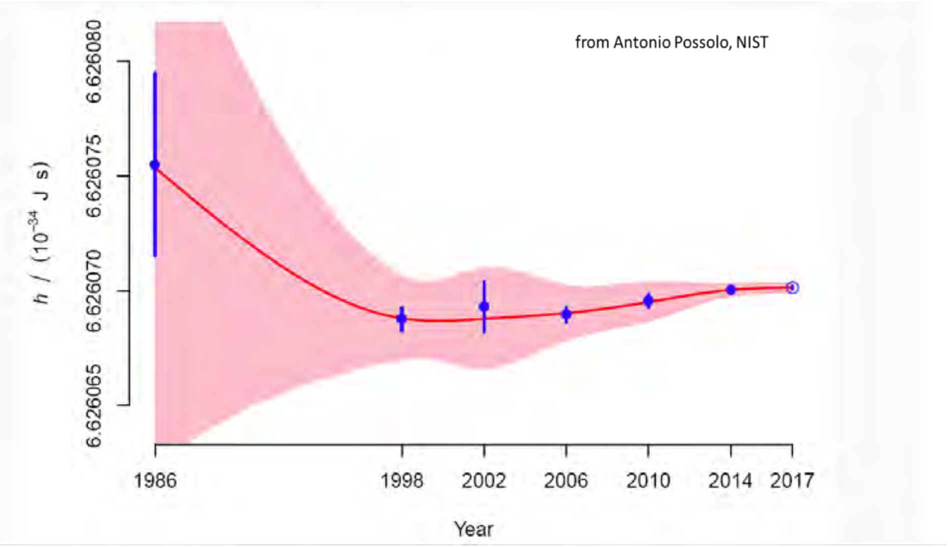
$$m_{Si} = A_r(Si).\frac{2h}{c}.\boxed{\begin{array}{c}\dfrac{R_\infty}{A_r(e).\alpha^2}\\ \\ u_r \sim 10^{-10}\end{array}}$$

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

01 - The need for Measurements and the Meter Convention

02 - A re-definition of the SI in 2018

03 – The impact of the new definitions

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Mesures

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

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

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

$2e/h$ will be smaller than $K_{\mathrm{J-90}}$ by the fractional amount 107 ×10^{-9}

h/e^2 will be larger than $R_{\mathrm{K-90}}$ by the fractional amount 18 ×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 $\Delta\nu_{\mathrm{Cs}}$".

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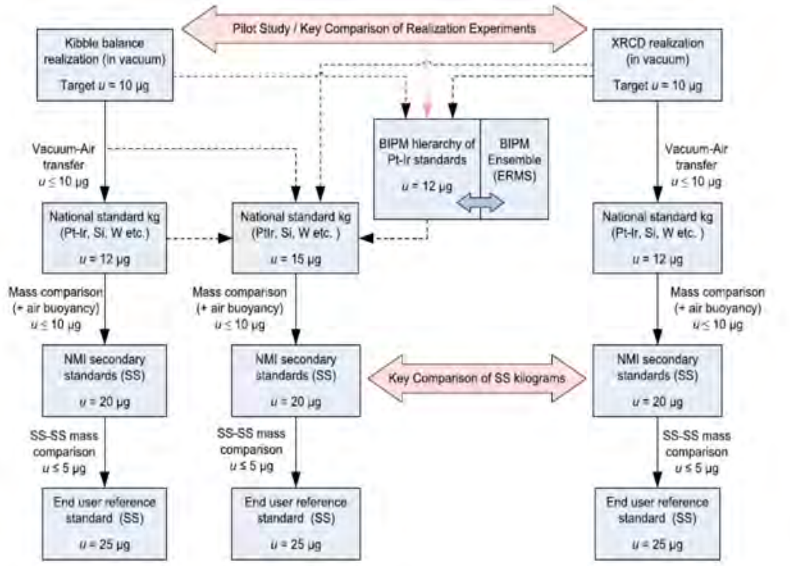
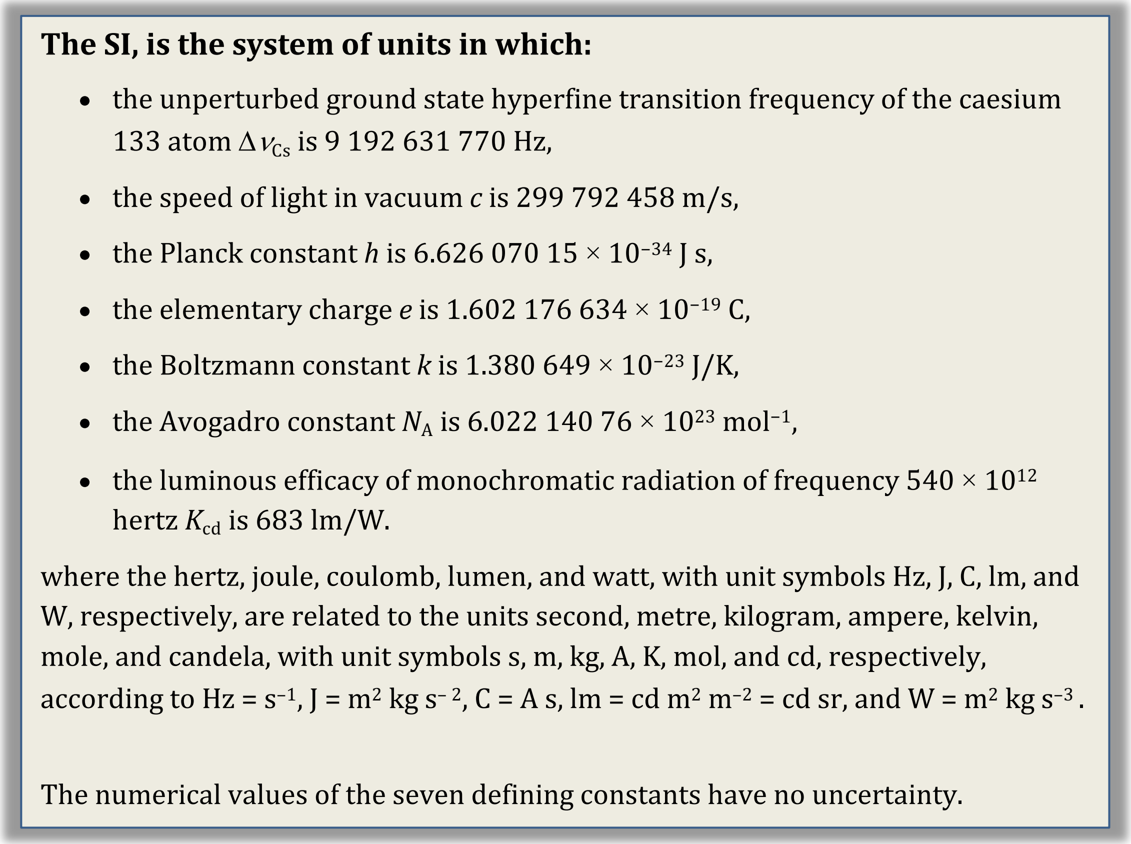
How does this work in practice?

- **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.**



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 $\Delta \nu_{\mathrm{Cs}}$ 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} 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 $\mathrm{Hz} = \mathrm{s}^{-1}$, $\mathrm{J} = \mathrm{m}^2\,\mathrm{kg}\,\mathrm{s}^{-2}$, $\mathrm{C} = \mathrm{A}\,\mathrm{s}$, $\mathrm{lm} = \mathrm{cd}\,\mathrm{m}^2\,\mathrm{m}^{-2} = \mathrm{cd}\,\mathrm{sr}$, and $\mathrm{W} = \mathrm{m}^2\,\mathrm{kg}\,\mathrm{s}^{-3}$.

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

The International System of Units

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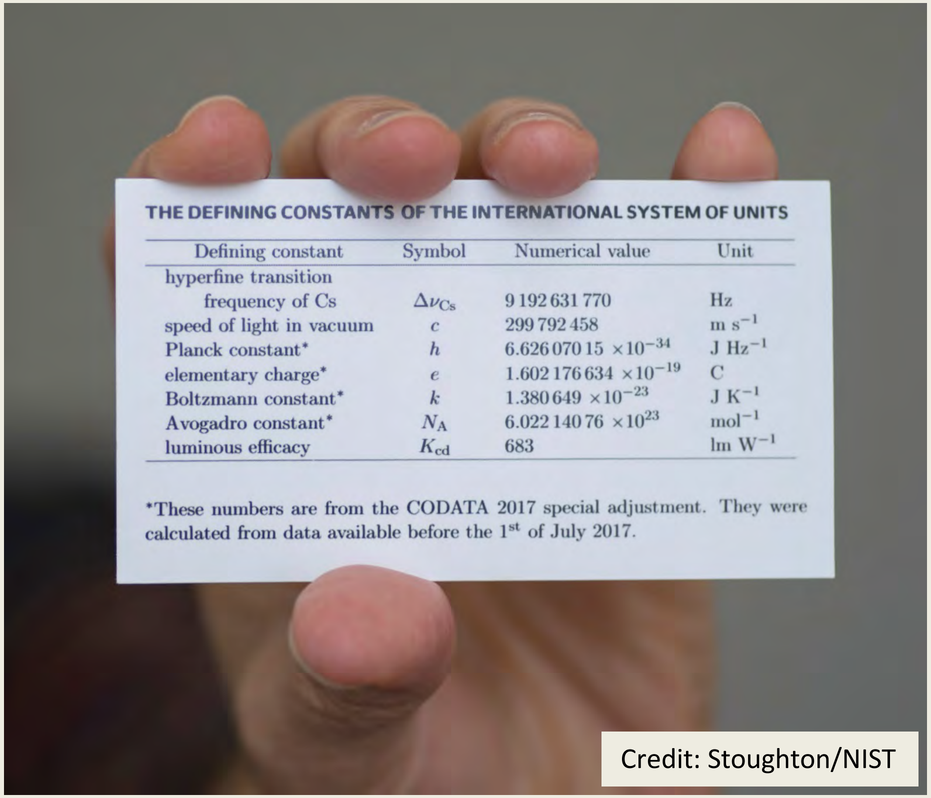


THE DEFINING CONSTANTS OF THE INTERNATIONAL SYSTEM OF UNITS

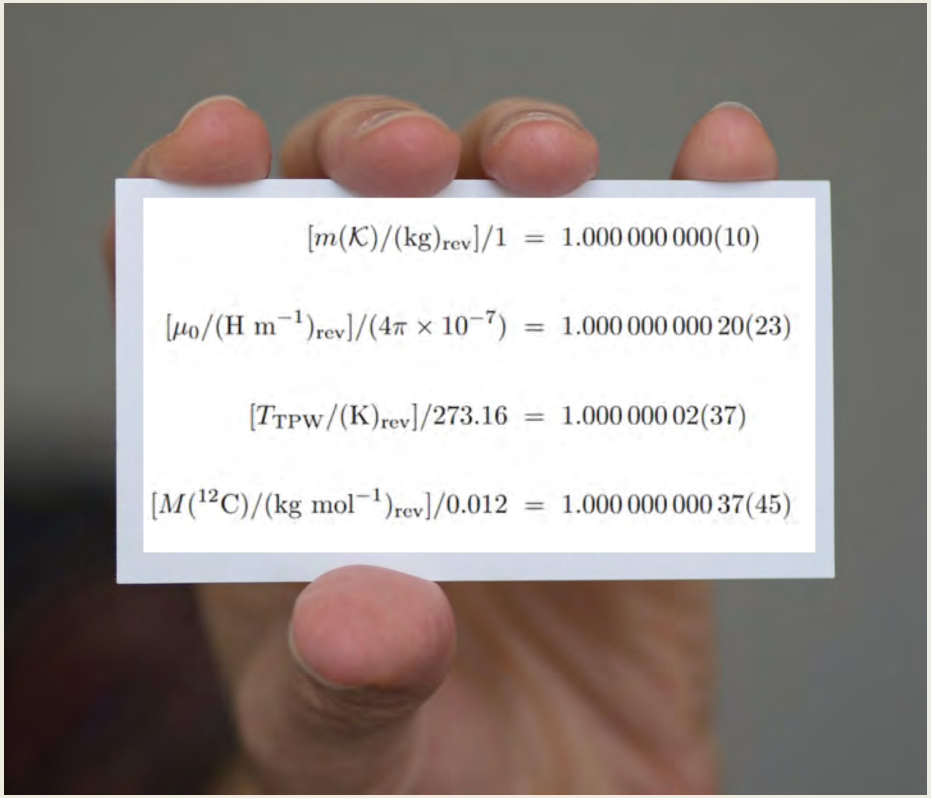
Defining constant	Symbol	Numerical value	Unit
hyperfine transition frequency of Cs	$\Delta\nu_{\mathrm{Cs}}$	9 192 631 770	Hz
speed of light in vacuum	c	299 792 458	$\mathrm{m\ s^{-1}}$
Planck constant*	h	$6.626\,070\,15 \times 10^{-34}$	$\mathrm{J\ Hz^{-1}}$
elementary charge*	e	$1.602\,176\,634 \times 10^{-19}$	C
Boltzmann constant*	k	$1.380\,649 \times 10^{-23}$	$\mathrm{J\ K^{-1}}$
Avogadro constant*	N_{A}	$6.022\,140\,76 \times 10^{23}$	$\mathrm{mol^{-1}}$
luminous efficacy	K_{cd}	683	$\mathrm{lm\ W^{-1}}$

*These numbers are from the CODATA 2017 special adjustment. They were calculated from data available before the 1st of July 2017.

Credit: Stoughton/NIST

The International System of Units

BUT
We have 4 new experimental quantities.



$$[m(\mathcal{K})/(\mathrm{kg})_{\mathrm{rev}}]/1 = 1.000\,000\,000(10)$$

$$[\mu_0/(\mathrm{H\ m^{-1}})_{\mathrm{rev}}]/(4\pi \times 10^{-7}) = 1.000\,000\,000\,20(23)$$

$$[T_{\mathrm{TPW}}/(\mathrm{K})_{\mathrm{rev}}]/273.16 = 1.000\,000\,02(37)$$

$$[M(^{12}\mathrm{C})/(\mathrm{kg\ mol^{-1}})_{\mathrm{rev}}]/0.012 = 1.000\,000\,000\,37(45)$$

Why does the “quantum” SI depend on very complicated mechanical experiments?


nature International weekly journal of science

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Archive > Volume 481 > Issue 7379 > News Feature > Article

NATURE | NEWS FEATURE

Frontier experiments: Tough science

Five experiments as hard as finding the Higgs.

Nicola Jones

04 January 2012 | Clarified: 05 January 2012

Why a mechanical experiment?

- The kilogram is macroscopic
- The present definition of the ampere is mechanical.

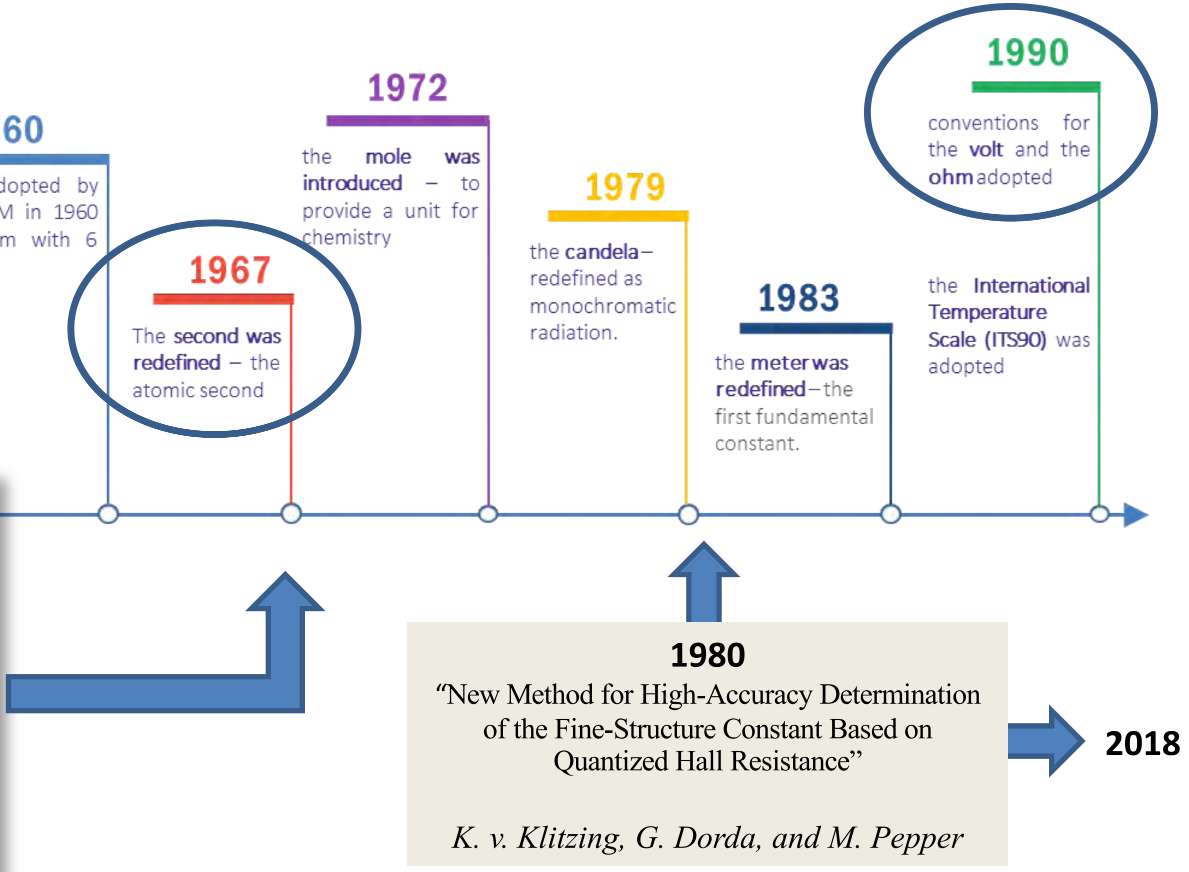
Why a two-phase experiment?

$$\boxed{m\, g\, v = \frac{h}{4} f_1 f_2}$$

- It must be independent of the present definition of the ampere
- It is also independent of the charge of the electron

Bureau International des Poids et Mesures

Towards an “**atomic**” or “**quantum**” SI



1960

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

- **kilogram**
- **second**
- **metre,**
- **ampere**
- **kelvin**
- **candela**

1967

The **second was redefined** – the atomic second

1972

the **mole was introduced** – to provide a unit for chemistry

1979

the **candela** – redefined as monochromatic radiation.

1983

the **meter was redefined** – the first fundamental constant.

1990

conventions for the **volt** and the **ohm** adopted

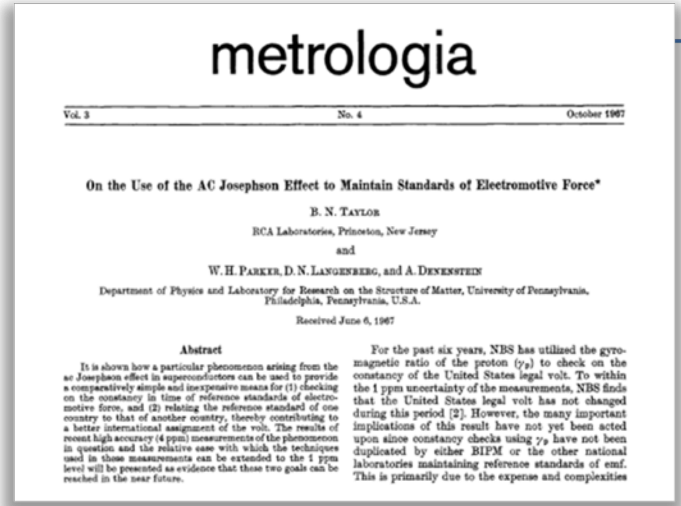
the **International Temperature Scale (ITS90)** was adopted

1980

“New Method for High-Accuracy Determination of the Fine-Structure Constant Based on Quantized Hall Resistance”

K. v. Klitzing, G. Dorda, and M. Pepper

2018



metrologia

Vol. 3 No. 4 October 1967

On the Use of the AC Josephson Effect to Maintain Standards of Electromotive Force*

B. N. Taylor

RCA Laboratories, Princeton, New Jersey

and

W. H. Parker, D. N. Langenberg, and A. Denenstein

Department of Physics and Laboratory for Research on the Structure of Matter, University of Pennsylvania, Philadelphia, Pennsylvania, U.S.A.

Received June 6, 1967

Abstract

It is shown how a particular phenomenon arising from the ac Josephson effect in superconductors can be used to provide a comparatively simple and inexpensive means for (1) checking on the constancy in time of reference standards of electromotive force, and (2) relating the reference standard of one country to that of another country, thereby contributing to a better international assignment of the volt. The results of recent high accuracy (4 ppm) measurements of the phenomenon in question and the relative ease with which the techniques used in these measurements can be extended to the 1 ppm level will be presented as evidence that these two goals can be reached in the near future.

For the past six years, NBS has utilized the gyromagnetic ratio of the proton (γ_p) to check on the constancy of the United States legal volt. To within the 1 ppm uncertainty of the measurements, NBS finds that the United States legal volt has not changed during this period [2]. However, the many important implications of this result have not yet been acted upon since constancy checks using γ_p have not been duplicated by either BIPM or the other national laboratories maintaining reference standards of emf. This is primarily due to the expense and complexities

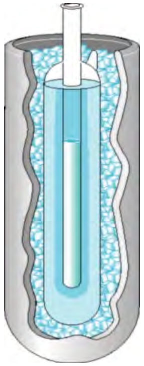
K

The kelvin – present definition

The current definition – from 1954.

The kelvin, unit of thermodynamic temperature, is the fraction 1/273.16 of the thermodynamic temperature of the triple point of water.The 1954 definition

$$T_{\mathrm{TPW}} = 273.16\ \mathrm{K}$$



Limitations of the Triple Point of Water

- Defines only one temperature,
- Based on uncontaminated water with a specified isotopic content,
- Can be influenced by: gradients, annealing etc.

In order to measure temperatures away from T_{TPW} = 273.16 K we use the

International Practical Temperature Scale (ITS-90).

But ITS-90 is decoupled from the present definition of the kelvin.

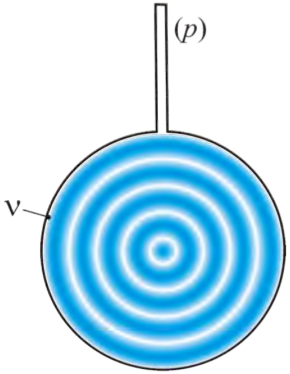
The principal of primary thermomtery

If an energy E is measured at a thermodynamic temperature T and if E is described by a function $f\,(kT)$

- At present, k is determined from $E = f\,(kT_{\mathrm{TPW}})$: T_{TPW} is exact.
- In the revised SI, T measured from $E = f\,(kT)$: k is exact.

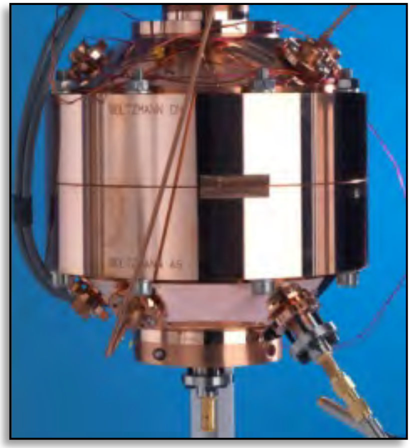
The acoustic gas thermometer

AGT



$$u_0^2 = \gamma kT / m$$
$$\gamma = c_p/c_V$$

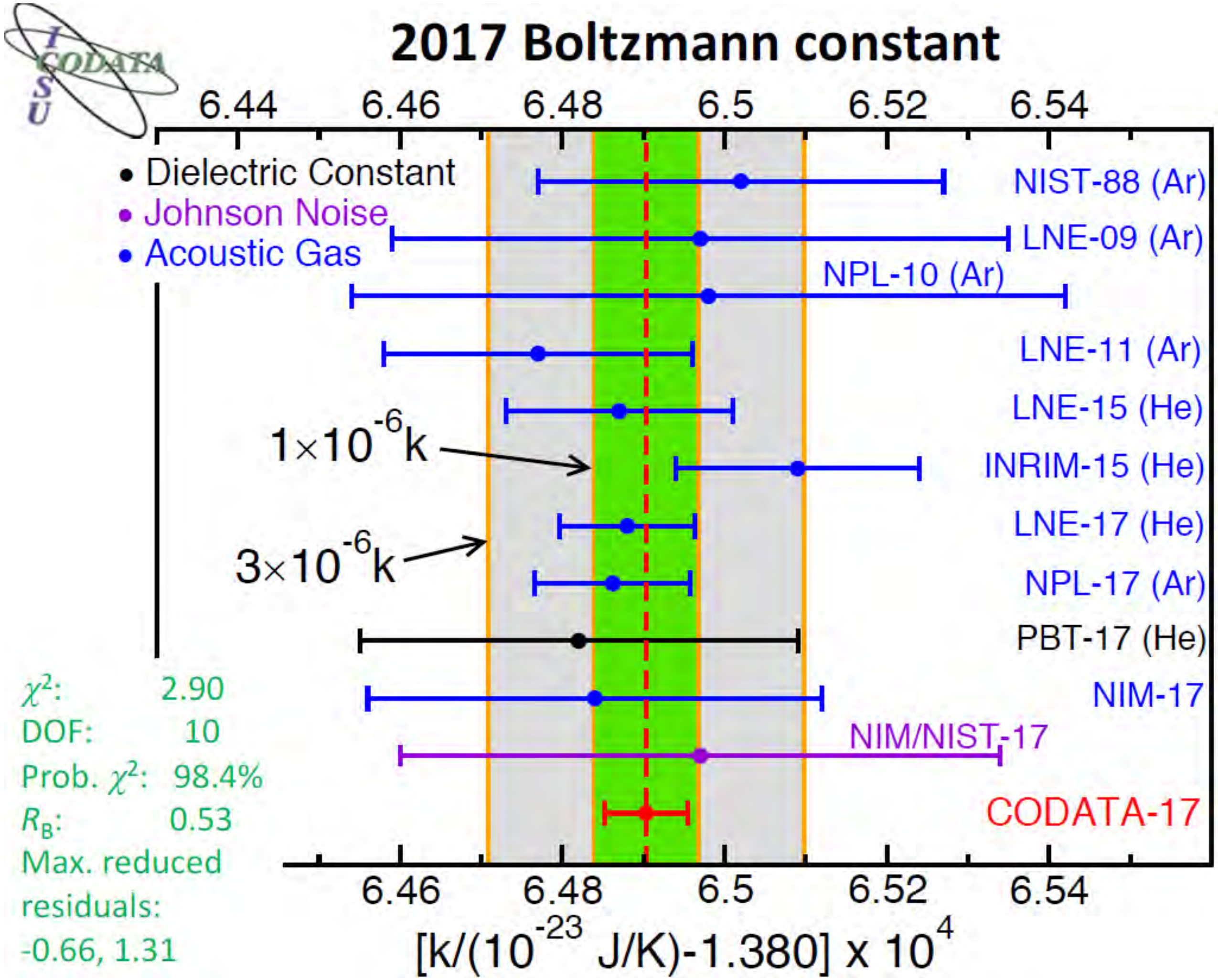
Courtesy of Joachim Fischer, PTB



The NPL Acoustic Gas Thermometer (with Argon)

		Estimate	$u_R/10^{-6}$	Weight
M	g mol^{-1}	39. 947 727(19)	0.373	28.3%
T	K	273.160 000(99)	0.364	26.8%
c_0^2	$\text{m}^2\,\text{s}^{-2}$	94756.245(45)	0.470	44.9%
R	J K^{-1} mol^{-1}	8.314 460 3 (58)	0.702	

M. de Podesta, D.F. Mark, R.C. Dymock, R. Underwood, T. Bacquart, G. Sutton, S. Davidson, G. Machin
Metrologia **54** 683-692 (2017)
$u(k)/k$ = 0.70 ppm



The data is consistent

Two independent methods with

$u_r < 3\cdot10^{-6}$

$$u_{rel}(k) = 3.7\cdot10^{-7}$$

Data from CODATA 2017

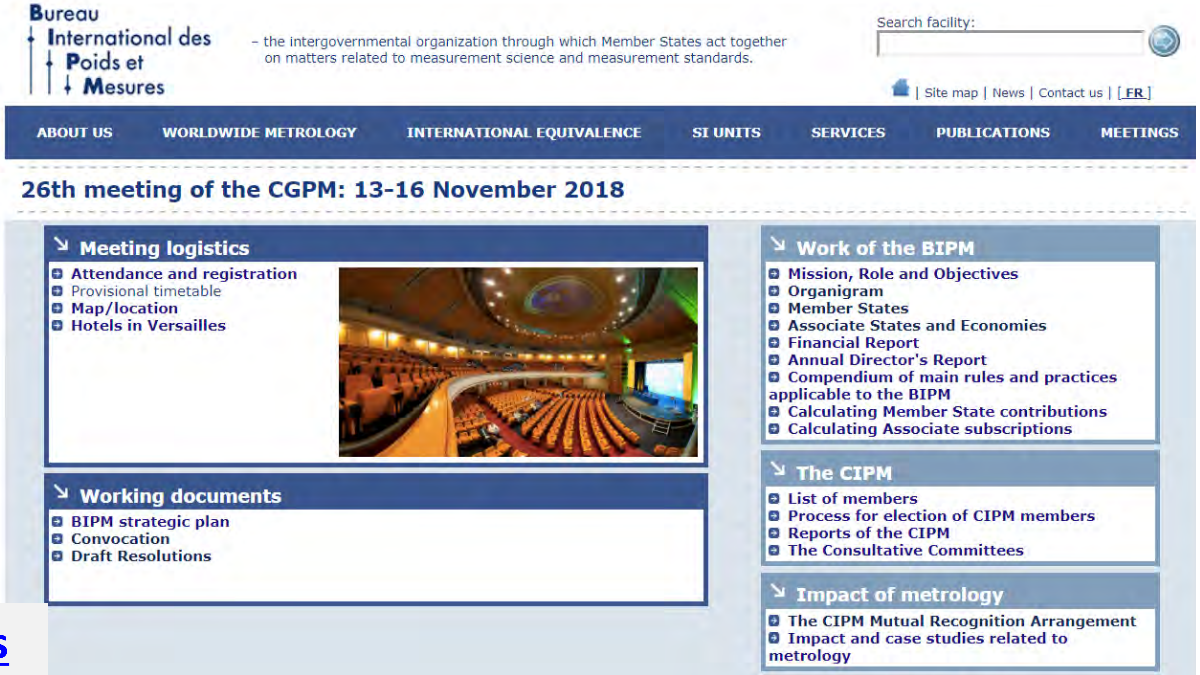
Writing the new definitions eg **the kelvin**

“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 $\Delta\nu_{\mathrm{Cs}}$”.

How does this work in practice?

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

26^{e} CGPM
Versailles
13-16 novembre 2018



Bureau International des Poids et Mesures – the intergovernmental organization through which Member States act together on matters related to measurement science and measurement standards.

26th meeting of the CGPM: 13-16 November 2018

Meeting logistics
- Attendance and registration
- Provisional timetable
- Map/location
- Hotels in Versailles

Working documents
- BIPM strategic plan
- Convocation
- Draft Resolutions

Work of the BIPM
- Mission, Role and Objectives
- Organigram
- Member States
- Associate States and Economies
- Financial Report
- Annual Director's Report
- Compendium of main rules and practices applicable to the BIPM
- Calculating Member State contributions
- Calculating Associate subscriptions

The CIPM
- List of members
- Process for election of CIPM members
- Reports of the CIPM
- The Consultative Committees

Impact of metrology
- The CIPM Mutual Recognition Arrangement
- Impact and case studies related to metrology

List of Draft Resolutions

A On the revision of the International System of Units (SI)

B On the definition of time scales

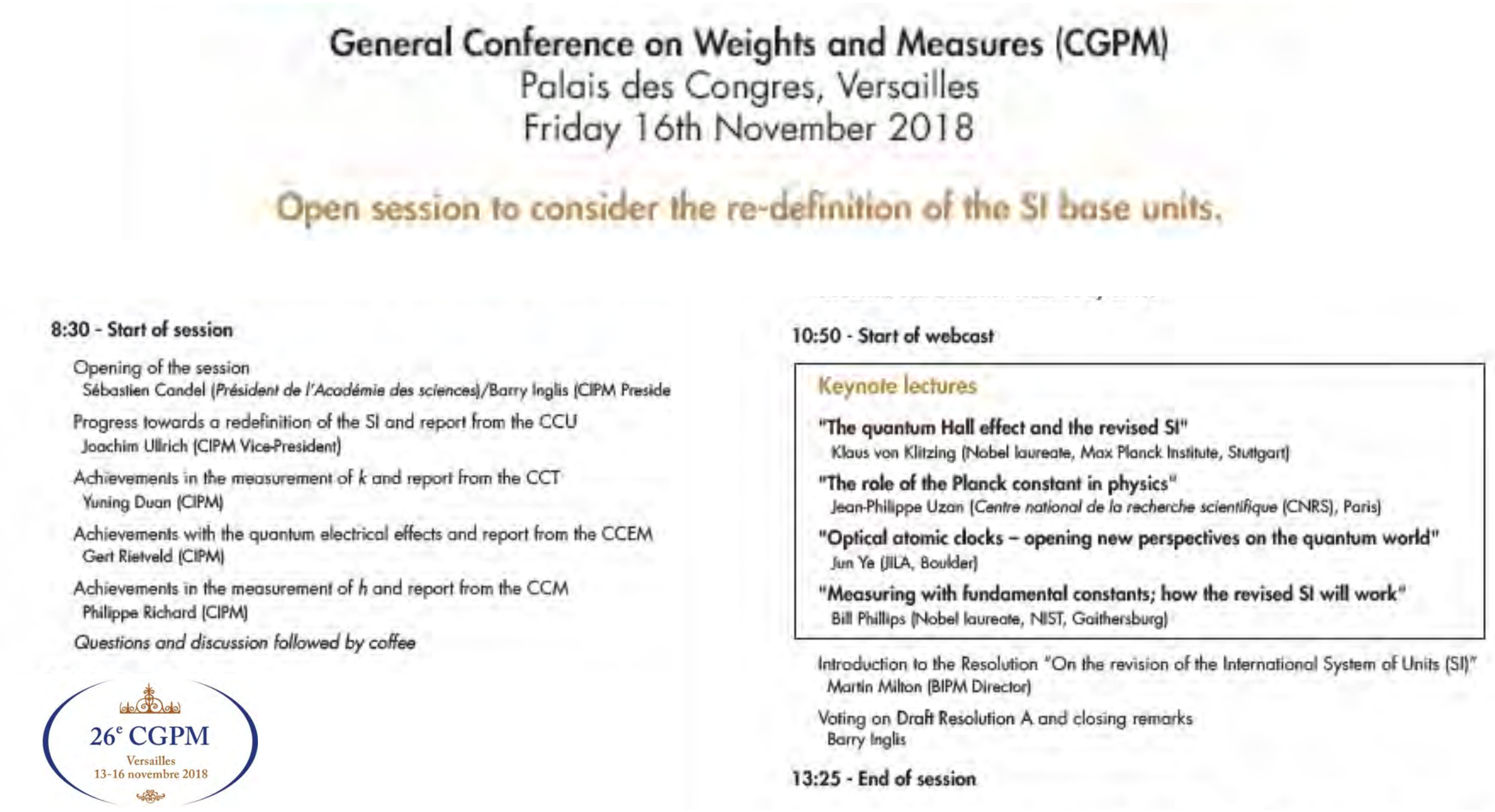
C On the objectives of the BIPM

D On the dotation of the BIPM for the years 2020 to 2023

E On financial arrears of Member States and the process of exclusion

General Conference on Weights and Measures (CGPM)
Palais des Congres, Versailles
Friday 16th November 2018

Open session to consider the re-definition of the SI base units.



General Conference on Weights and Measures (CGPM)
Palais des Congres, Versailles
Friday 16th November 2018

Open session to consider the re-definition of the SI base units.

8:30 - Start of session

Opening of the session
Sébastien Candel (*Président de l'Académie des sciences*)/Barry Inglis (CIPM Preside

Progress towards a redefinition of the SI and report from the CCU
Joachim Ullrich (CIPM Vice-President)

Achievements in the measurement of *k* and report from the CCT
Yuning Duan (CIPM)

Achievements with the quantum electrical effects and report from the CCEM
Gert Rietveld (CIPM)

Achievements in the measurement of *h* and report from the CCM
Philippe Richard (CIPM)

Questions and discussion followed by coffee

26e CGPM
Versailles
13-16 novembre 2018

10:50 - Start of webcast

Keynote lectures

"The quantum Hall effect and the revised SI"
Klaus von Klitzing (Nobel laureate, Max Planck Institute, Stuttgart)

"The role of the Planck constant in physics"
Jean-Philippe Uzan (*Centre national de la recherche scientifique* (CNRS), Paris)

"Optical atomic clocks – opening new perspectives on the quantum world"
Jun Ye (JILA, Boulder)

"Measuring with fundamental constants; how the revised SI will work"
Bill Phillips (Nobel laureate, NIST, Gaithersburg)

Introduction to the Resolution "On the revision of the International System of Units (SI)"
Martin Milton (BIPM Director)

Voting on Draft Resolution A and closing remarks
Barry Inglis

13:25 - End of session

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

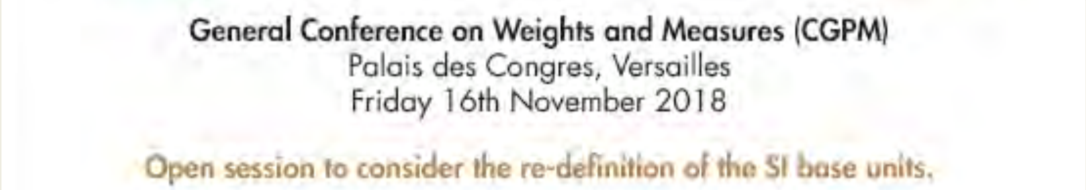
- The realisation of units will be possible using new methods.

The challenge in the future will be to maintain comparability of "primary realisations"

- This is the same challenge that we have had with (all) other measurement units.

Capacity
Building &
Knowledge

Thank you … and tune in on 16th November

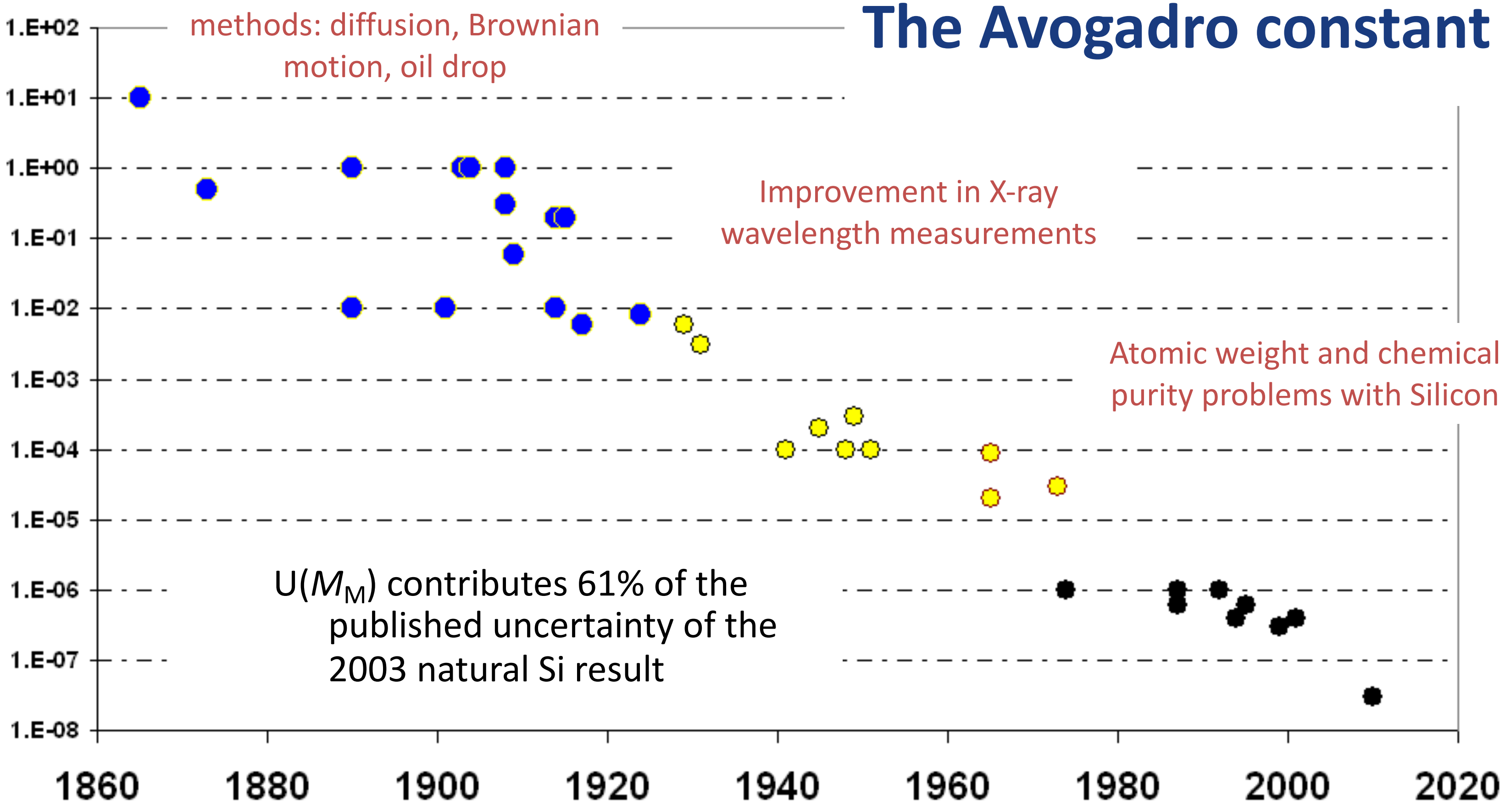


General Conference on Weights and Measures (CGPM)
Palais des Congres, Versailles
Friday 16th November 2018

Open session to consider the re-definition of the SI base units.

Bureau
International des
Poids et
Mesures

The Avogadro constant



Invention of new physical methods: diffusion, Brownian motion, oil drop

Improvement in X-ray wavelength measurements

Atomic weight and chemical purity problems with Silicon

U(M_M) contributes 61% of the published uncertainty of the 2003 natural Si result