“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

Bureau International des Poids et Mesures

Outline

01 – The metric system and the Metre Convention

02 – The re-definition of the SI in 2018

03 – Implementing the new definitions

04 – Towards a new definition of the second

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

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But, in 1812 – Napoleon abandoned the Metric System !

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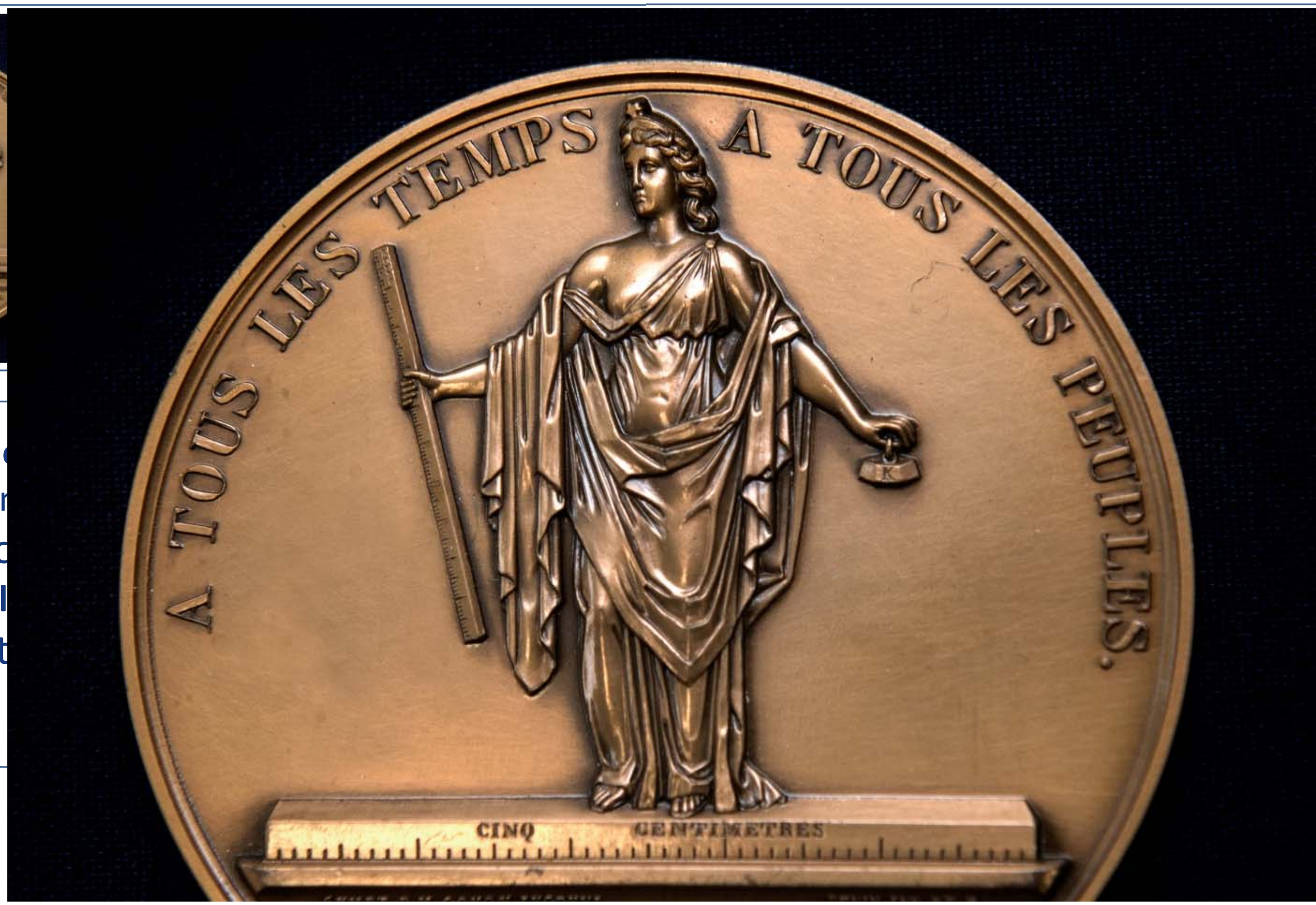
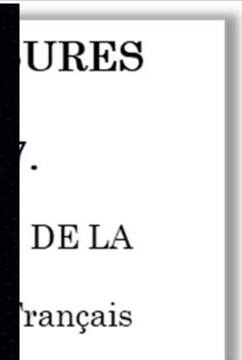
…. in 1837 it was re-introduced

Why was the Metric system of so much interest?





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- **The kil**
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Why was the Metric system of so much interest?

USAGE EXCLUSIF DES MESURES DECIMALES
LOI DU 4 JUILLET 1837.
CONVENTION NATIONALE
– DECRET DU 14 THERMIDOR AN 1 DE LA REPUBLLIQUE
Fse – LOUIS PHILIPPE 1. ROI DES Français

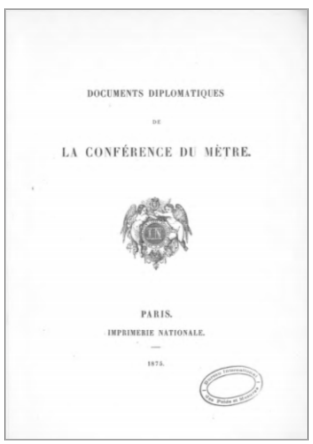
But confusion developed about the definitions of the metre and the kilogram.
Were they:

- 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, 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

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

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 representatives of Member States.

CIPM – Comité International des Poids et Mesures

Eighteen individuals of different nationalities elected by the CGPM.

Scientific and technical secretariat (in Sèvres)

- *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 First President of the CIPM (1875 – 1891)

Carlos Ibáñez e Ibáñez de Ibero,
1st Marquis of Mulhacén,
(April 14, 1825 - January 28 or 29, 1891)

Also the First President of the
International Geodetic Association

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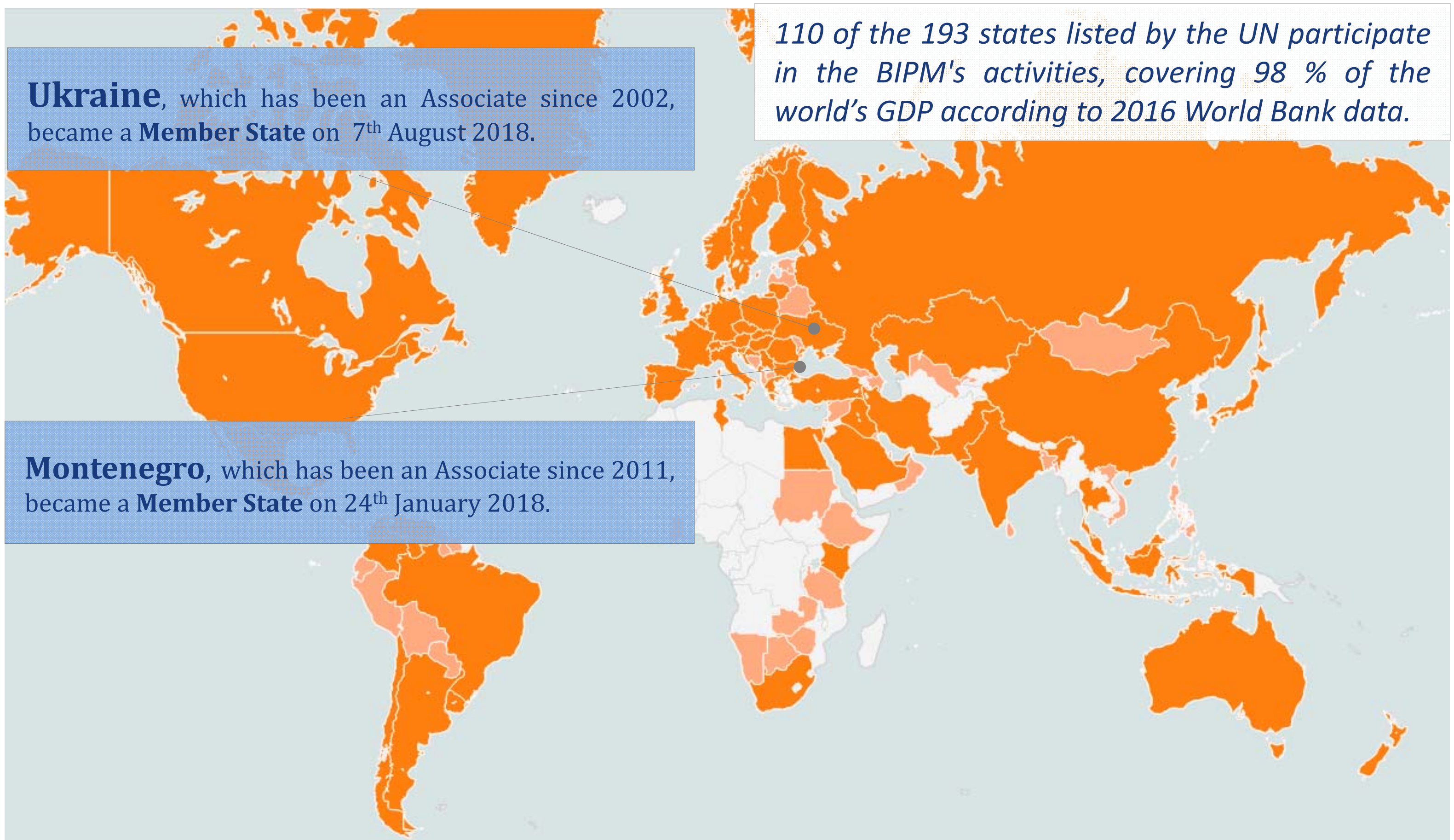
Member States and Associates

As of 14 November 2018, there are:

- 59 Member States
- 42 Associates of the CGPM (States and Economies)



Ukraine, which has been an Associate since 2002, became a **Member State** on 7th August 2018.

Montenegro, which has been an Associate since 2011, became a **Member State** on 24th January 2018.

110 of the 193 states listed by the UN participate in the BIPM's activities, covering 98 % of the world's GDP according to 2016 World Bank data.

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Outline

The **International System** of Units (SI)

Prefixes

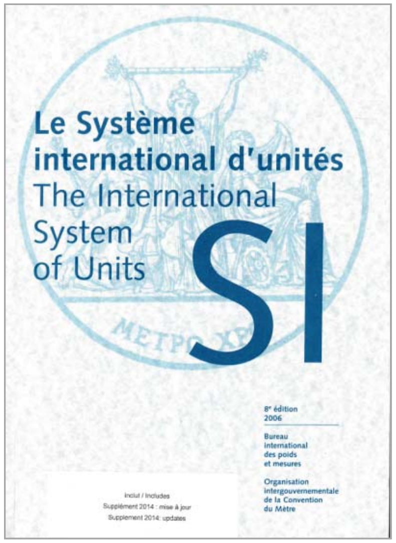
Table 5. SI prefixes

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.

A brief history of the 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

2018

The 26th CGPM agreed to change the definitions of :

- kilogram
- ampere
- kelvin
- mole

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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	$m^2\ kg\ s^{-3}$
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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}
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catalytic activity	katal	kat		$s^{-1}\ mol$

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Seven base units (As defined before November 2018)

3 definitions based on fundamental (or conventional) constants:

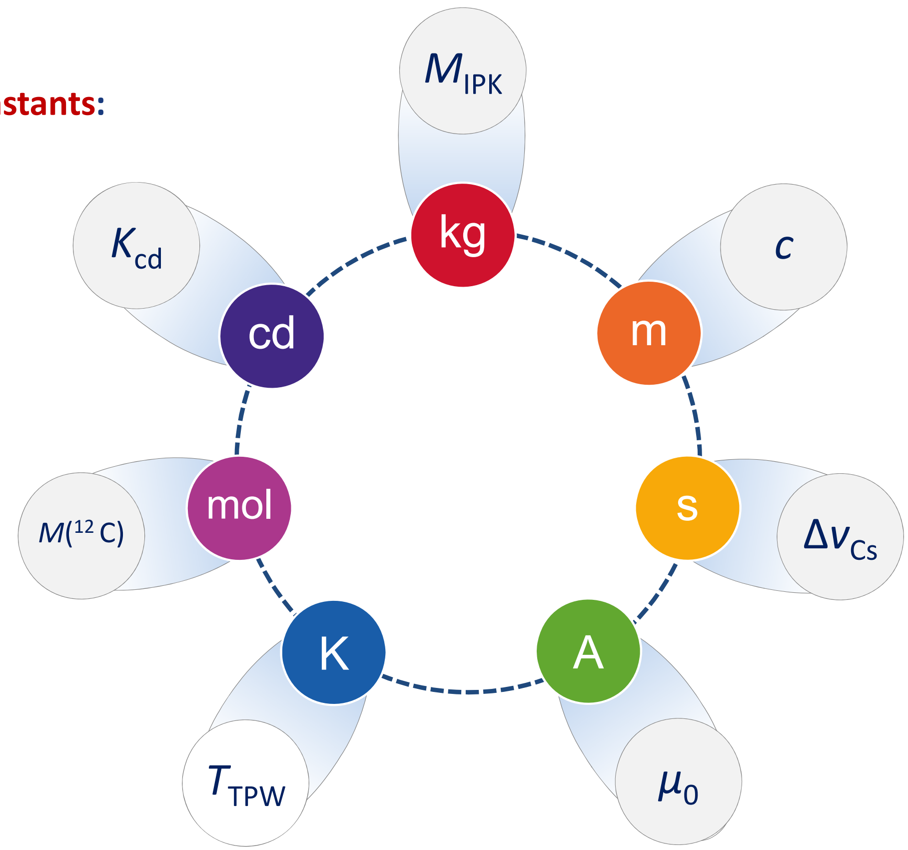
- metre (c)
- ampere (μ_0)
- candela (K_{cd})

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})



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Seven base units – *some limitations*

3 definitions based on fundamental (or conventional) constants:

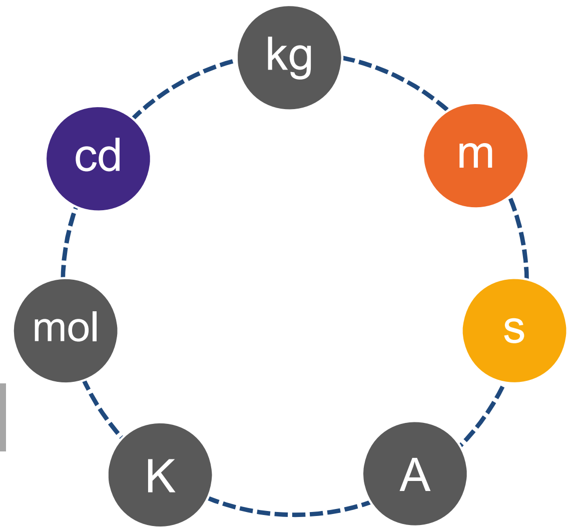
- metre (*c*)
- ampere (*μ* - *Superseded by the 1990 convention*
- candela (K_{cd})

3 definitions based on atomic or material properties:

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

1 definition based on an artefact:

- kilogram (*M* - *artefact – may not be stable ?*



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The 26th General Conference on Weights and Measures

The 59 States Party to the Metre Convention agreed:

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

Seven base units

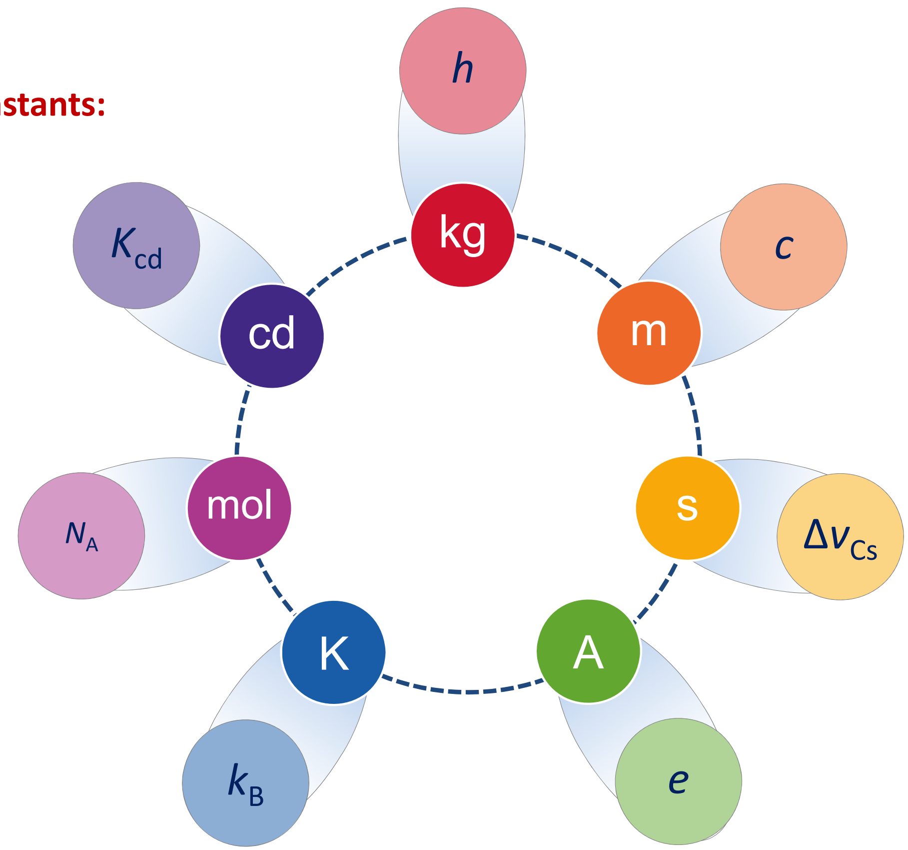
Since November 2018,
we have 4 new definitions

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 an atomic property:

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



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Seven base units

…same base units but different links

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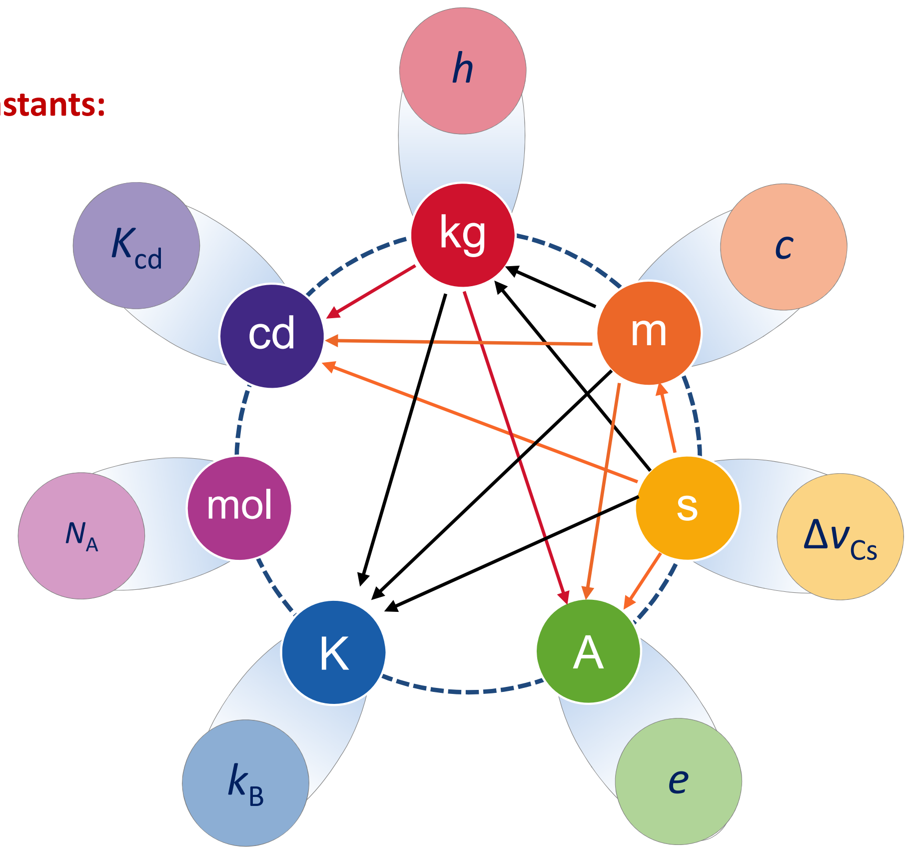

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Outline

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A

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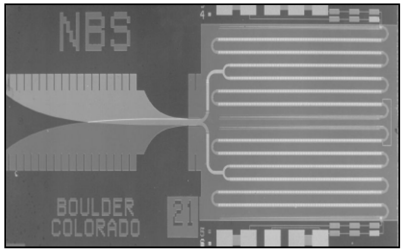
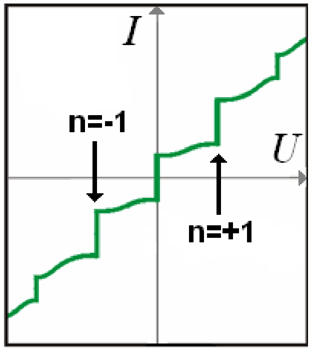
Since 1990, macroscopic quantum effects have been the basis for the reproduction of the electrical units

Josephson effect

Nobel Prize 1973



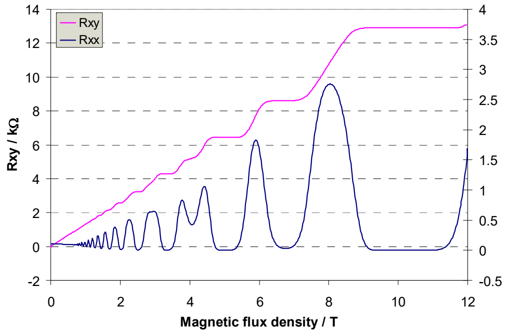


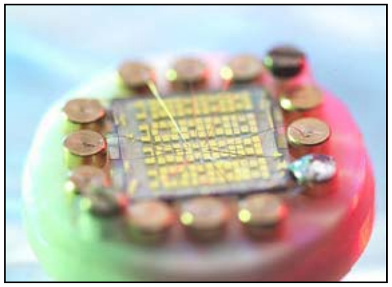
$$U_{J} = n\frac{f}{K_{J}}, \qquad K_{J} = \frac{2e}{h}$$

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

Quantum-Hall effect

Nobel Prize 1985





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

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

- But: this convention was not within the SI
  (because it is not consisitent with $\mu_0 \equiv 4\pi \cdot 10^{-7}$ N A^{-2})

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

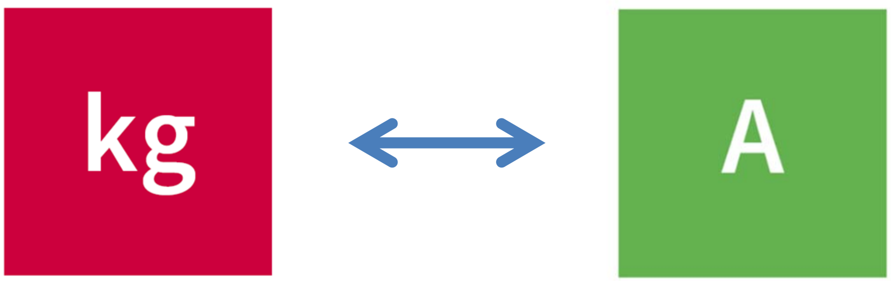
Note –there will be very small changes to the volt and the ohm

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

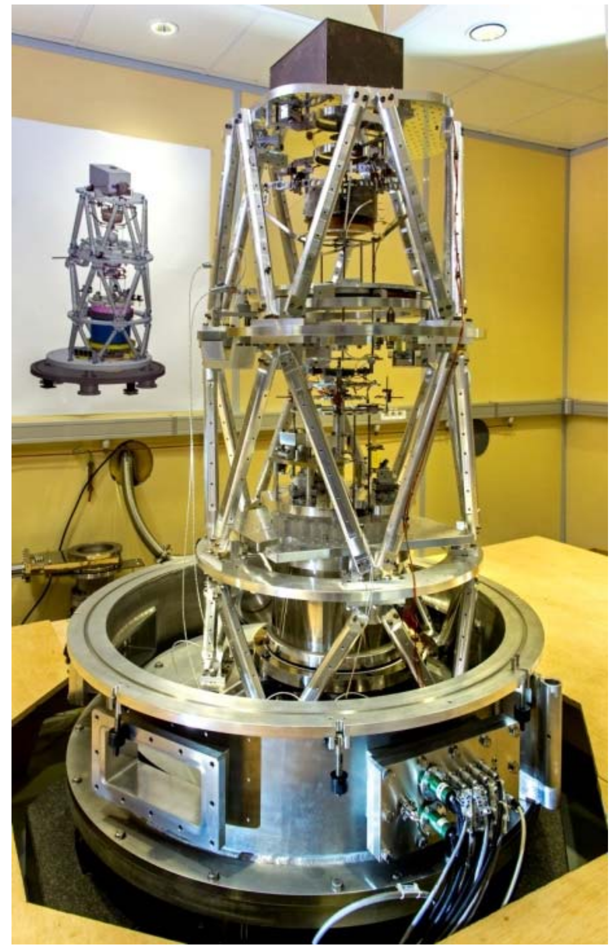
h/e^2 will be larger than $R_{K\text{-}90}$ by the fractional amount 18 $\times 10^{-9}$

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 named the Kibble Balance after its inventor.



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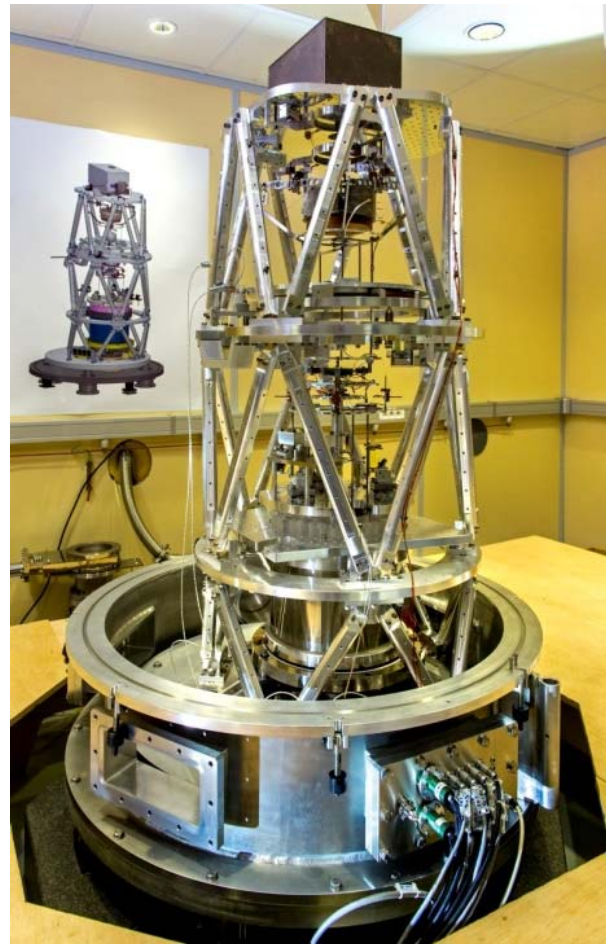
The Kibble balance

In the static phase	$m\,g = I\,B\,L$
In the dynamic phase	$U = v\,B\,L$
If the coil and the field are constant:	$U\,I = m\,g\,v$

Assuming the exactness of the formulae for K_J and R_K

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

h



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 $\Delta\nu_{Cs}$".

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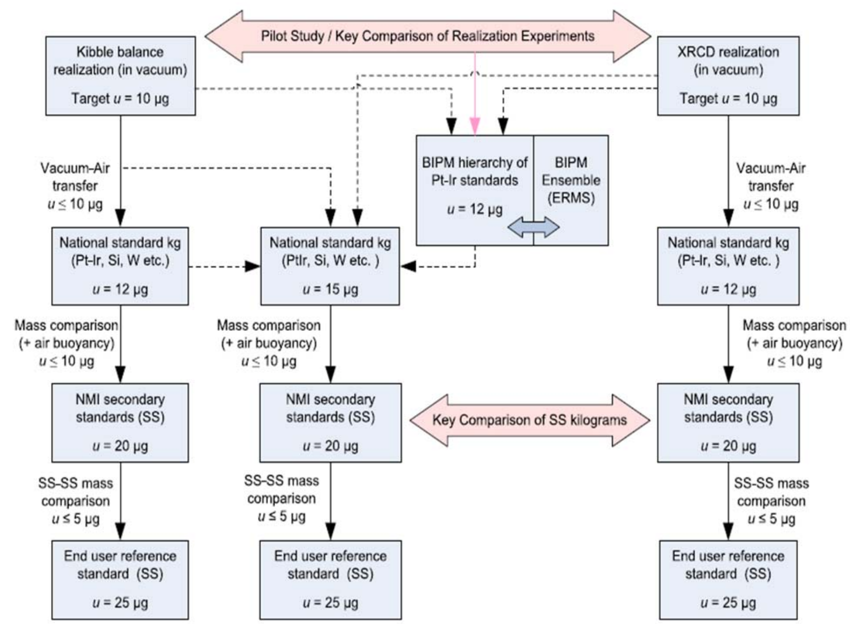
Writing the new definitions eg **the kilogram**

"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.**



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Advantages of the change – the size of the kg (!)

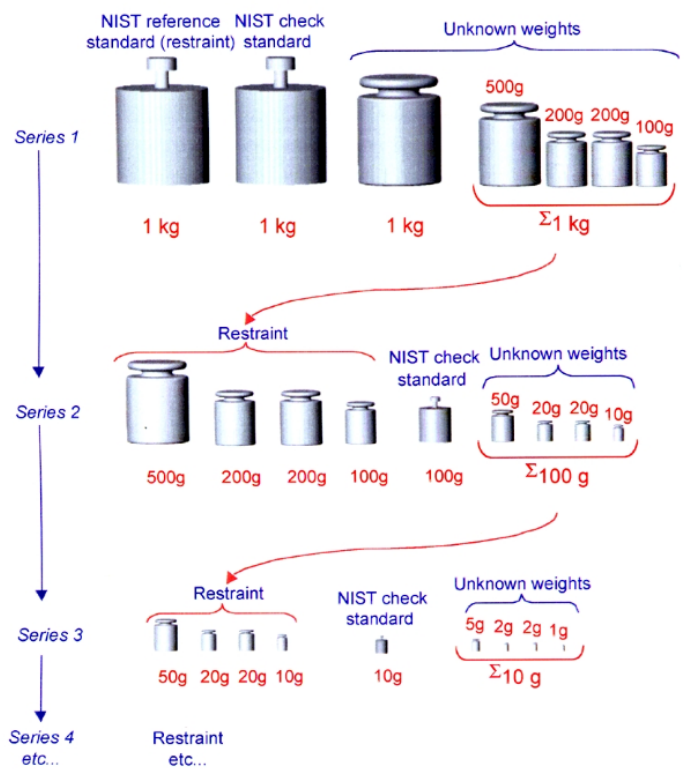

Fig. 3. A schematic description of the weighing designs used in the dissemination to submultiples of the kilogram.

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

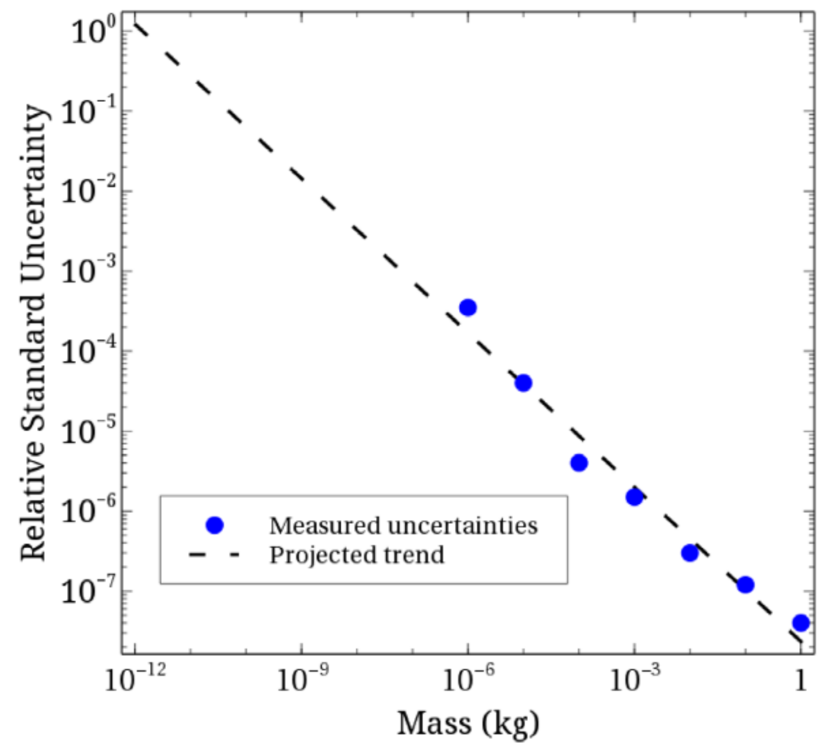

Figure 1. Relative uncertainty in mass as a function of mass value. Dashed line is a linear fit to the data shown.

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

K

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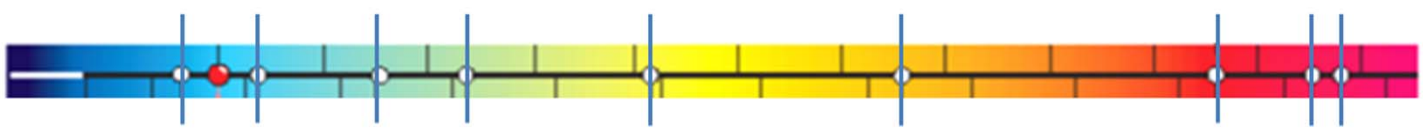
Writing the new definitions eg **the kelvin**

"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.**



The International System of Units

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

Bureau International des Poids et Mesures

The SI, is the system of units in which:

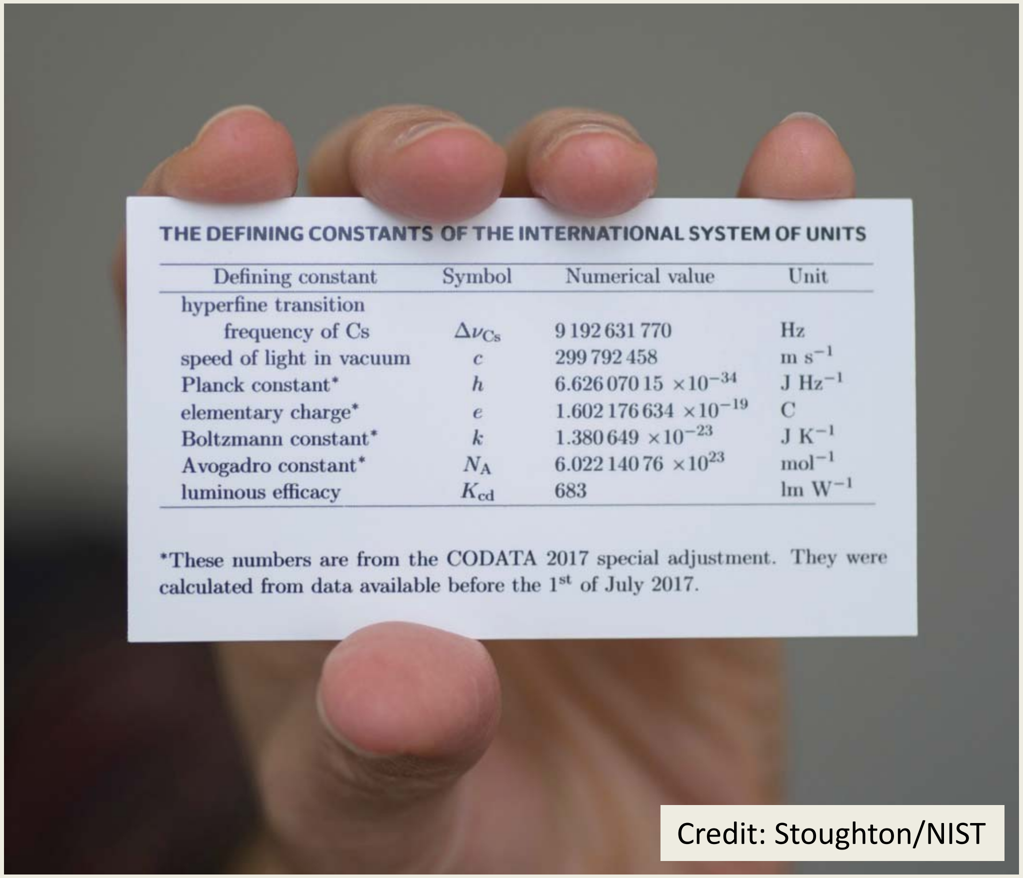
- the unperturbed ground state hyperfine transition frequency of the caesium 133 atom $\Delta\nu_{Cs}$ is 9 192 631 770 Hz,
- the speed of light in vacuum c is 299 792 458 m/s,
- the Planck constant h is $6.626\,070\,15 \times 10^{-34}$ J s,
- the elementary charge e is $1.602\,176\,634 \times 10^{-19}$ 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} 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.

The International System of Units

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



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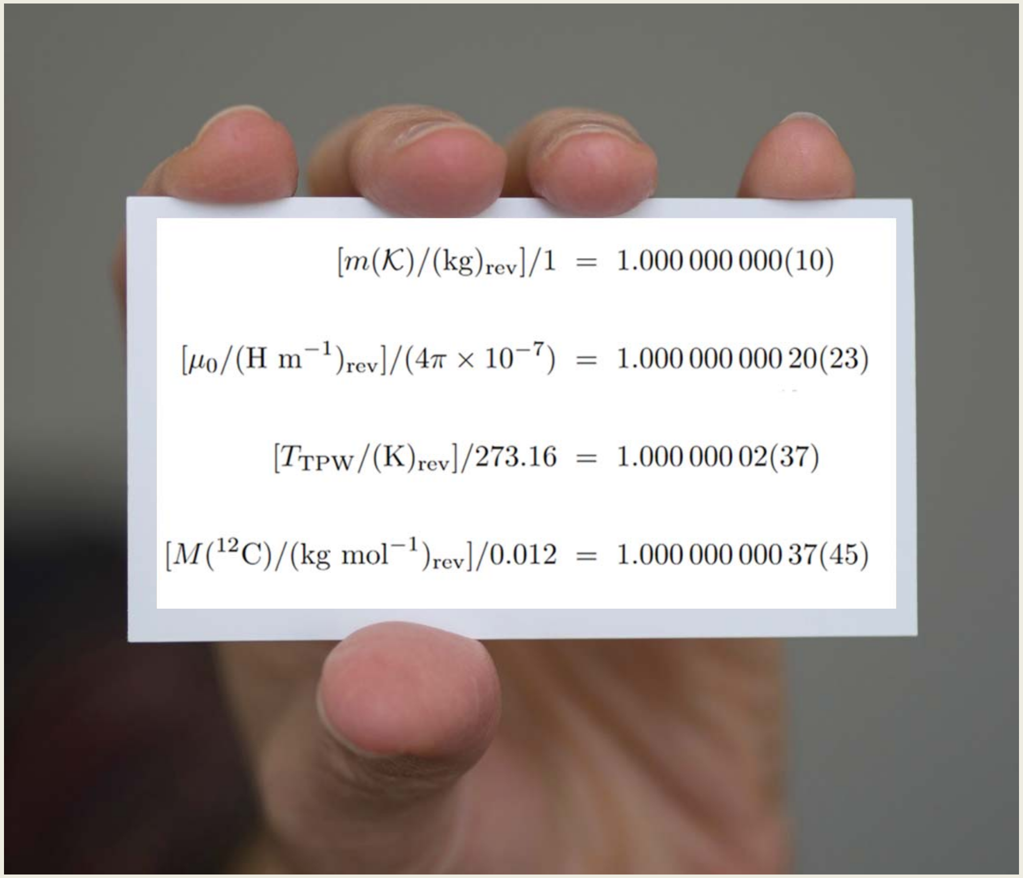
The International System of Units

<u>But, ..</u>
We have four quantities that must now be determined by experiment.



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

Why a mechanical experiment?

- The kilogram is macroscopic
- The previous definition of the ampere was mechanical.

Why such a complex expt ?

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

- It needs two phases to be independent of the former definition of the ampere
  - It is also independent of the charge of the electron

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

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

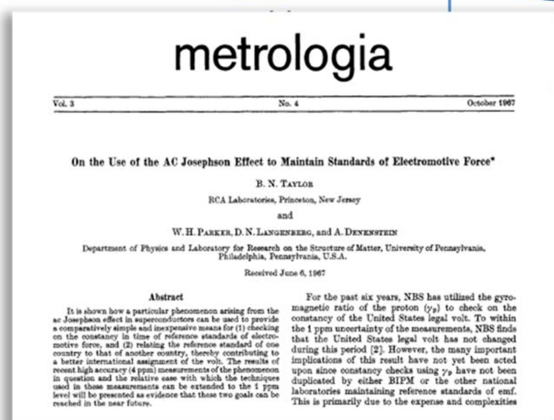
conventions for the **volt** and the **ohm** adopted

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

2018

The 26th CGPM agreed to change the definitions of :

- kilogram
- ampere
- kelvin
- mole



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

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

S

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26th General Conference on Weight and Measures

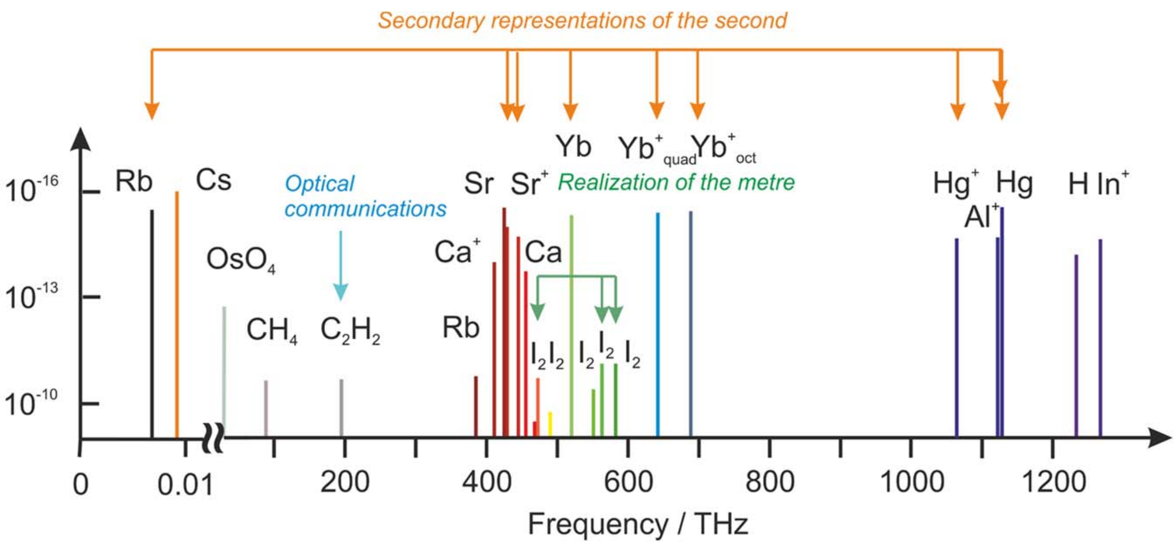
The UTC and the TAI , **have never been defined formally** by the General Conference (despite several resolutions and recommendations),

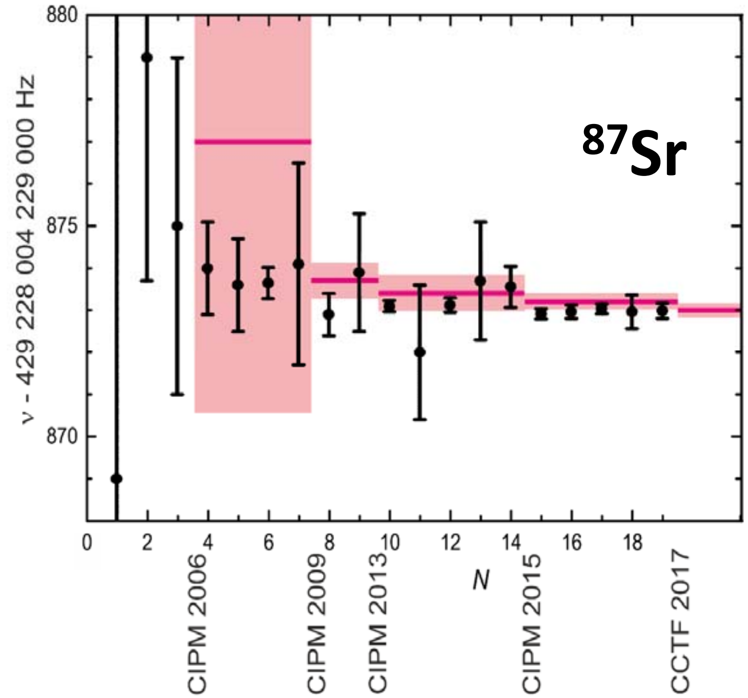
Resolution 2 of the 26th meeting of the CGPM (2018) confirmed:

- International Atomic Time (TAI) is a continuous time scale produced by the BIPM based on the best realizations of the SI second. TAI is a realization of Terrestrial Time (TT), a time coordinate in the Geocentric Reference System,
- Coordinated Universal Time (UTC) is a time scale produced by the BIPM with the same rate as TAI, but differing from TAI only by an integral number of seconds,

The Consultative Committee for Time and Frequency (CCTF)

The CCTF maintains the list of recommended values for frequency and wavelength standards

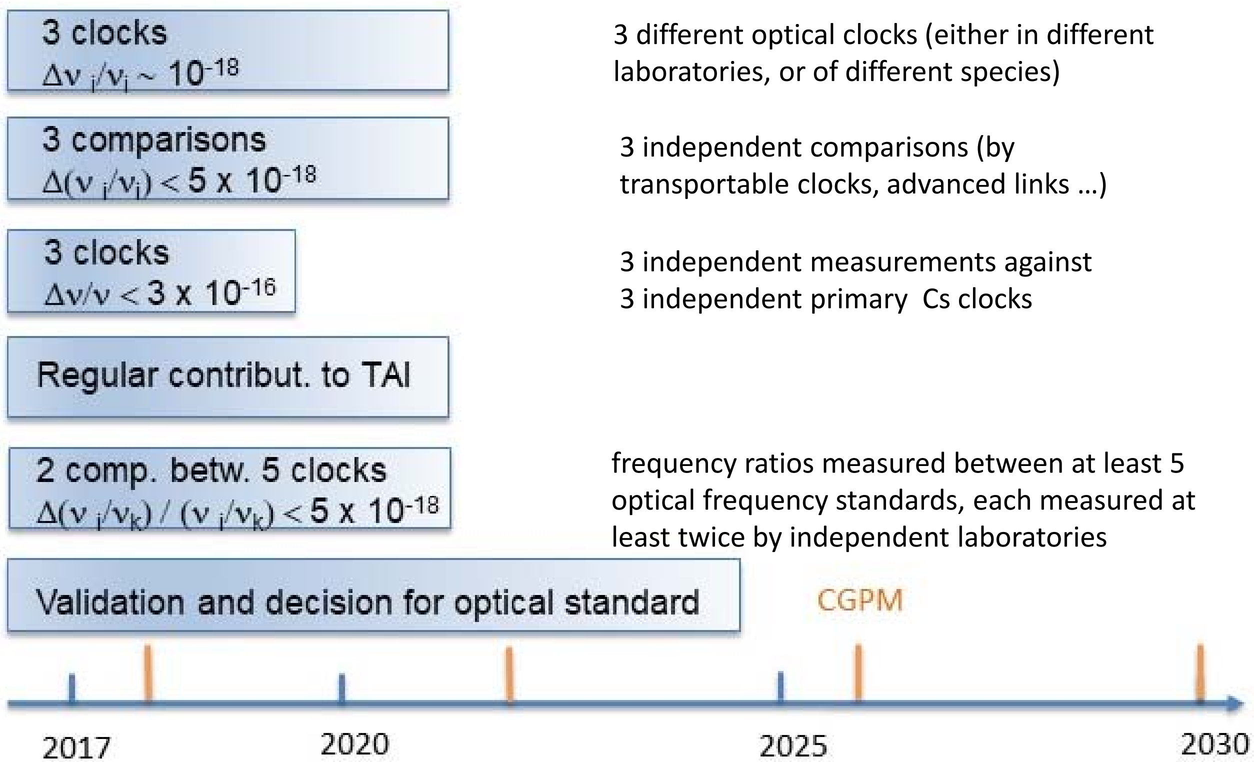




Fritz Riehle et al 2018 Metrologia 55 188

https://www.bipm.org/en/publications/mises-en-pratique/standard-frequencies.html

CCTF roadmap … towards a new redefinition for the second



3 different optical clocks (either in different laboratories, or of different species)

3 independent comparisons (by transportable clocks, advanced links …)

3 independent measurements against 3 independent primary Cs clocks

frequency ratios measured between at least 5 optical frequency standards, each measured at least twice by independent laboratories

New CCTF President

Noël Dimarcq directeur-adjoint de l'Observatoire de la Côte d'Azur,

succède à **Luc Érard**.

Summary

- The new definitions use "**the rules of nature to create the rules of measurement**".
- The new definitions will provide **long-term stability**
- The challenge in the future will be **to maintain comparability** of "primary realisations"
- **There is still more to do !**
  - A roadmap is in place to plan work towards an "optical second"

Thank you … and visit the talks from the CGPM on You Tube

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