“The re-definition of the base units of the SI: how we achieved it”

Dr Martin J.T Milton

Director, BIPM

28th November 2018

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

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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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But, in 1812 – Napoleon abandoned the Metric System !

Why was the Metric system of so much interest?

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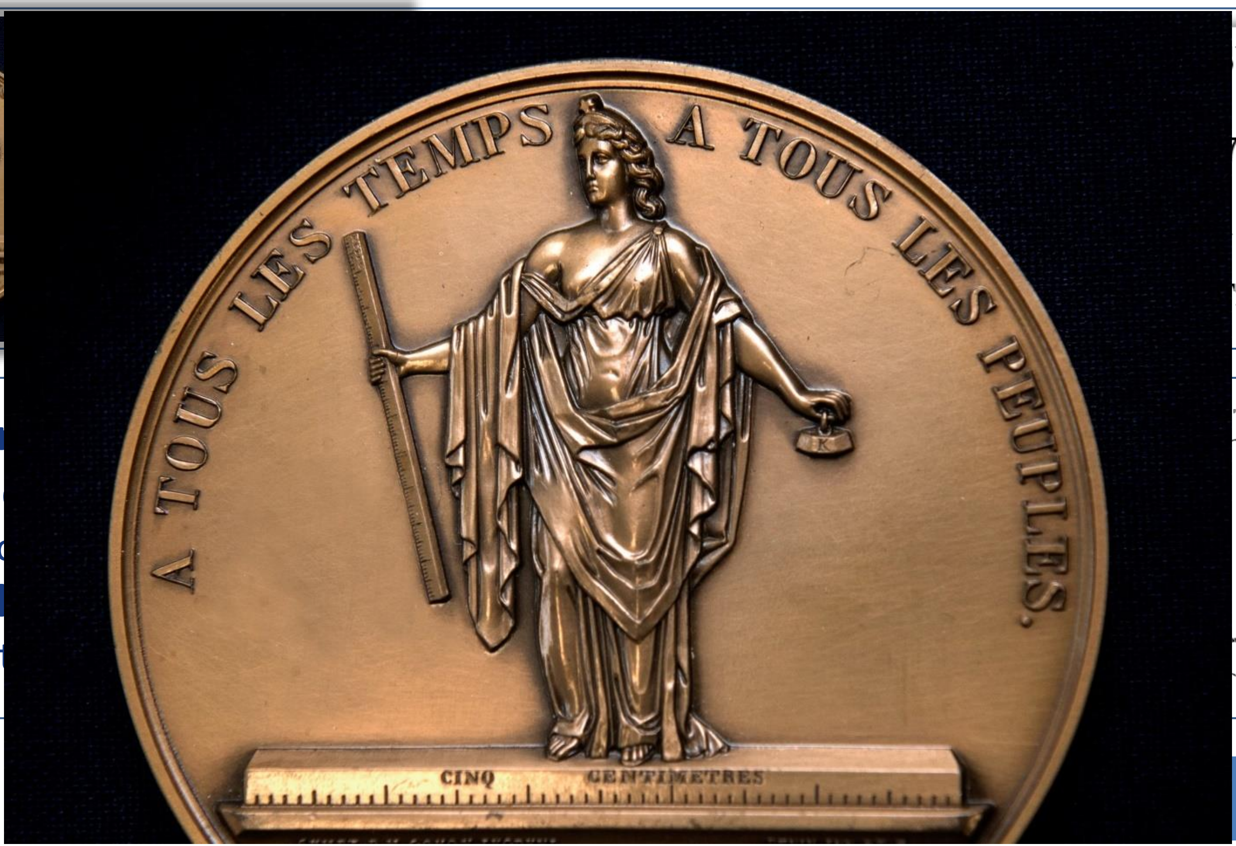
.... in 1837 it was re-intrduced

Why was the Metric system of so much interest?



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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

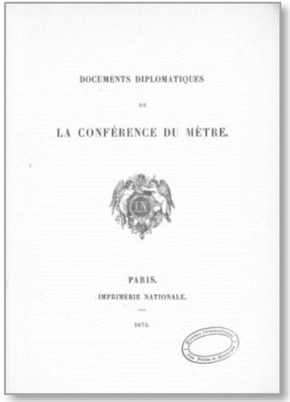
But confusion developed about the definitions of the metre and the kilogram.
Were they:

- 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

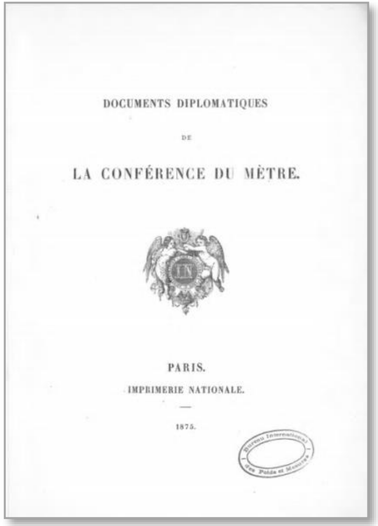
The Metre Convention was signed in Paris

by 17 nations

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

the 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].

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 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.*

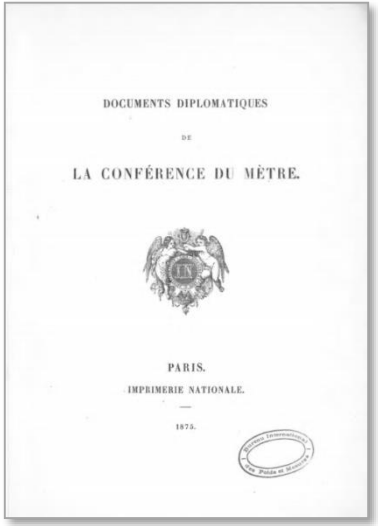
Article 3 states that

*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)***

Bureau International des Poids et Mesures

the Metre Convention

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

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

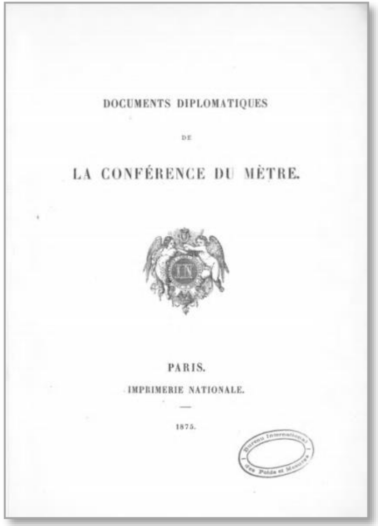
The personnel of the Bureau shall be a Director, two assistants and the number of employees necessary.

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

Bureau International des Poids et Mesures

the Metre Convention

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

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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.

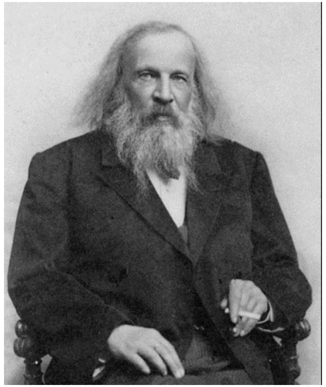
BIPM Staff

- *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)

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

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

Marie and Pierre Curie
collaborated with the BIPM

Bureau
International des
Poids et
Mesures

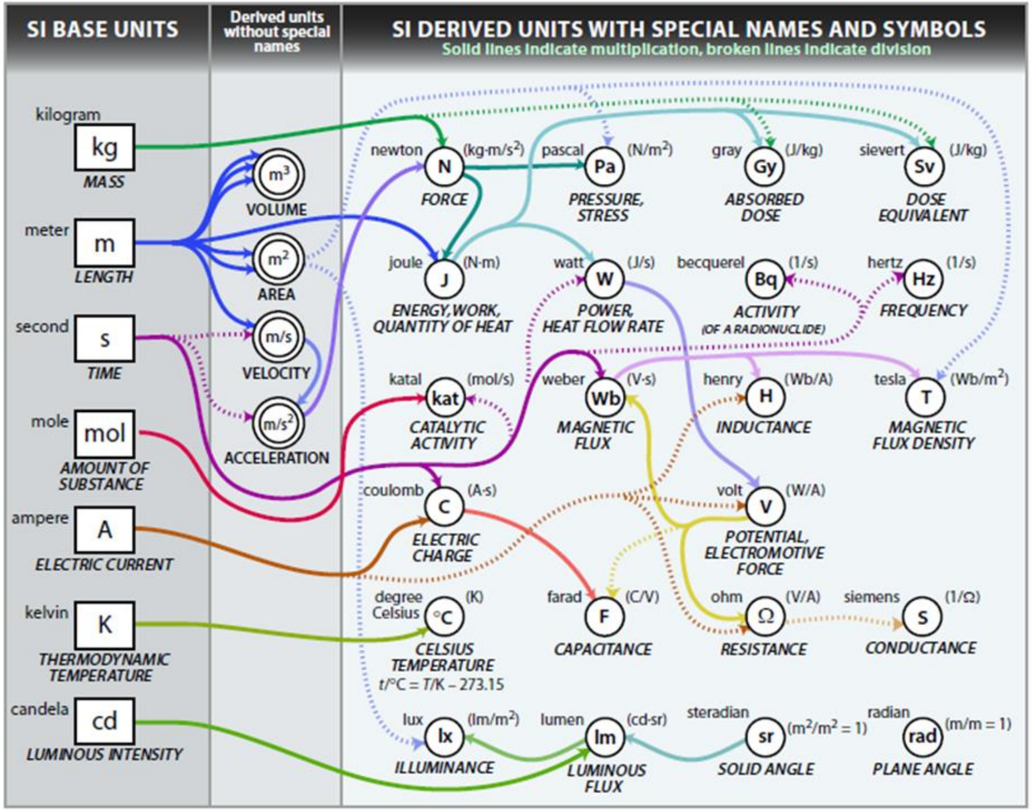
Outline

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

3 definitions based on fundamental (or conventional) constants:

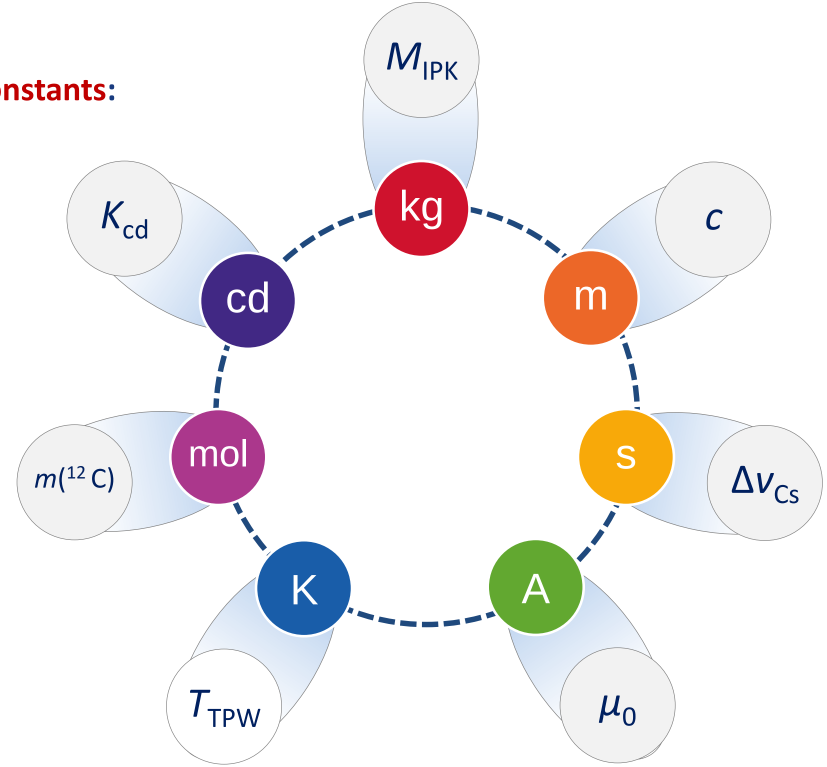
- metre (c)
- ampere (μ_0)
- candela (K_{cd})

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

The 26th CGPM agreed to change the definitions of four of them

3 definitions based on fundamental (or conventional) constants:

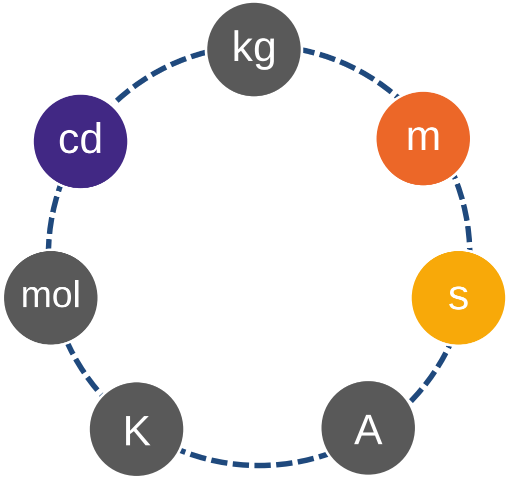
- metre (c)
- ampere *- Superseded by the 1990 convention*
- candela (K_{cd})

3 definitions based on atomic or material properties:

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

1 definition based on an artefact:

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



Seven base units

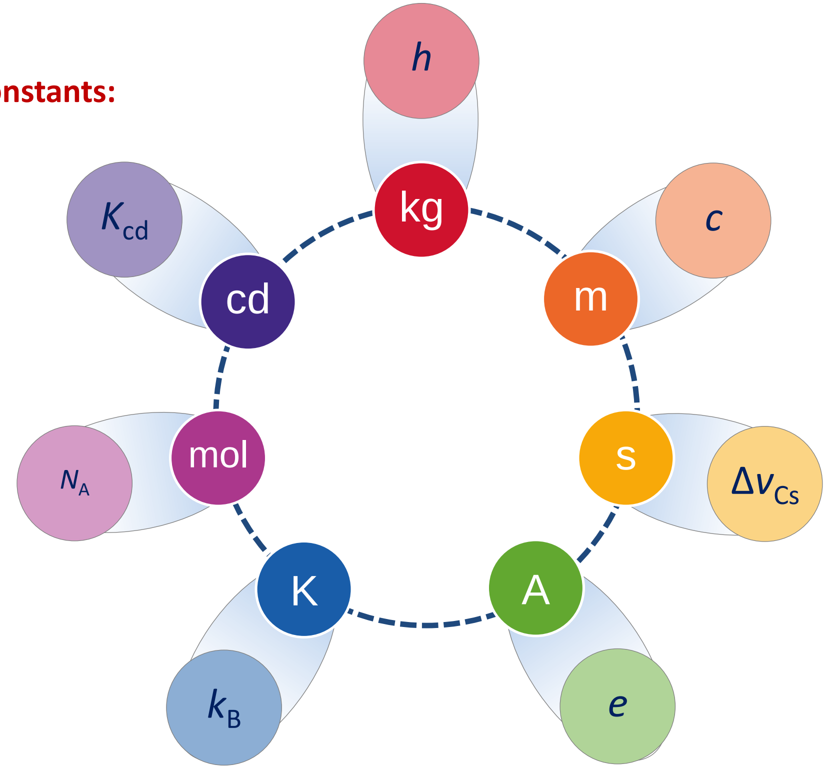
We now have 4 new definitions

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 atomic property:

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



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Seven base units

...same base units but different links

6 definitions based on fundamental (or conventional) constants:

- metre (c)
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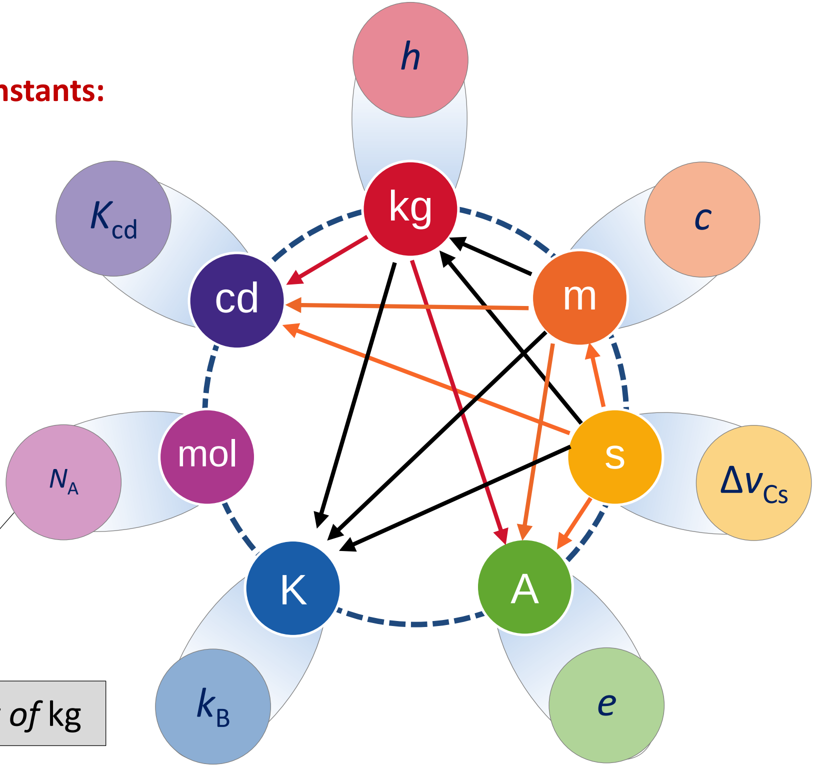

mol *is now independent of* kg

Outline

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Welcome to the Open session to consider the revision of the SI

https://www.youtube.com/watch?v=jVRsXNaC1hM

#siredefinition

A

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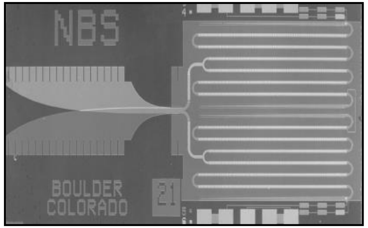
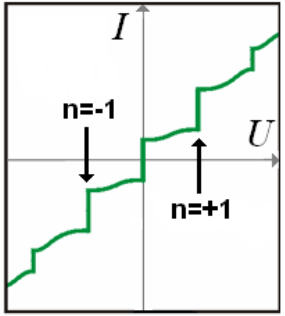
Since 1990, macroscopic quantum effects have been the basis for the reproduction of the electrical units

Josephson effect

Nobel Prize 1973



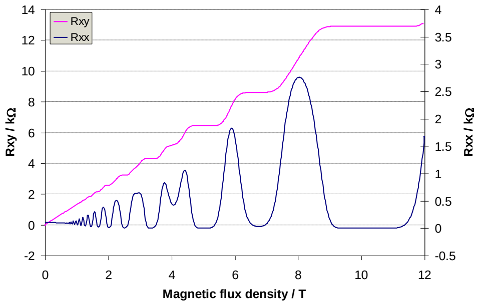


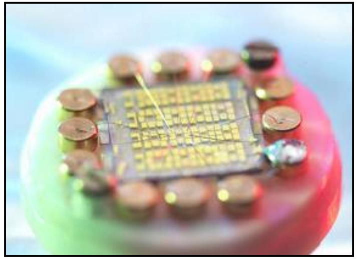
$$U_J = n\frac{f}{K_J}, \qquad K_J = \frac{2e}{h}$$

$K_{J\text{-}90} \equiv$ **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**

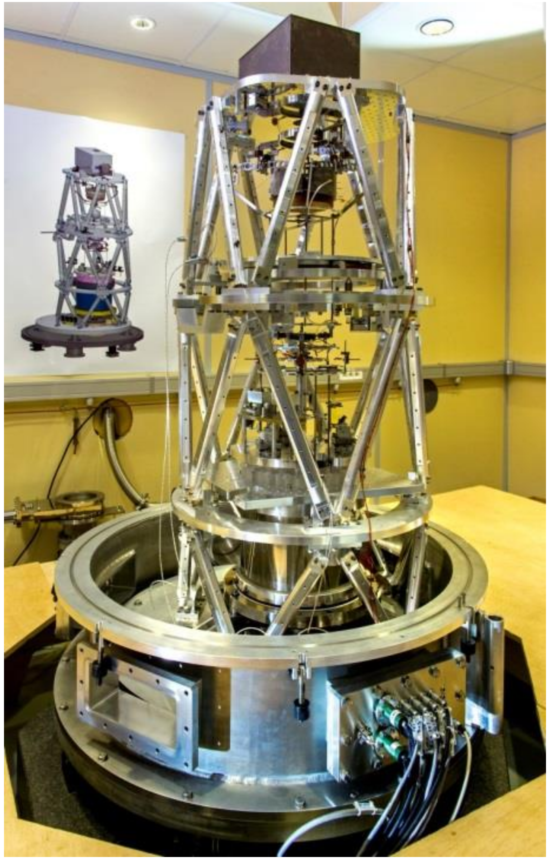
- But: this convention is not within the SI (because they may not lead to $\mu_0 \equiv 4\pi \cdot 10^{-7}$ N A^{-2})

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.



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 $\times 10^{-9}$

kg

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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Writing the new definitions eg **the kilogram**

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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.**

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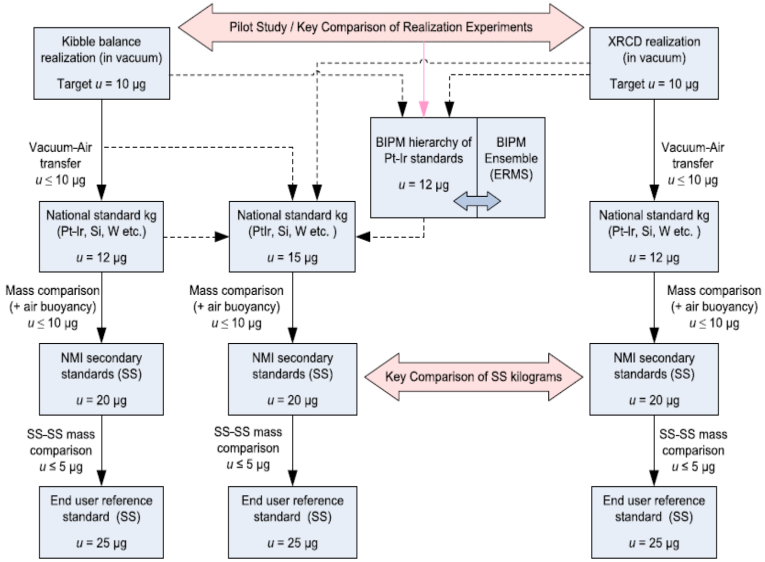

Advantages of the change – the size of the kg (!)

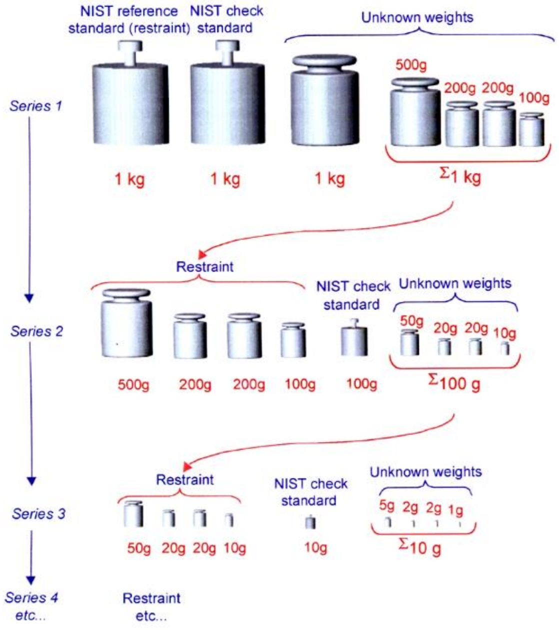

Fig. 3. A schematic description of the weighing designs used in the dissemination to submultiples of the kilogram.

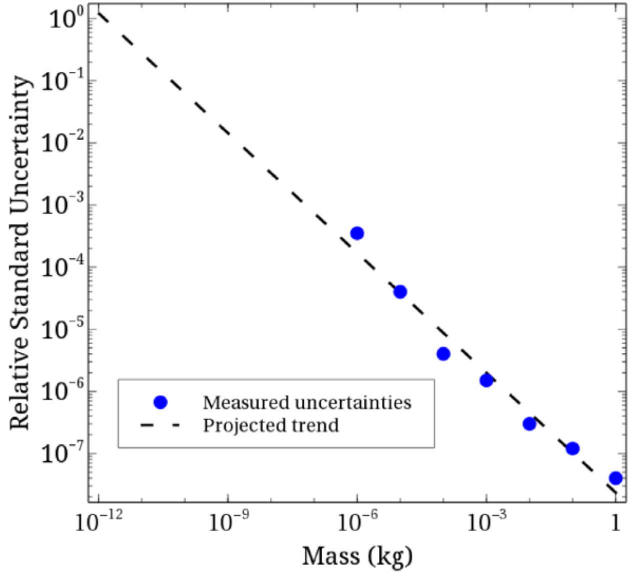

Figure 1. Relative uncertainty in mass as a function of mass value. Dashed line is a linear fit to the data shown.

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

K

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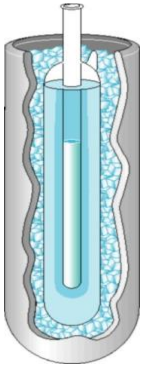
The kelvin – present definition

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

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



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.

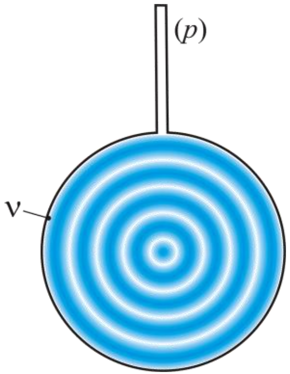
The principal of primary thermomtery

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

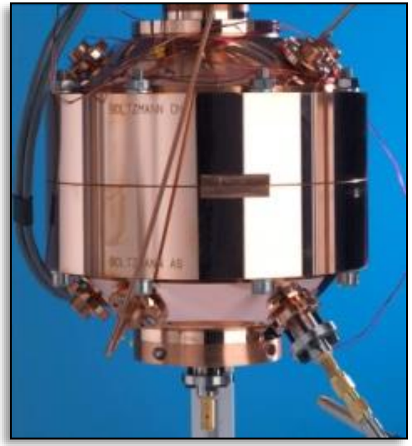
The acoustic gas thermometer

AGT



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

Courtesy of Joachim Fischer, PTB

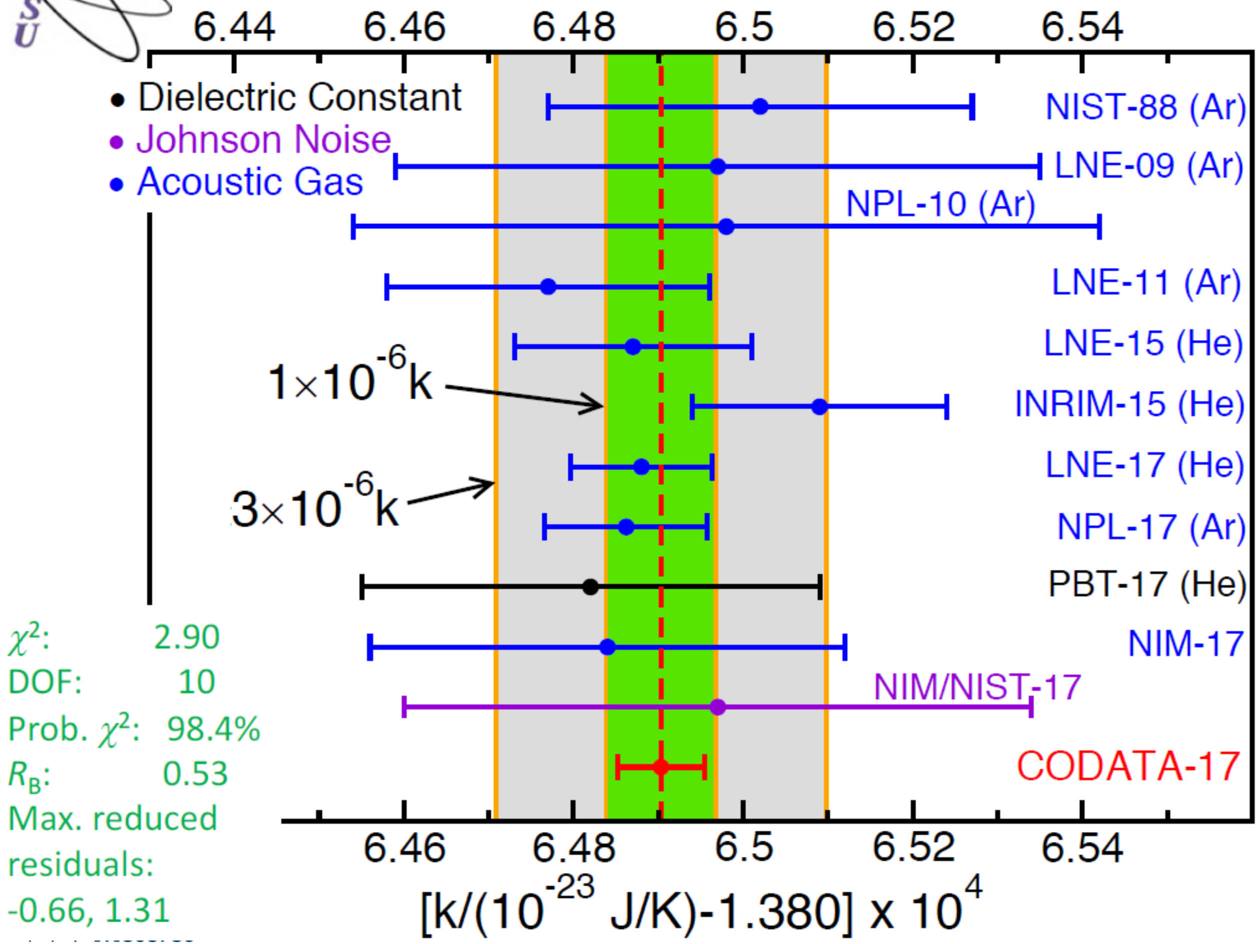


The NPL Acoustic Gas Thermometer (with Argon)

		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	m^2 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

2017 Boltzmann constant



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 × 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.

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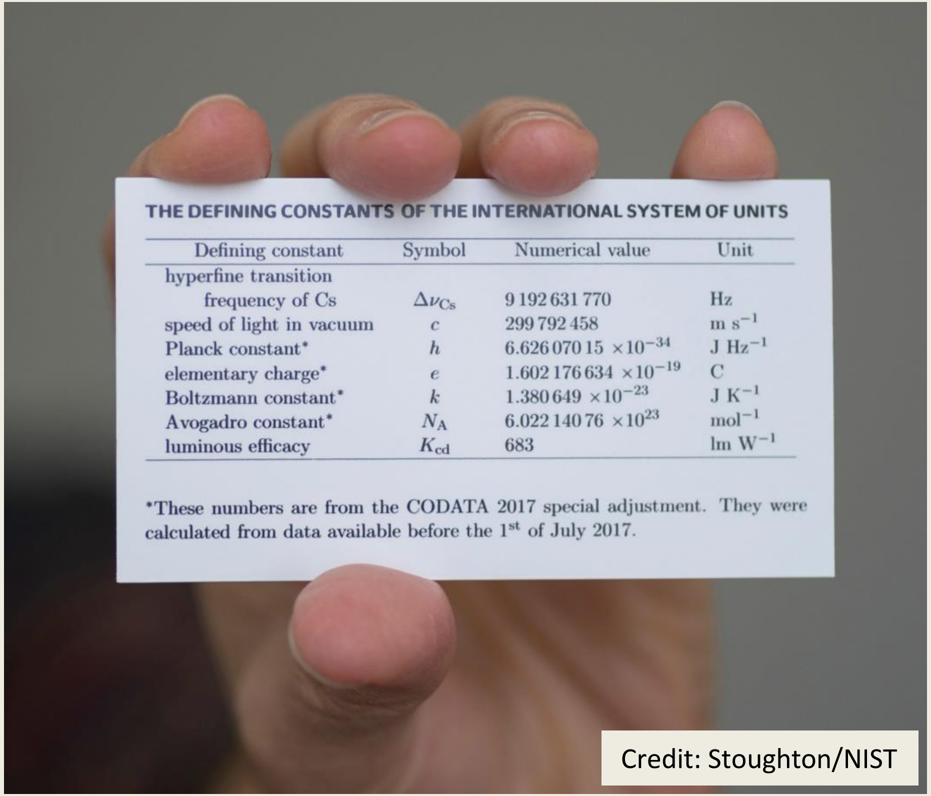
The International System of Units

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



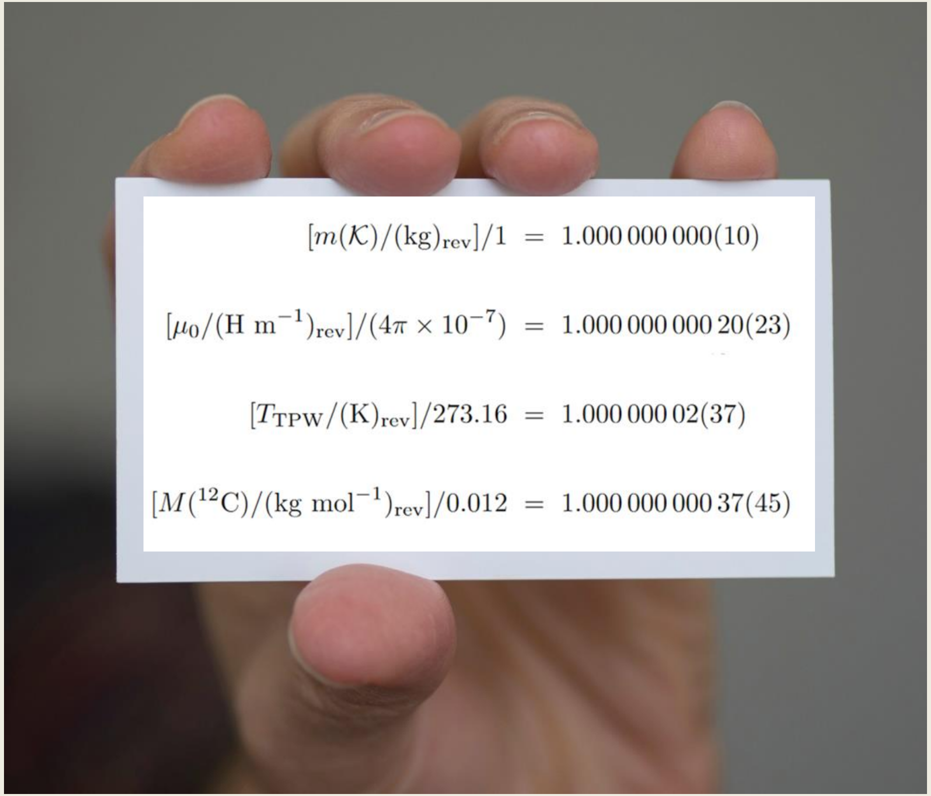
Credit: Stoughton/NIST

Bureau International des Poids et Mesures

The International System of Units

BUT

We have 4 new experimental quantities.



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

nature International weekly journal of science

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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?

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

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

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

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

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

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
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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

2018

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.

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Celebrating the revision of the SI !

https://www.youtube.com/watch?v=V7myhT_CwYc

#siredefinition

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

https://www.youtube.com/thebipm

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