La revisione del Sistema Internazionale di unità di misura

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INRiM
ISTITUTO NAZIONALE
DI RICERCA METROLOGICA

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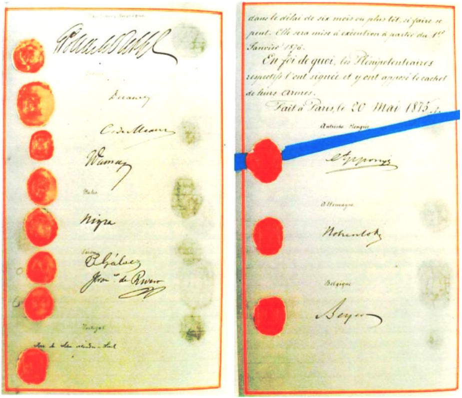
The Metre Convention

Paris, 20 May 1875: an international treaty

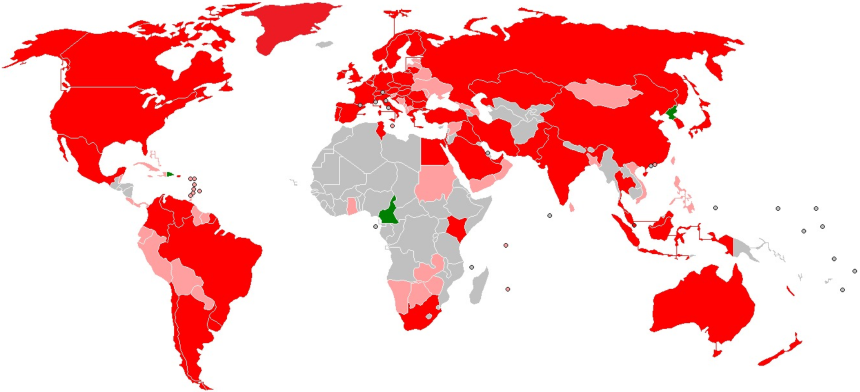


Original signatories: Argentina, Austria-Hungary, Belgium, Brazil, Denmark, France, Germany, Italy, Peru, Portugal, Russia, Spain, Sweden and Norway, Switzerland, Turkey, United States of America, and Venezuela

[for His Majesty the King of Italy: Chevalier Constantino Nigra, Knight of the Grand Cross of his Orders of St. Maurice and St. Lazarus, and of the Crown of Italy, Grand Officer of the Legion of Honor, . . . Extraordinary and Minister Plenipotentiary at Paris]

The Metre Convention

The signatories today



The SI, 1960-today : what does *not* change

Base and derived units

Base units

Symbol	Unit name
s	second
m	metre
kg	kilogram
A	ampere
K	kelvin
mol	mole
cd	candela

Base and derived units

Base units

Symbol	Unit name
s	second
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mol	mole
cd	candela

Derived units

$$\mathrm{s}^{\alpha}\,\mathrm{m}^{\beta}\,\mathrm{kg}^{\gamma}\,\mathrm{A}^{\delta}\,\mathrm{K}^{\epsilon}\,\mathrm{mol}^{\zeta}\,\mathrm{cd}^{\eta},$$

where α, β, γ, δ, ϵ, ζ and η are (usually) integers.

SI units for electromagnetic quantities

Derived units with special names

Derived quantity	name	symbol	expression in terms of base units
frequency	hertz	Hz	s^{-1}
energy	joule	J	$m^2\,kg\,s^{-2}$
power	watt	W	$m^2\,kg\,s^{-3}$
electric charge	coulomb	C	$s\,A$
electric potential difference	volt	V	$m^2\,kg\,s^{-3}\,A^{-1}$
electric capacitance	farad	F	$m^{-2}\,kg^{-1}\,s^{-4}\,A^2$
electric resistance	ohm	Ω	$m^2\,kg\,s^{-3}\,A^{-2}$
electric conductance	siemens	S	$m^{-2}\,kg^{-1}\,s^3\,A^2$
magnetic flux	weber	Wb	$m^2\,kg\,s^{-2}\,A^{-1}$
magnetic flux density	tesla	T	$kg\,s^{-2}\,A^{-1}$
inductance	henry	H	$m^2\,kg\,s^{-2}\,A^{-2}$

SI prefixes and suffixes

The SI adopts a series of prefix names and prefix symbols to form the names and symbols of the decimal multiples and submultiples of units, ranging from 10^{24} to 10^{-24}.

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

The SI, 1960-2019

SI, 1960-2019

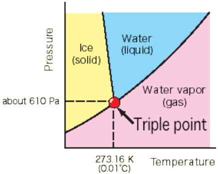
The seven base units

- m — The **metre** is the length of the path travelled by light in vacuum during a time interval of 1/299792458 of a second.
- kg — The **kilogram** is the unit of mass; it is equal to the mass of the international prototype of the kilogram.
- s — The **second** is the duration of 9 192 631 770 periods of the radiation corresponding to the transition between the two hyperfine levels of the ground state of the caesium-133 atom.
- A — 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 m apart in vacuum, would produce between these conductors a force equal to 2×10^{-7} newton per metre of length.
- K — The **kelvin**, unit of thermodynamic temperature, is the fraction 1/273.16 of the thermodynamic temperature of the triple point of water.
- mol — The **mole** is the amount of substance of a system which contains as many elementary entities as there are atoms in 0.012 kg of carbon 12.
- cd — The **candela** is the luminous intensity, in a given direction, of a source that emits monochromatic radiation of frequency 540×10^{12} hertz and that has a radiant intensity in that direction of 1/683 watt per steradian.

SI, 1960-2019: Definition of units

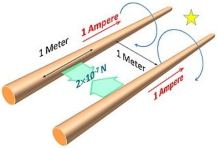
an **artefact**:

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



a **natural property**

> *The kelvin is the fraction 1/273.16 of the thermodynamic temperature of the triple point of water.*



an **idealized experiment**

> *The ampere is that constant current which, if maintained in two straight parallel conductors of infinite length [...] would produce a force equal to 2×10^{-7} newton per metre of length*

SI, 1960-2019: Realization of the units

Realization (VIM 5.1 ↗)

The realization of the definition of a unit can be provided by a measuring system, a material measure, or a reference material.

SI, 1960-2019: Realization of the units

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The realization of the definition of a unit can be provided by a measuring system, a material measure, or a reference material.

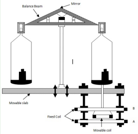
SI 1960-2019:

an artefact:

The international prototype of the kilogram is the realization of the kilogram.

a device

A triple point of water cell is a realization of the kelvin.



an experiment

The current balance is a realization of the ampere.

The ampere, 1960-2019

The definition of the base unit ampere is mechanical:

> *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 2×10^{-7} newton per metre of length.*

All electromagnetic derived units have an ultimately mechanical definition also.

These quantities are **exact**:

$\mu_0 = 4\pi \times 10^{-7}$ H/m the *magnetic constant*;

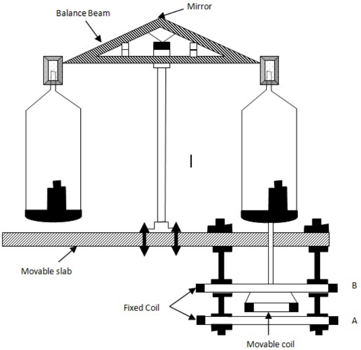
$\epsilon_0 = \left(\mu_0 c^2\right)^{-1} = 8.854\,187\,817\ldots$ pF/m, the *electric constant*

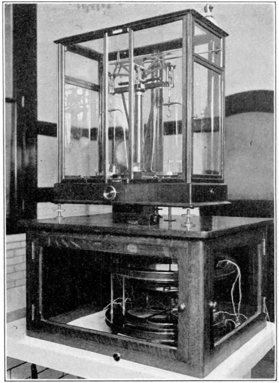
$Z_0 = \mu_0\, c = \sqrt{\mu_0\, \epsilon_0^{-1}} = 376.730\,313\,4\ldots\ \Omega$, the *impedance of free space*

μ_0, ϵ_0 constant $\Rightarrow$ realization of SI units of impedance.

Realization of the ampere

The (electrodynamic) ampere balance (Vigoreux, 1965)





Ampère force law:

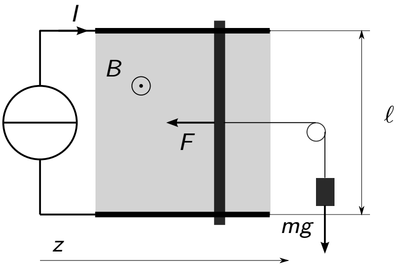
$$F = \frac{\mu_0}{4\pi} \int_{\Gamma_1} \int_{\Gamma_2} \frac{I_1 \, d\ell_1 \times I_2 \, d\ell_2 \times \boldsymbol{r}_{21}}{|\boldsymbol{r}_{21}|^2}$$

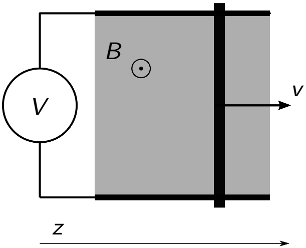
If $I_1 = I_2$, $F = \mu_0 k I^2$ where k is computed from geometrical measurements

Realization of the electrical watt

The watt balance, or Kibble balance

Solves the problem of geometrical measurements!





- Weighing mode: $F = mg = B\ell I = \frac{\mathrm{d}\Phi}{\mathrm{d}z} I$
- Moving mode: $E = \frac{\mathrm{d}\Phi}{\mathrm{d}t} = \frac{\mathrm{d}\Phi}{\mathrm{d}z}\frac{\mathrm{d}z}{\mathrm{d}t} = \frac{\mathrm{d}\Phi}{\mathrm{d}z} v$

$$mgv = EI;$$

mechanical power = electrical power

The Kibble balance

(Robinson and Schlamminger, 2016)

Solves the problem of geometrical measurements!

weighing mode

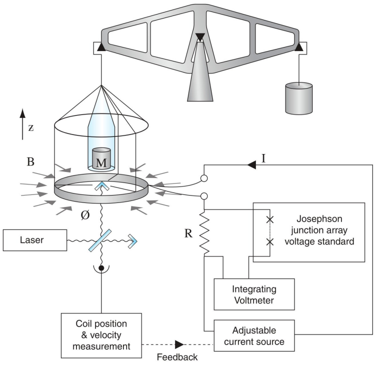


Figure 1. The Kibble balance in weighing mode.

moving mode

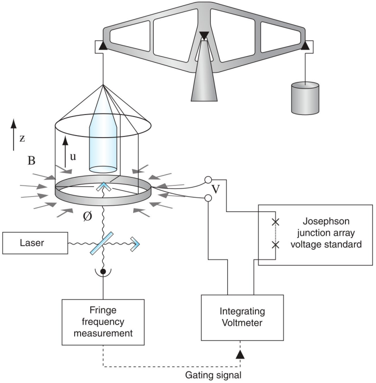
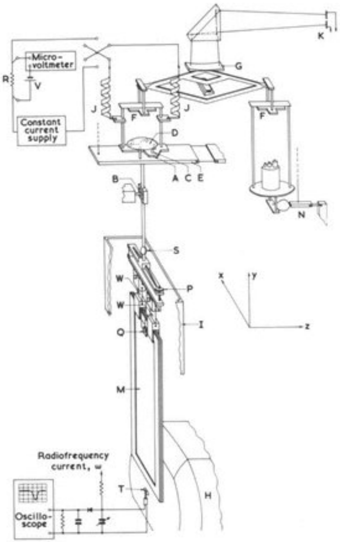


Figure 2. The Kibble balance in moving mode.

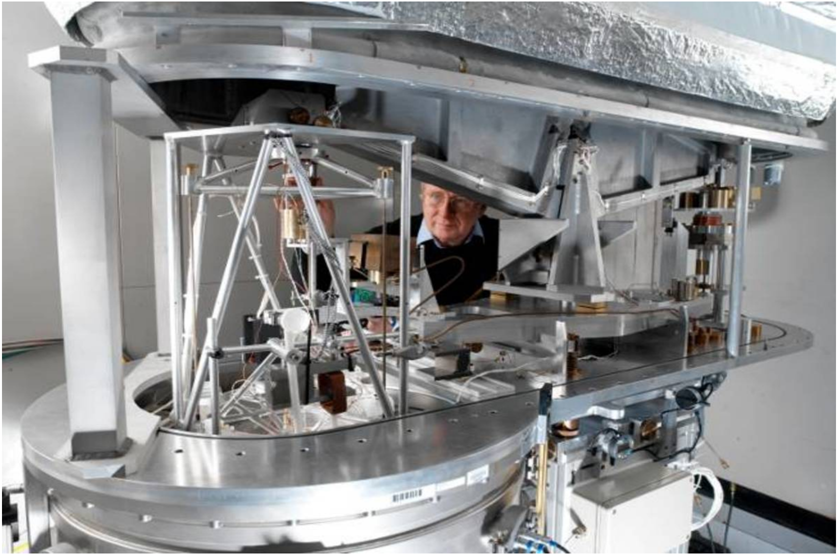
The Kibble balance evolution

NPL, Kibble (1976) for the gyromagnetic ratio of the proton

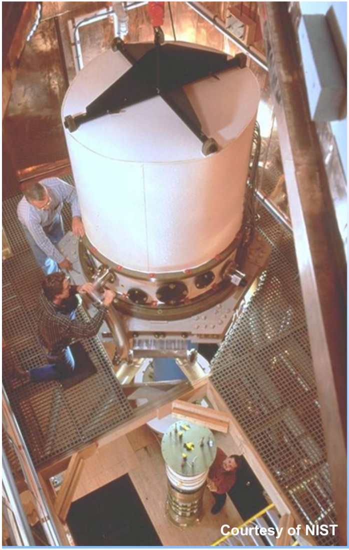


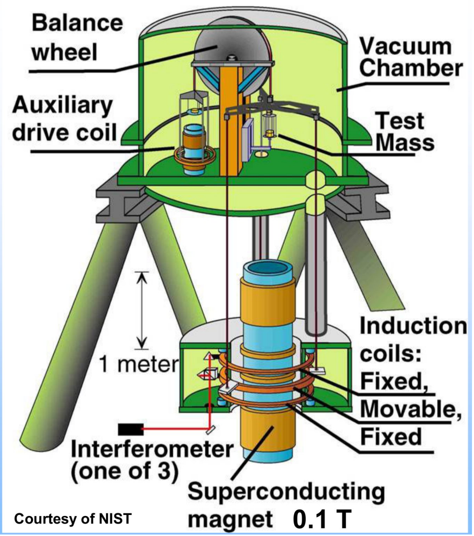
The Kibble balance: evolution

NRC, Bryan P. Kibble and I. Robinson, 2011



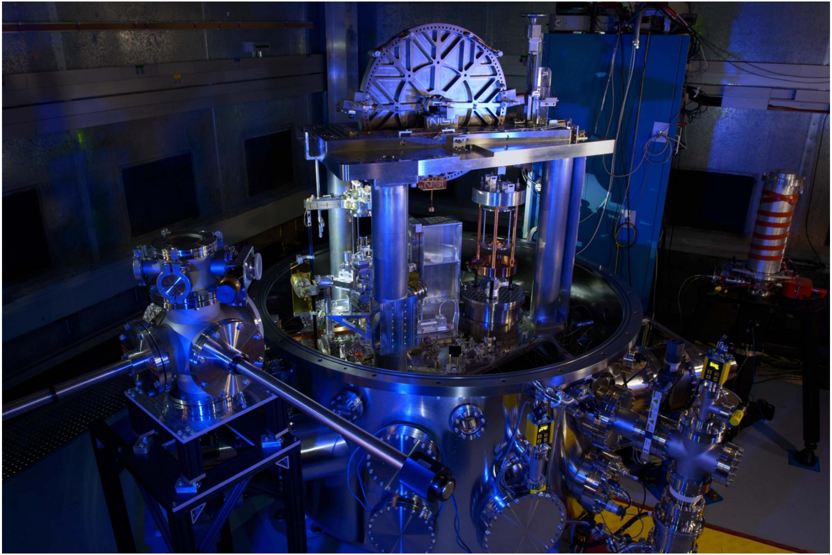
The Kibble balance: evolution
NIST-3





The Kibble balance: evolution

The last generation: NIST-4, 2016



The Kibble balance: evolution

The last generation: NPL, 2017

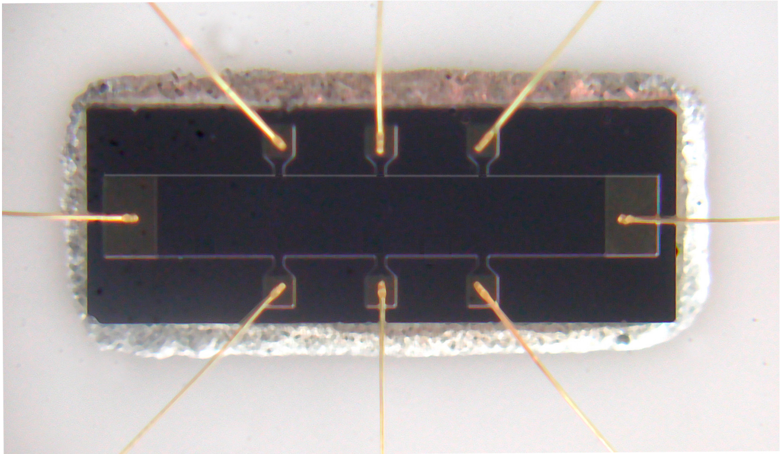
Quantum electrical metrology

Quantum electrical metrology experiments

Macroscopic quantum effect that display an electrical quantity related to fundamental constants

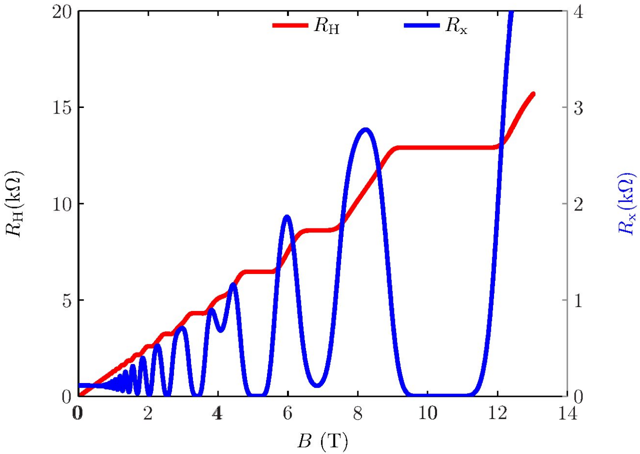
- quantized resistance: the quantum Hall effect
- quantized flux counting: the Josephson effect
- quantized charge counting: single-electron counting devices

The quantum Hall effect



AlGaAs/GaAs Hall bar heterostructure, 1 mm × 0.4 mm;

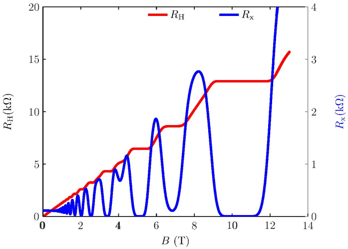
The quantum Hall effect



— $R_H = V_H/I$ Hall resistance;

— $R_x = V_x/I$ longitudinal resistance.

The quantum Hall effect



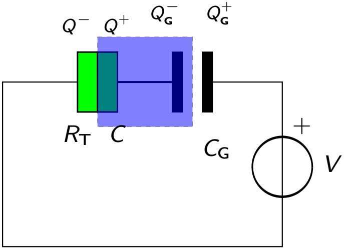
Each plateau i is centered on a resistance value $R_H = R_K/i$, with i integer

$$R_K = \frac{h}{e^2} = \frac{\mu_0 c}{2\alpha}.$$

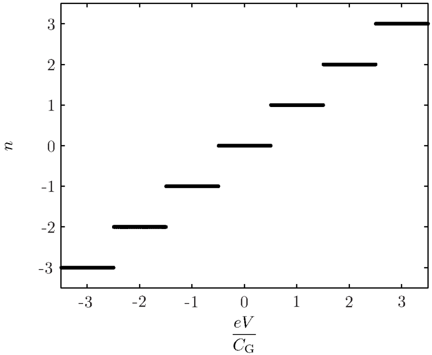
R_K is linked to the fine structure constant α which can be measured by non-electrical means.

Quantized charge counting

Single charge confinement

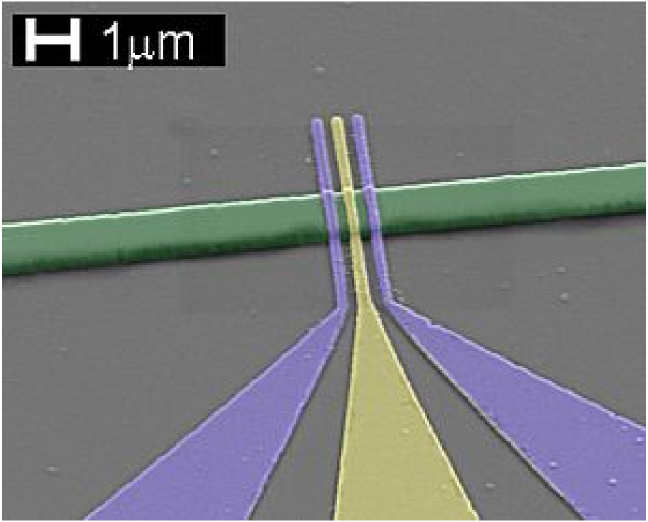


Single-electron box, coupled to an external circuit with a tunnel junction (with tunnel resistance R_T and capacitance C) and a capacitor C_G.



occupation number n versus applied bias voltage V.

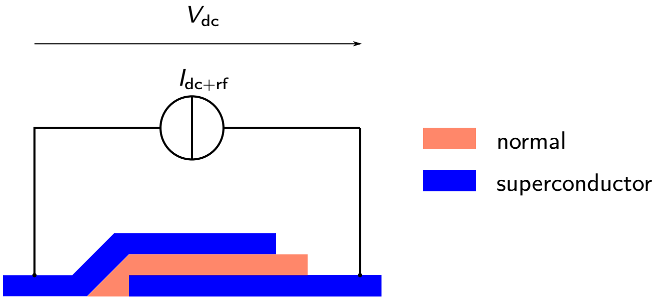
Quantized charge counting
Nanodevices



Courtesy: PTB
Semiconductor single-electron pump.

Counting flux quanta

Josephson junctions



Josephson junction:

- two superconductors coupled by a tunneling barrier
- have coupled wavefunctions

Counting flux quanta: The Josephson effect

Applying a rf voltage excitation at frequency f_{ac}, at every cycle n flux quanta are counted across the junction:

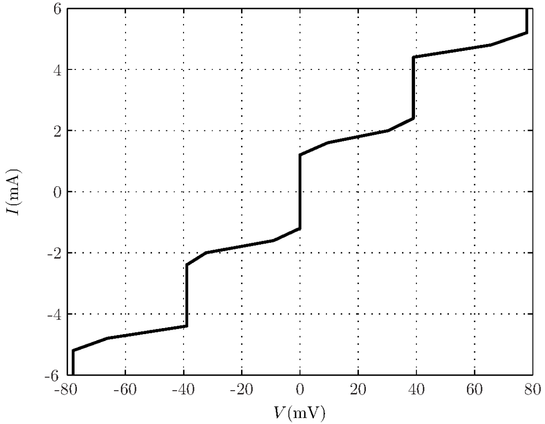
$$V_{dc} = n\Phi_0 f_{ac} = \frac{n f_{ac}}{K_J}$$

where K_J is the Josephson constant.

Feasible drive frequencies: $f_{ac} = 70\,\text{GHz} \quad \Rightarrow \quad V_{dc} = 150\,\mu\text{V}$.

Counting flux quanta

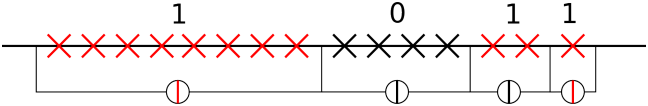
frequency to voltage converter: the (inverse AC) Josephson effect

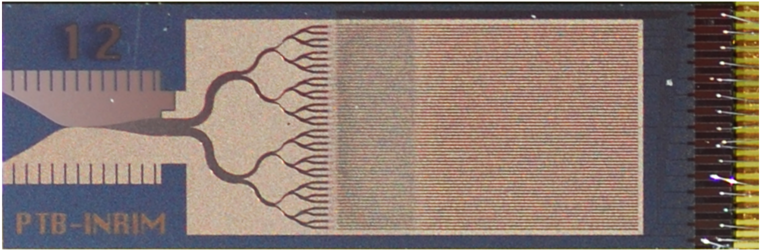


The $I - V$ characteristic of a Josephson array (256 junctions) under microwave irradiation. Steps $n = 0, \pm 1, \pm 2$ are visible. $f \approx 73\,\mathrm{GHz}$

Counting flux quanta
Josephson binary DAC

Binary-weighted Josephson DAC





Josephson junction binary array chip. 13 bit+sign DAC with 8192 superconducting-normal metal-insulator-superconductor (SNIS) junctions. The junctions are geometrically arranged over 32 parallel strips of 256 junctions each. $f = 70\,\text{GHz}$. $V_{\text{fullscale}} \approx \pm 1.2\,\text{V}$

The SI 1960-2019: status of the quantum experiments

Knowledge in 1989 (CODATA):

$K_J = 483\,597.9(2)\,\mathrm{GHz/V}$ $[4 \times 10^{-7}]$

$R_K = 25\,812.807(5)\,\Omega$ $[2 \times 10^{-7}]$

but, *reproducibility* of Josephson and quantum Hall experiments in different experiments and different laboratories was much higher: 10^{-9}–10^{-10}

Solution: invent non-SI units! 18th CGPM resolution 6: Valid since January 1, 1990:

$K_{J\text{-}90} = 483\,597.9\,\mathrm{GHz/V}$ [exact]

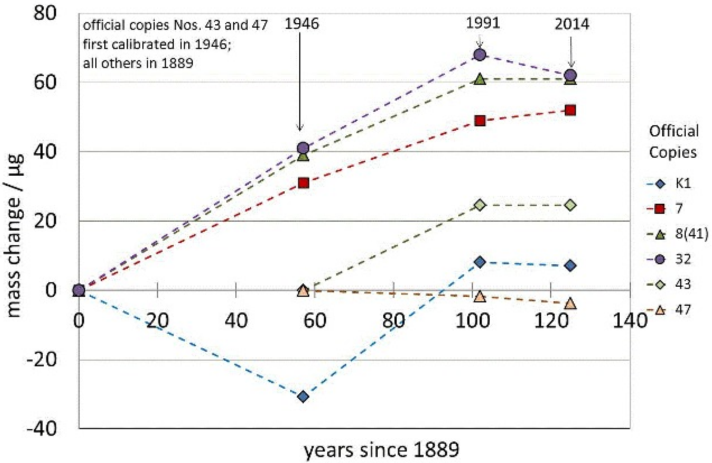
$R_{K\text{-}90} = 25\,812.807\,\Omega$ [exact]

To $K_{J\text{-}90}$ and $R_{K\text{-}90}$ the conventional units Ω_{90}, H_{90}, F_{90}, A_{90}, W_{90} are associated.

These are the electrical units in use until 2019.

The SI, 1960-2019 : Problems

Problem: The drift of the International Prototype



The International Prototype Kilogram compared with its *témoins*

IPK might have lost 35 µg over 130 years

Problem: The SI and conventional units

Two incompatible systems

Becuase of improvements in the measurement of fundamental constants, the conventional and SI units started to drift apart. For example, CODATA 2014:

$$K_J = 483\,597.8525(30)\,\mathrm{GHz/V} \qquad [6.1 \times 10^{-9}]$$
$$R_K = 25\,812.807\,455\,5(59)\,\Omega \qquad [2.3 \times 10^{-10}]$$

Therefore

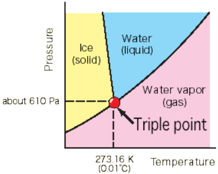
$$V_{90} = 1 + 9.8(6) \times 10^{-8}\,\mathrm{V}$$
$$\Omega_{90} = 1 - 1.764(2) \times 10^{-8}\,\Omega$$

$\Rightarrow$ Unacceptable deviation of the conventional units respect to the SI units

Problem: uniformity of unit definitions

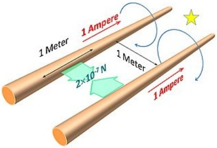
an artefact:

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



a natural property

> *The kelvin is the fraction* 1/273.16 *of the thermodynamic temperature of the triple point of water.*



an idealized experiment

> *The ampere is that constant current which, if maintained in two straight parallel conductors of infinite length [...] would produce a force equal to 2×10^{-7} newton per metre of length*

Two decades of discussions . . .

INSTITUTE OF PHYSICS PUBLISHING METROLOGIA

Metrologia **42** (2005) 71–80 doi:10.1088/0026-1394/42/2/001

Redefinition of the kilogram: a decision whose time has come

Ian M Mills[1], Peter J Mohr[2], Terry J Quinn[3], Barry N Taylor[2] and Edwin R Williams[2]

The revision of the SI, 2019-

Formal decision: the CGPM

26th General Conference of Weights and Measures

26e CGPM
Versailles
13-16 novembre 2018

Implementation day: May 20, 2019, the World Metrology Day

The revised SI, 2019-

The SI is the system of units in which:

- s The unperturbed ground state hyperfine transition frequency of the caesium 133 atom $\Delta\nu_{\mathrm{Cs}}$ is 9 192 631 770 Hz;
- m the speed of light in vacuum c is 299 792 458 m/s;
- kg the Planck constant h is $6.626\,070\,15 \times 10^{-34}$ J s;
- A the elementary charge e is $1.602\,176\,634 \times 10^{-19}$ C;
- K the Boltzmann constant k is $1.380\,649 \times 10^{-23}$ J/K;
- mol the Avogadro constant N_{A} is $6.022\,140\,76 \times 10^{23}\ \mathrm{mol}^{-1}$;
- cd the luminous efficacy of monochromatic radiation of frequency 540×10^{12} Hz, K_{cd}, is 683 lm/W,

where the hertz, joule, coulomb, lumen, and watt, with unit symbols Hz, J, C, lm, W, respectively, are related to the units second, metre, kilogram, ampere, kelvin, mole, and candela, with unit symbols s, m, kg, A, K, mol, cd, respectively, according to $\mathrm{Hz} = \mathrm{s}^{-1}$, $\mathrm{J} = \mathrm{m}^2\mathrm{kgs}^{-2}$, $\mathrm{C} = \mathrm{A\,s}$, $\mathrm{lm} = \mathrm{cd\,sr}$, $\mathrm{W} = \mathrm{m}^2\mathrm{kg\,s}^{-3}$.

The SI, 2019-: the base units kilogram and ampere

The kilogram:

> *The kilogram, symbol kg, is the SI unit of mass. It is defined by taking the fixed numerical value of the Planck constant h to be* $6.626\,070\,15 \times 10^{-34}$ *when expressed in the unit J s, which is equal to* $\mathrm{kg\,m^2\,s^{-1}}$*, where the metre and the second are defined in terms of c and* $\Delta\nu_{\mathrm{Cs}}$*.*

The ampere:

> *The ampere, symbol A, is the SI unit of electric current. It is defined by taking the fixed numerical value of the elementary charge e to be* $1.602\,176\,634 \times 10^{-19}$ *when expressed in the unit C, which is equal to A s, where the second is defined in terms of* $\Delta\nu_{\mathrm{Cs}}$*.*

The SI, 2019-: the base units kilogram and ampere

The kelvin:

The kelvin, symbol K, is the SI unit of thermodynamic temperature. It is defined by taking the fixed numerical value of the Boltzmann constant k to be $1.380\,649 \times 10^{-23}$ when expressed in the unit JK^{-1}, which is equal to $kgm^2\ s^{-2}\ K^{-1}$, where the kilogram, metre and second are defined in terms of h, c and $\Delta\nu_{Cs}$.

The mole:

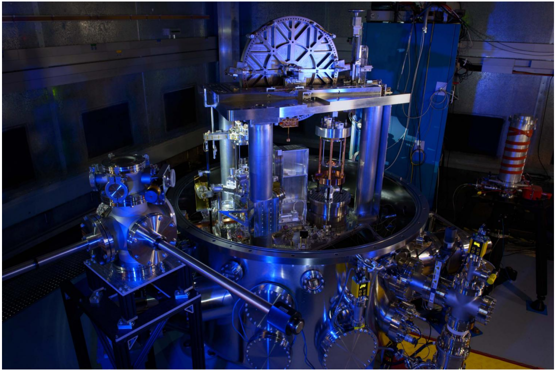
The mole The mole, symbol mol, is the SI unit of amount of substance. One mole contains $6.022\,140\,76 \times 10^{23}$ elementary entities. This number is the fixed numerical value of the Avogadro constant, N_A, when expressed in the unit mol^{-1} and is called the Avogadro number.

The SI, 2019- : an electrical realization of the kilogram

The Kibble balance, revisited

h is **exact**;

$\Rightarrow$ The Kibble balance, if traceable to K_J and R_K, is a realization of the kilogram.



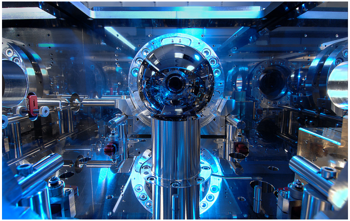
The SI, 2019- : a mechanical realization of the kilogram

Silcon atom counting

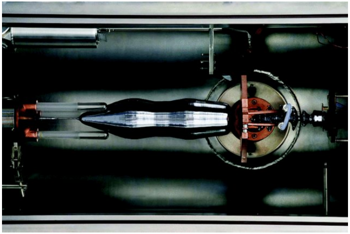
$$M_{\text{sphere}} = N \cdot m_{\text{Si}} = \frac{V_{\text{sphere}}}{v_{\text{cell}}} m_{\text{Si}}$$

Count the atoms

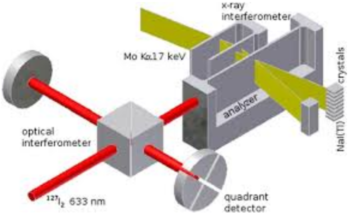
V_{sphere}: spherical interferometer



m_{Si}: single ^{28}Si crystal



v_{cell}: X-ray + optical interferometer



m_{Si}/h: known $[10^{-9}]$
from atomic experiments

$$M_{\text{sphere}} = \frac{V_{\text{sphere}}}{v_{\text{cell}}} \left(\frac{m_{\text{Si}}}{h}\right) h$$

And h is fixed in the new SI!

The SI, 2019- : a new status of quantum metrology

e has a fixed value **exact**;

$\Rightarrow$ any electron-counting experiment is a realization of the ampere;

$R_K = \frac{h}{e^2}$ is **exact**;

$\Rightarrow$ the quantum Hall effect is a realization of the ohm;

$K_J = \frac{2e}{h}$ is **exact**;

$\Rightarrow$ the Josephson effect is a realization of the volt;

$\Rightarrow$ The combined Josephson and quantum Hall effects, through Ohm's law, is a realization of the ampere.

8/12/2017
Version 1.0

CCEM Guidelines for Implementation of the ‘Revised SI’

Consultative Committee for Electricity and Magnetism

- $V_{90} \Rightarrow V$: $d = +1.067 \times 10^{-7}$
- $\Omega_{90} \Rightarrow \Omega$: $d = +1.779 \times 10^{-8}$

What to do with maintained standards?

$d < 2.5\,U$: no action until next recalibration

$d > 2.5\,U$: numerical correction to be applied

The new SI, 2019-

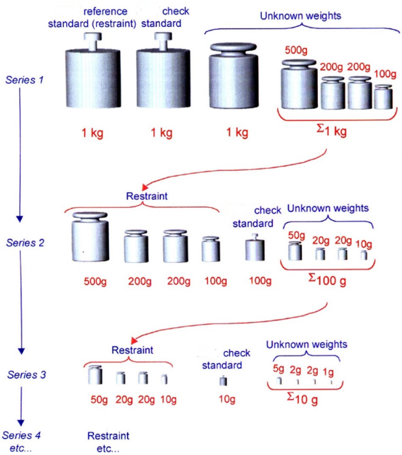
Unit definitions do not suggest preferred realisations;

Any physical experiment that satisfies the definition is a realization of the unit

Units can be realized at any level (multiple or submultiple)

Any laboratory can realise the SI units at the uncertainty level of interest

Example: electrostatic realisation of the mg

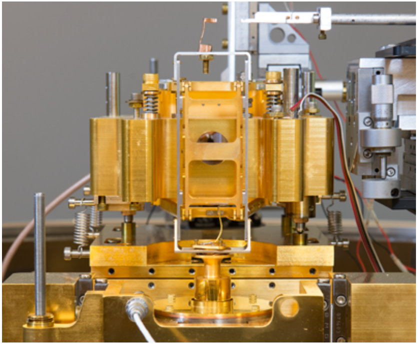


PAPER

Milligram mass metrology using an electrostatic force balance

Gordon A Shaw[1], Julian Stirling[1], John A Kramar[2], Alexander Moses[1], Patrick Abbott[1], Richard Steiner[1], Andrew Koffman[1], Jon R Pratt[1] and Zeina J Kubarych[1]

Published 28 September 2016 • © 2016 US Govt. Copyright (NIST)
Metrologia, Volume 53, Number 5
Focus on Realization, Maintenance and Dissemination of the New Kilogram



Example: a commercial quantum realisation of the volt

supracon
SQUID AND MICROFABRICATION TECHNOLOGIES

SQUID | Standards | Microfabrication | Company

- **AC Quantum Voltmeter**
  - AC components
  - AC calibration modes (Samples)
  - AC specifications
  - AC voltage standard array
- DC Josephson Voltage Standard
- Nanoscale calibration

AC Quantum Voltmeter

The **AC Quantum Voltmeter** is a programmable Josephson voltage standard system applicable for the highest level of precision voltage measurements from DC up to kHz frequencies.
It was developed by the Physikalisch-Technische Bundesanstalt Braunschweig (PTB) in cooperation with the companies esz AG and Supracon AG.

It facilitates a variety of voltage calibrations and measuring functions:

- **Primary DC & AC Josephson voltage standard** up to kHz frequencies
- Calibration of **calibrators**
- Calibration of **secondary voltage standards**
- Calibration of **voltmeter linearity**
- Calibration of **thermal converters** (optional)
- **Voltage source** with ultimate precision and lowest noise level

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METROLOGY

Pressure gets an upgrade

A 400-year-old method for measuring the quantity has a rival based on quantum physics.

BY ELIZABETH GIBNEY

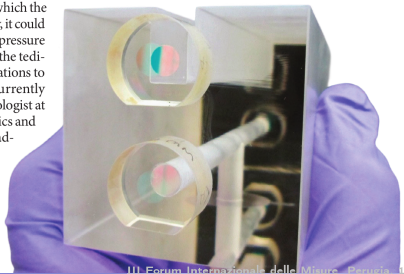
Researchers in the United States have developed a new way to define and measure pressure and its unit, the pascal — one that they say will, within a year, begin to replace the mercury-based measurement methods that have been in use since 1643.

Pressure is conventionally defined as force per unit area, and the pascal is a force of 1 newton per metre squared. For nearly 400 years, values at air pressure and below have been measured using mercury-based instruments called manometers. The US National Institute of Standards and Technology (NIST) in Gaithersburg, Maryland, holds one of a handful of the world's most precise manometers, known as primary standards — huge instruments that serve as the benchmarks against which all other pressure sensors are calibrated. But NIST scientists have now developed a highly precise method for measuring pressure that is based on treating it as energy density. This is an equivalent physical description to force per unit area because it is derived from the same combination of 'base' units, the most fundamental units of measure in the International System of Units (SI).

The NIST method involves probing atoms of gas in a cavity directly with a laser to determine their pressure. The team hopes to show in the next year that its apparatus can rival the manometer — and to encourage other metrology labs to use it as their primary standard.

If widely accepted by the metrology community, the method would do away with the need for mercury, which is toxic and faces international bans. Moreover, the new technique allows metrologists to measure pressure directly, using a fundamental constant of nature, and does not rely on previous measurements of other quantities, such as density, on which the manometer depends. In theory, it could also allow anyone to measure pressure from first principles without "the tedious work of" a chain of calibrations to a primary standard that is currently required, says Bo Gao, a metrologist at the Technical Institute of Physics and Chemistry of the Chinese Academy of Sciences in Beijing, who works on a related method to measure low temperatures. The technique could enable faster measurements with more-portable equipment, benefiting industries such as aviation and semiconductor manufacturing.

Metrologists have long wanted to replace manometers, the principles of which date back to the mercury pressure gauge invented by Italian physicist Evangelista Torricelli in 1643. Modern manometers have two tall columns of mercury, and measure the force exerted on a surface due to a pressure by balancing it against the force generated by the weight of mercury.



NIST

The FLOC measures gas pressure using lasers.

A new role for the national metrology institutes?

NIST-on-a-chip initiative

NIST Search NIST NIST MENU

PHYSICAL MEASUREMENT LABORATORY

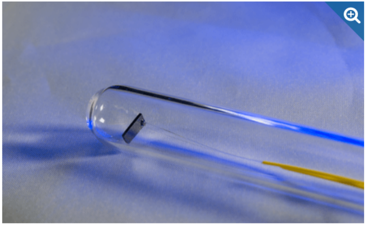
NIST on a Chip

- Overview
- Atomic Vapor +
- Electromagnetic Field Metrology
- Integration of physical and chemical/biological measurements
- Mass and Force +
- Microfluidics +
- Photonic Sensors +
- Quantum Optics and Radiometry +

NIST-on-a-Chip Portal

NIST has embarked on a sweeping program that will revolutionize measurement services and metrology by bringing them out of the lab and directly to the user. To that end, we are developing a suite of intrinsically accurate, quantum-based measurement technologies intended to be deployed nearly anywhere and anytime, performing uninterrupted *without the need for NIST's traditional measurement services.*

They will enable users to make precision measurements referenced to the International System of Units (SI) on factory floors, in hospital

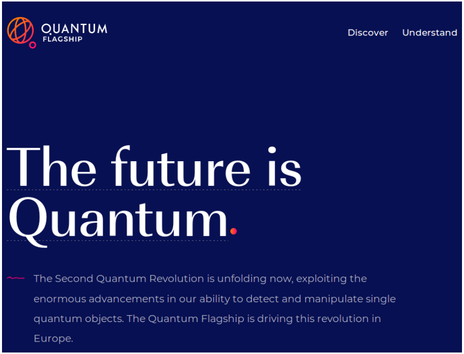


Close up of a photonic thermometer prototype, revealing the top of the chip

and in Europe?

The quantum flagship, 1 b€ initiative

From the draft Strategic Research Agenda, pillar *Quantum metrology and sensing*:
"[. . .] application targets here are for enhanced measurement and metrology of current, resistance, voltage and magnetic fields [. . .] integration of quantum electrical standards for self-calibration in instrumentation providing highly-accurate measurements [. . .]"



Thank you!

... and have a look at the INRIM poster on the European project
GIQS - Graphene Impedance Quantum Standard