CCU: Consultative Committee for Units

President:
Prof. Dr Joachim Ullrich

Executive Secretary:
Dr Estefanía de Mirandés

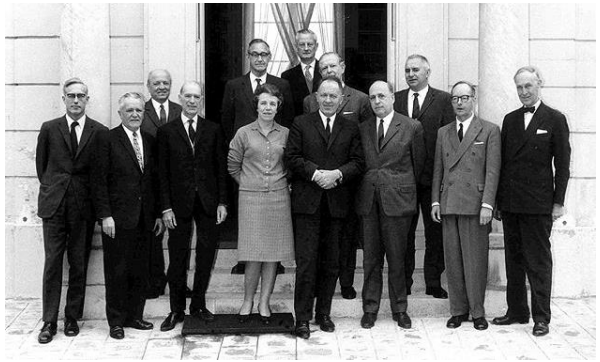
Bureau International des Poids et Mesures

Date established:

1964, to replace the "Commission for the System of Units", set up by the CIPM in 1954

CCU: Consultative Committee for Units

23rd meeting of the CCU (2017)



1st meeting of the CCU (1967)

- provide advice about **units of measurement**
- develop the **International System of Units (SI)**
- prepare the ***SI Brochure***

CCU: Consultative Committee for Units

23rd meeting of the CCU (2017)

Members of the CCU

- 11 National Metrology Institutes
- 3 Personal members
- 1 Ex officio member

Liaisons of the CCU

- 3 International Unions
- 5 International Commissions & Committees
- 2 Intergovernmental Organizations or International bodies

CCU: Consultative Committee for Units

- Global forum for progressing the state-of-the art

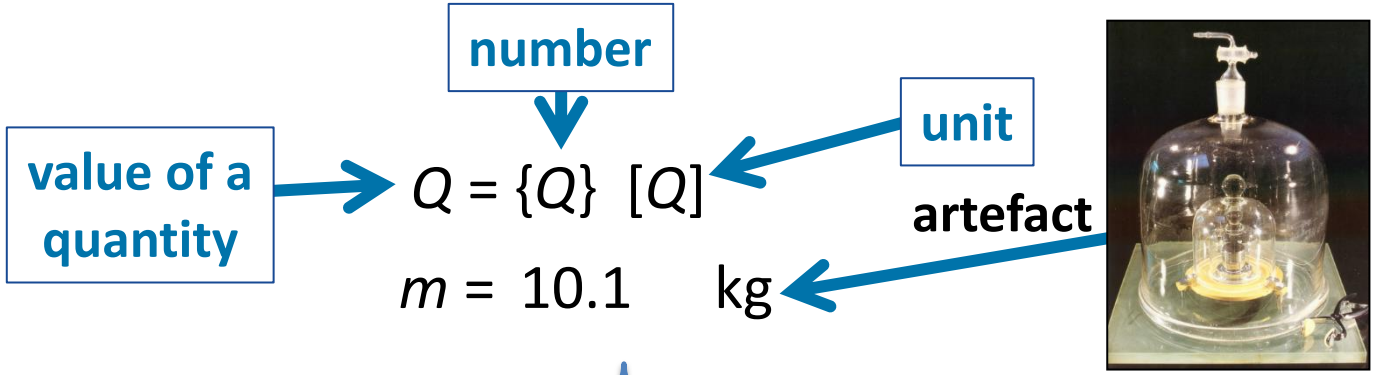
  → **CCU is the only global forum for units**

- Facilitating dialogue between NMIs and all stakeholders

  → **Always through international consensus**

- Global comparability of measurements

Quantities and Measurement Units



$m = 10.1$ kg

$t = 55.4$ s

$v = 87.4$ km/h

Quantities and Measurement Units

number

value of a quantity → $Q = \{Q\}\ [Q]$

unit

$m = 10.1(2)\,\mathrm{kg}$

$t = 55.4(1)\,\mathrm{s}$

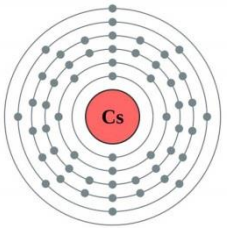
$\Delta\nu\,(^{133}\mathrm{Cs})_{\mathrm{hfs}} = 9\,192\,631\,770.5\,(6)\,\mathrm{s}^{-1}$

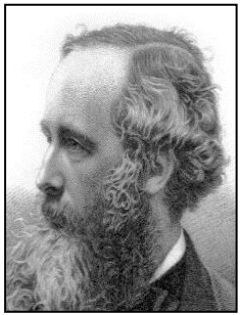
artefact

material property

measurem. prescription

defining





constant of nature

$$1\ \mathrm{s} = \frac{9\,192\,631\,770}{\Delta\nu\,(^{133}\mathrm{Cs})_{\mathrm{hfs}}}$$

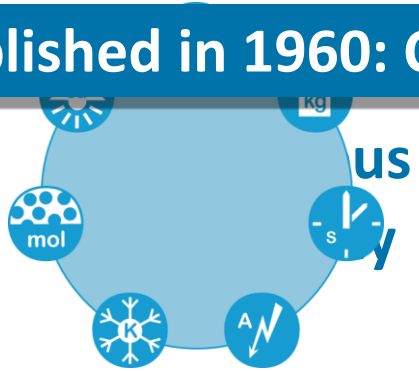
unce

Define a unit by fixing the numerical value of a constant of nature

The International System of Units: SI

Established in 1960: CGPM

Base units



us

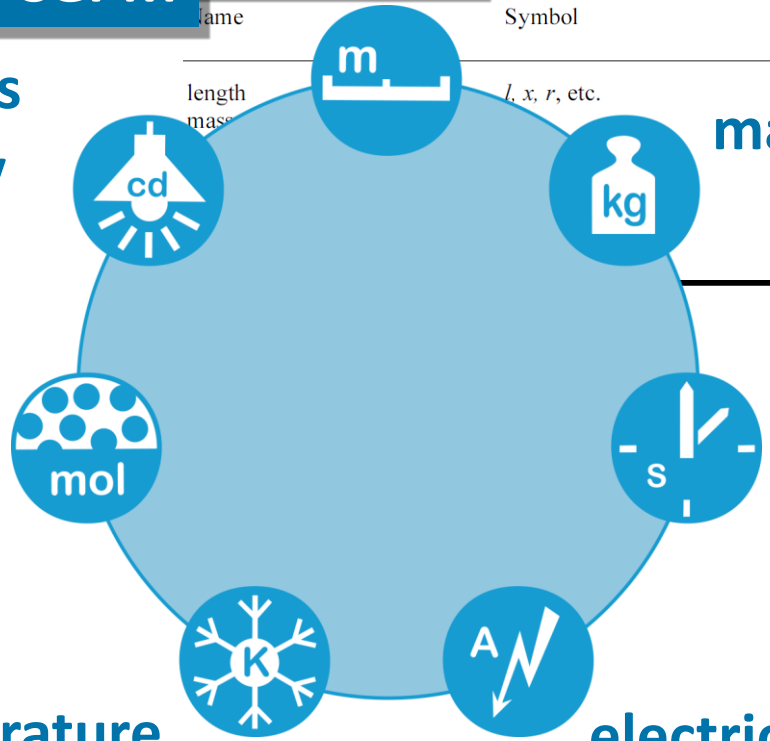
y

th		SI base un
Name	Symbol	Name
length	*l, x, r*, etc.	metre
mass		kilogram
		second
		ampere
		kelvin
		mole
		candela

	s
	A
	K
	mol
	cd

Le Système international d'unités
The International System of Units
SI

mass



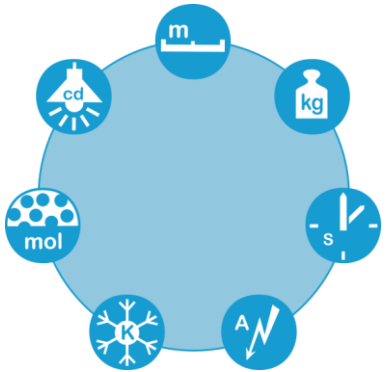
amount of substance

time

temperature

electric current

The International System of Units: SI



Base units

Derived units with special names

Dimensions of quantities

→ A set of coherent SI units

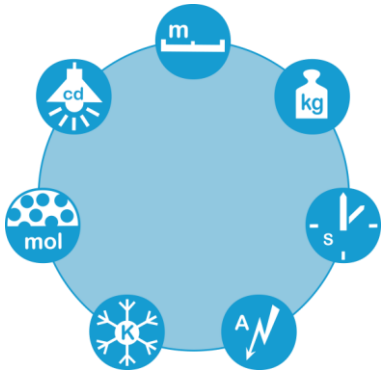
Derived units

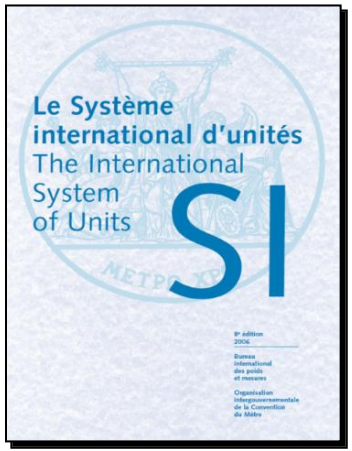
$[v] = \mathrm{m\,s^{-1}}$

$[c] = \mathrm{mol\,m^{-3}}$

		SI base unit	Expressed in terms of other SI units	Expressed in terms of SI base units
Name	Symbol	Name	Symbol	
				m/m
				m^2/m^2
				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	$m^{-2}\,kg^{-1}\,s^3\,A^2$
frequency	hertz [d]	Hz		s^{-1}
force	newton	N		$m\,kg\,s^{-2}$

The International System of Units: SI





Base units

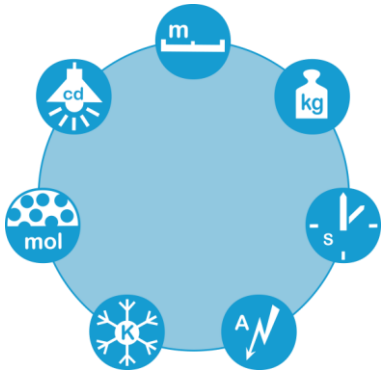
Derived units

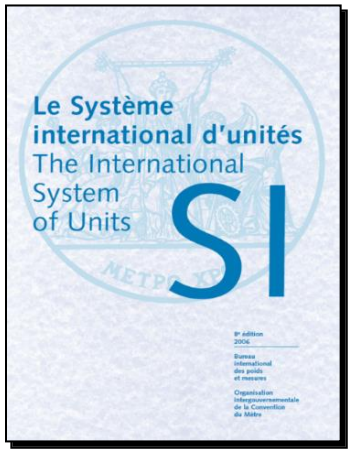
Dimensions of quantities

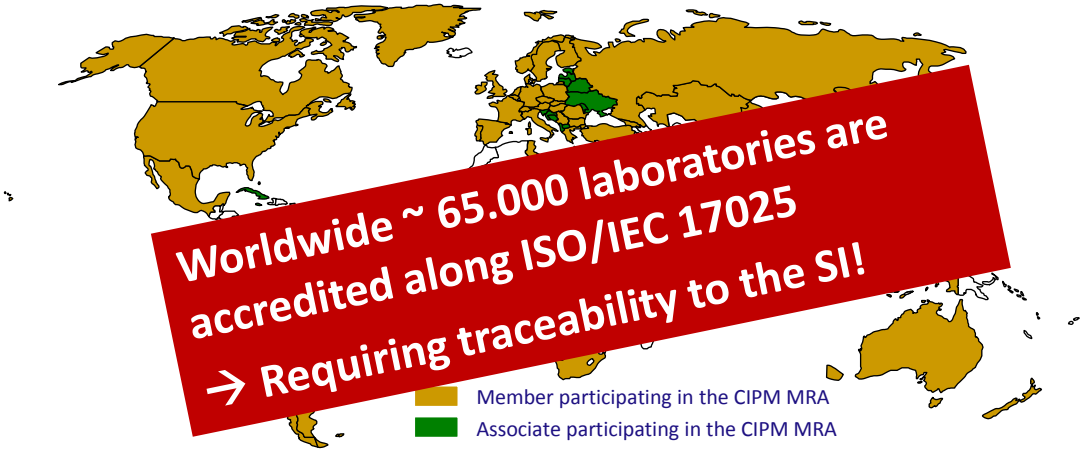
→ A set of coherent SI units

- **A global measurement infrastructure**
- **Validity of light from an LED**
  - **CO_2 concentration in the air**
  - **Creatinine concentration in blood serum**
  - **Dose equivalent outside nuclear reactors**
  - **….**

The International System of Units: SI







- A global measurement infrastructure
- Valid world wide: CIPM-MRA signed by
  - → 97.6 % of the world economy
  - → The cornerstone of international quality infrastructure (QI)

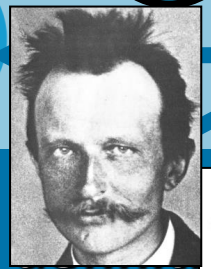
The International System of Units: SI

Redefinitions

- 1967: second
- 1983: metre
- 1990: ohm, volt

$$1\ \mathrm{m} = \frac{c}{299\,792\,458}\ \mathrm{s}$$

length c



2018: ~ 2×10^{-16}

time $\Delta\nu_{\mathrm{hfs}}$

$$1\ \mathrm{s} = \frac{9\,192\,631\,770}{\Delta\nu\,(^{133}\mathrm{Cs})_{\mathrm{hfs}}}$$

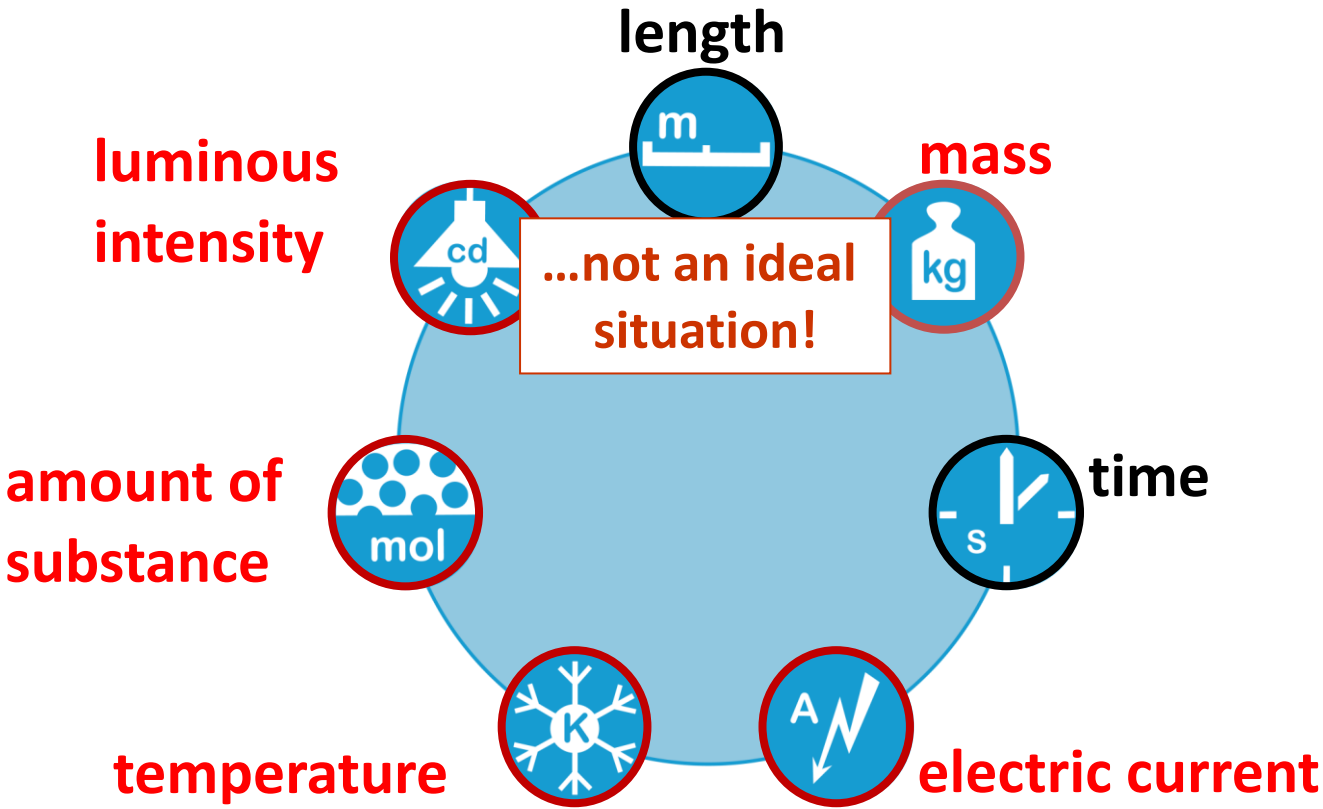
$$R_{\mathrm{K}} = \frac{h}{e^2} \approx 25\,813\ \Omega \ \Leftrightarrow\ R_{\mathrm{K-90}}$$

$$K_{\mathrm{J}} = \frac{2e}{h} \approx 483\,598\ GHz/V \ \Leftrightarrow\ K_{\mathrm{J-90}}$$

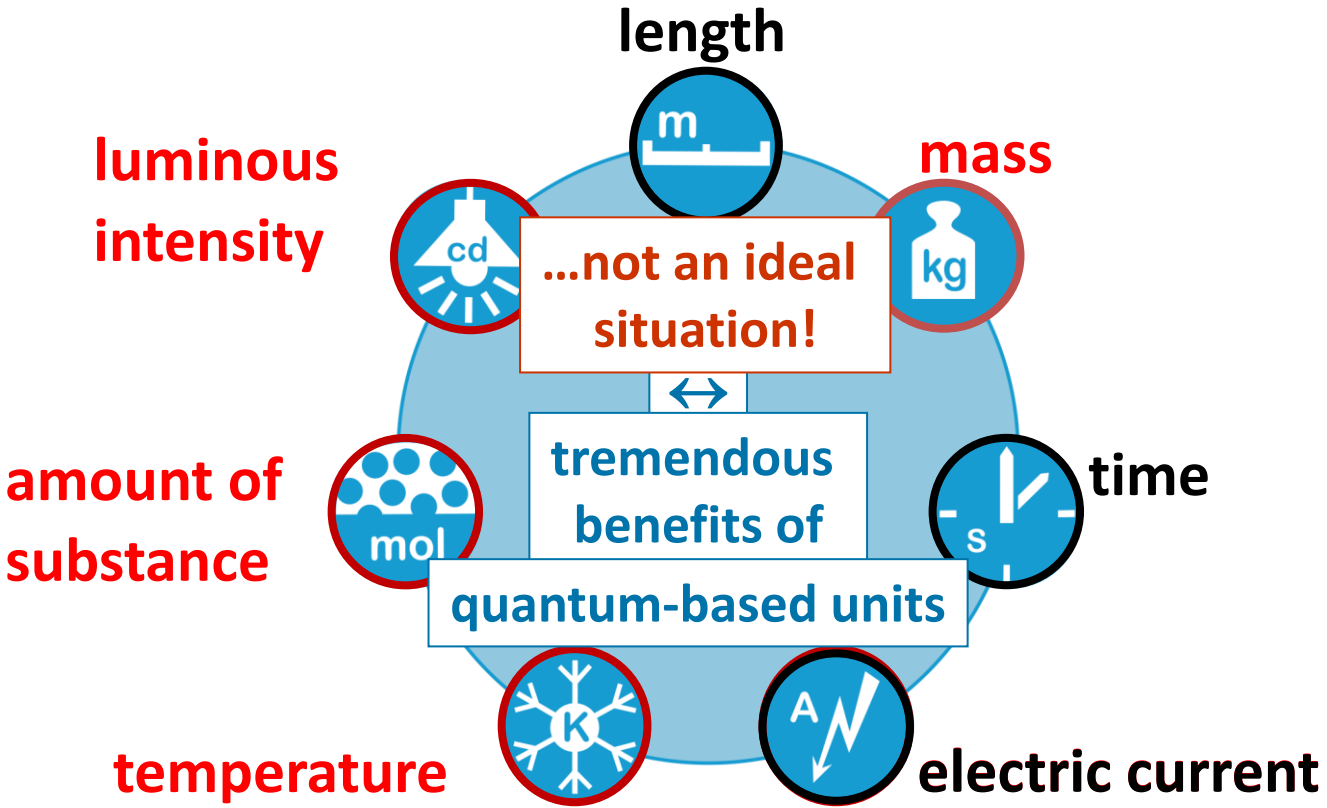
$R_{\mathrm{K}}, K_{\mathrm{J}}$

electric current

The International System of Units: SI

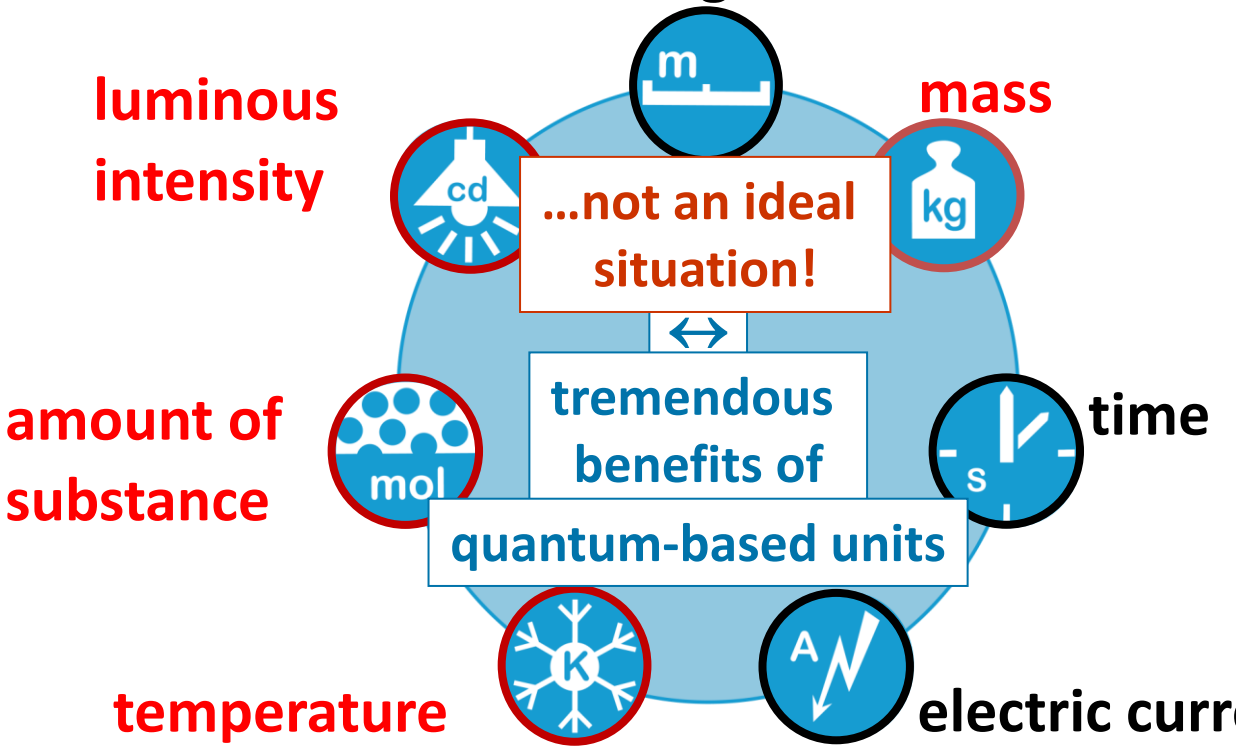


The International System of Units: SI



The International System of Units: SI

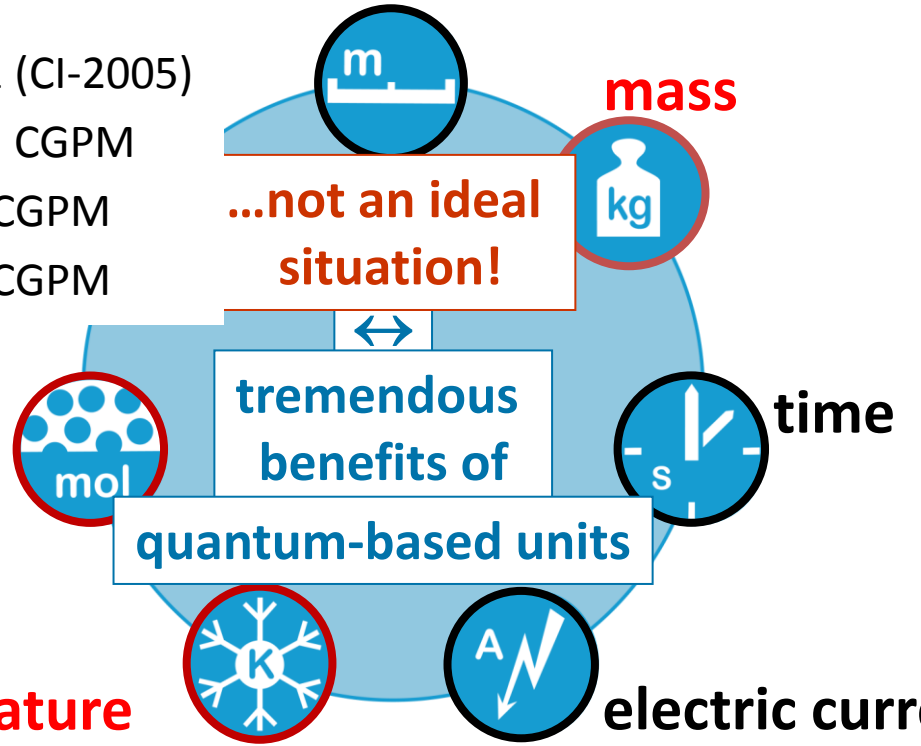
Build a coherent and consistent quantum-based system of units



The International System of Units: SI

Build a coherent and consistent quantum-based system of units

- CIPM Recommendation 1 (CI-2005)
- Resolution 12 of the 23rd CGPM
- Resolution 1 of the 24th CGPM
- Resolution 1 of the 25th CGPM



The International System of Units: SI

Build a coherent and consistent quantum-based system of units

- CIPM Recommendation 1 (CI-2005)
- Resolution 12 of the 23rd CGPM
- Resolution 1 of the 24th CGPM
- Resolution 1 of the 25th CGPM

→ **Resolution 1 of the 26th CGPM**

→ **13 years and 7 CCU meetings!**

Publications

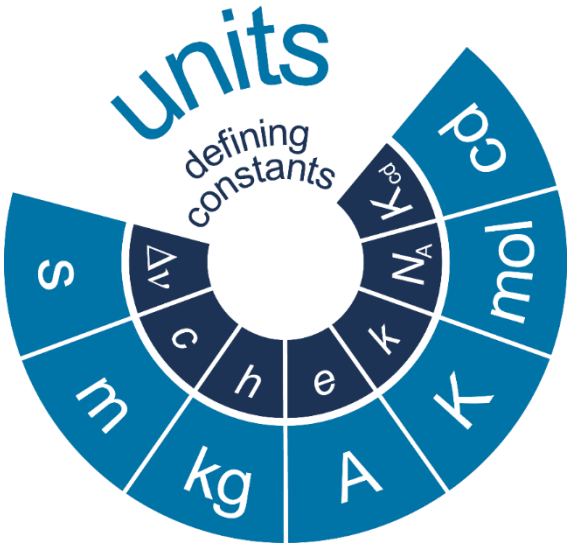
Redefinition of the kilogram: a decision whose time has come, Metrologia 42, 71 (2005).

and

Redefinition of the kilogram, ampere, kelvin and mole: a proposed approach to implementing CIPM recommendation 1 (CI-2005), Metrologia 43, 227 (2006).

Ian M Mills
Peter J Mohr
Terry Quinn
Barry N Taylor
Edwin M Williams

Defining Constants



Hyperfine transition ^{133}Cs	$\Delta\nu$
Speed of Light	c
Planck constant	h
Elementary charge	e
Boltzmann constant	k
Avogadro constant	N_A
Luminous Efficacy	K_{cd}

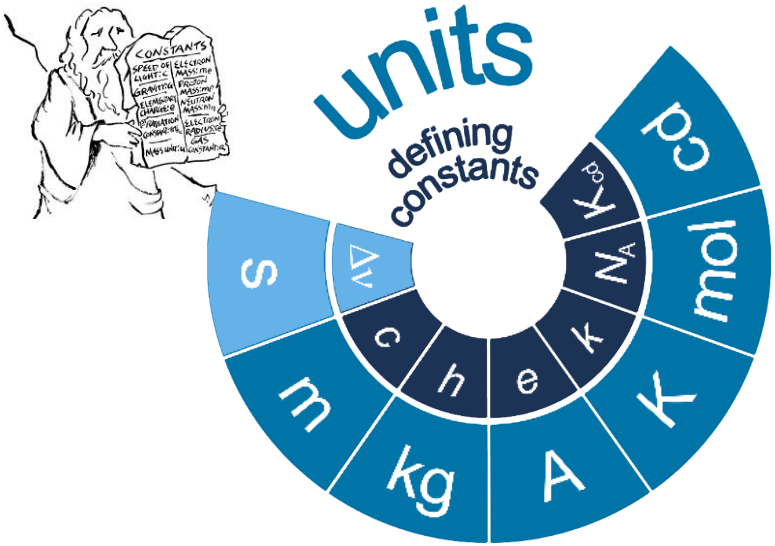
In the ‚old' SI:
Define the units → Measure the constants in nature (uncertainty)

...for all times and cultures

Now in the revised SI:
Fix numerical values of defining constants -> Determine the units

...throughout the universe

Defining Constants Creating the Units

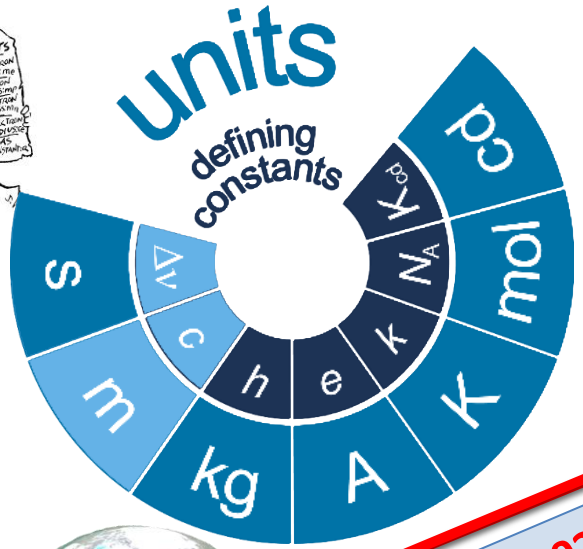


Relative uncertainty: $2 \cdot 10^{-16}$

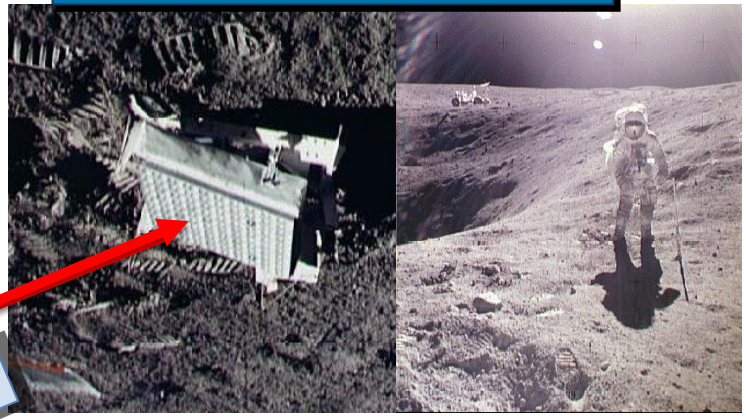
(1 second in 160 million years)

…for GPS, science,…

Defining Constants Creating the Units



c = 299 792 458 m/s

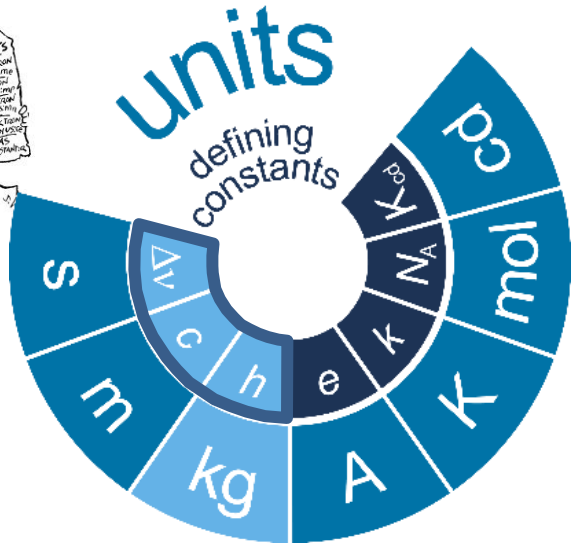


Apollo-11-Crew, 1969

d = 384 402, … km

$2t$ = 2,56 … s → $d = c \cdot t$

Defining Constants Creating the Units

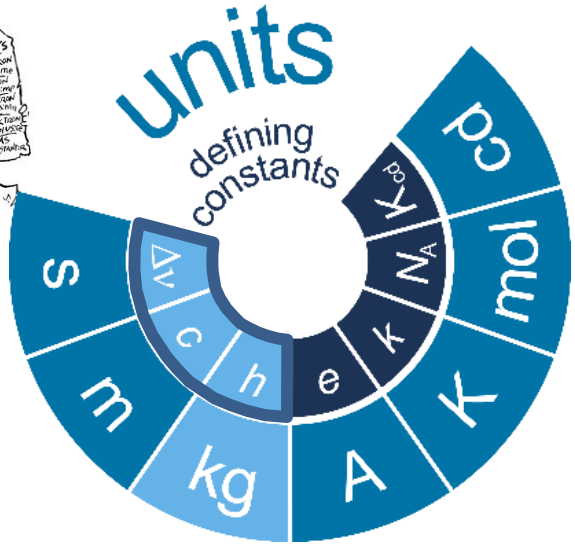


$$m = n_A \cdot m_e(h,c,\Delta\nu_{Cs}) \cdot m_A/m_e$$

Quantum mechanics with the Planck constant gives mass to the atoms

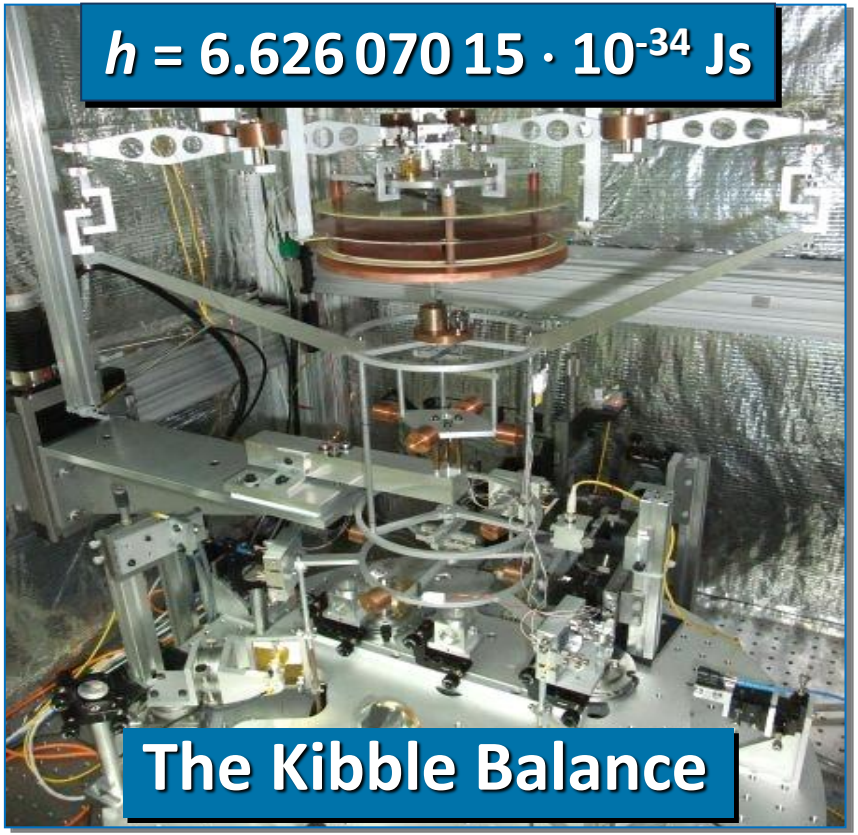
The Silicon Route

Defining Constants Creating the Units

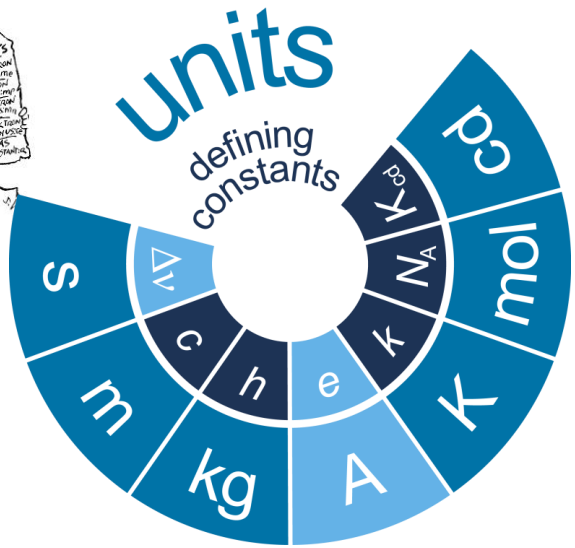


$$m \cdot g \cdot v = h \cdot K_J^2 \cdot R_K / 4$$

Balance weight with electromagnetic force

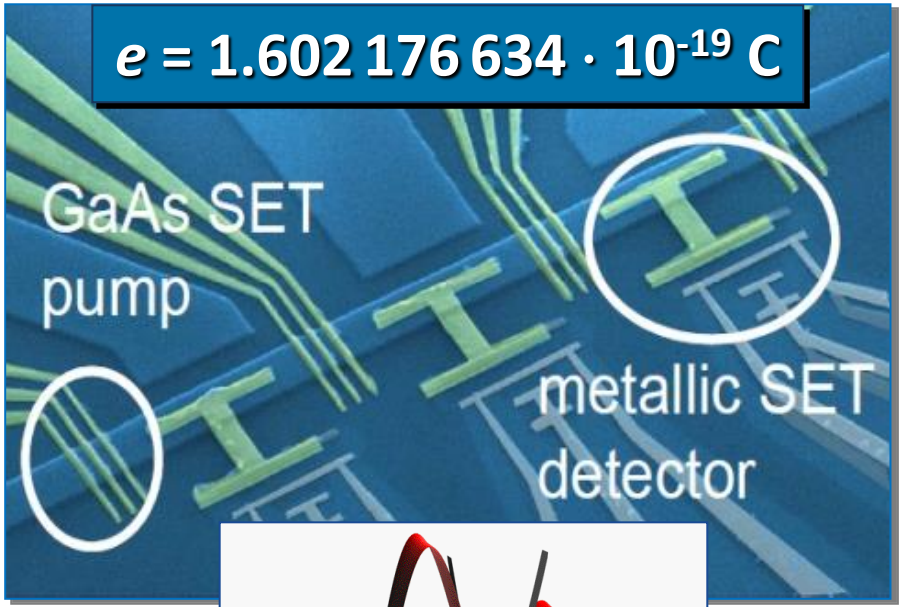


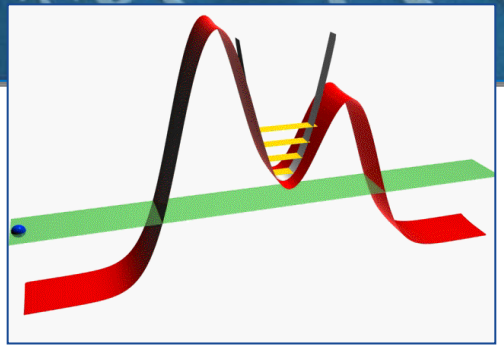
Defining Constants Creating the Units



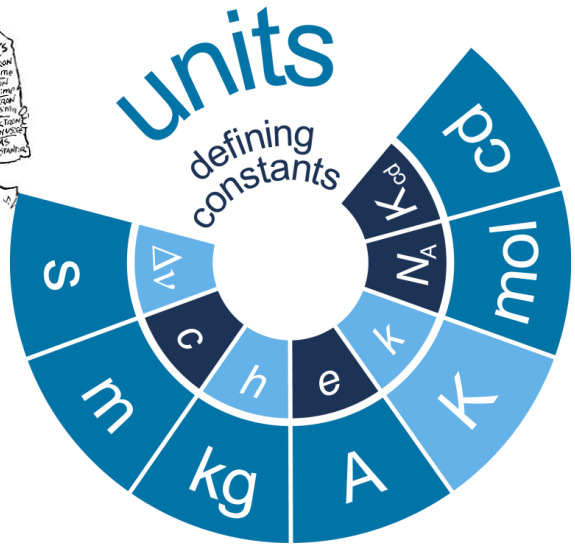
$$I = \langle n \rangle \cdot e \cdot f$$

Count the flow of electrons in a second





Defining Constants Creating the Units

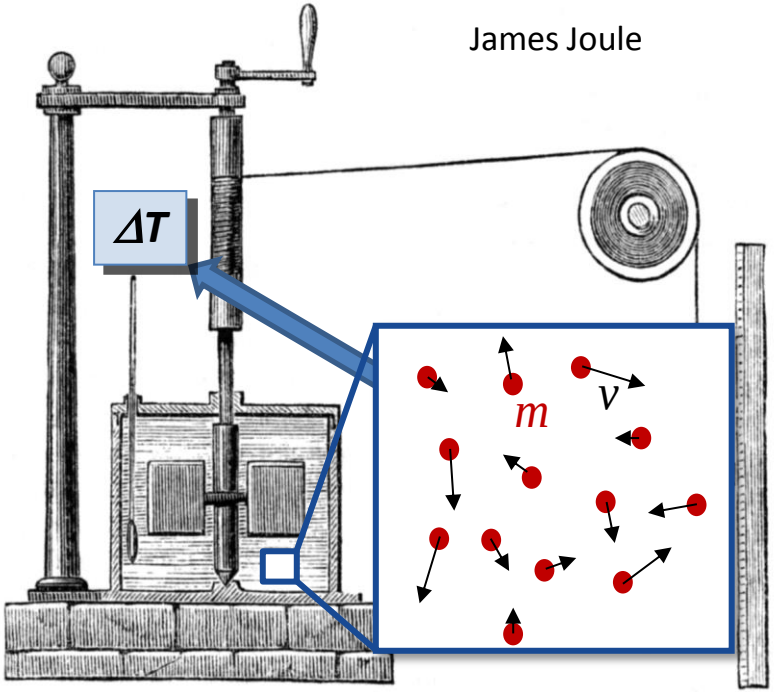


$$\overline{E}_{kin} = (½)m\cdot\overline{v}^2 = (\tfrac{3}{2})\cdot k\cdot T$$

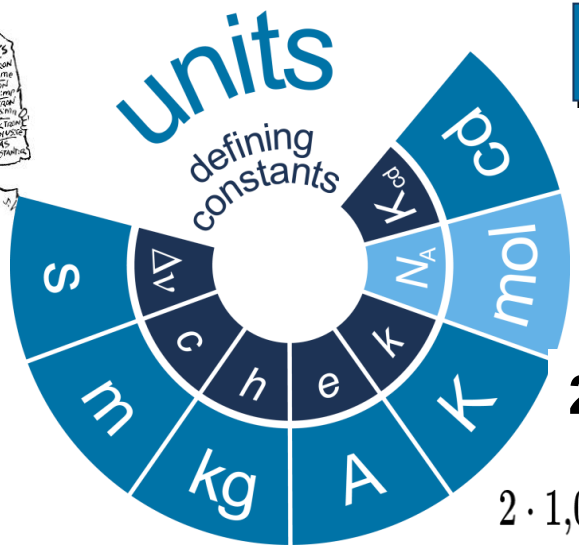
Energy is proportional to Temperature : ideal gas

$$k_B = 1.380\,649 \cdot 10^{-23}\ \text{J/K}$$

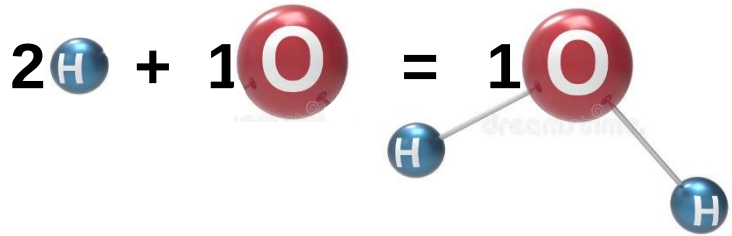
James Joule



Defining Constants Creating the Units



$N_A = 6.022\,140\,76 \cdot 10^{23}\ /\text{mol}$



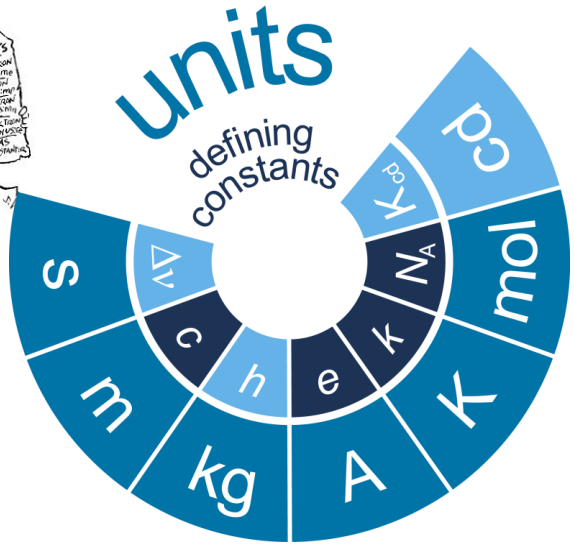
$2N_A m_H + N_A m_O = N_A m_{H_2O}$

$$2 \cdot 1{,}00794\ \frac{\text{g}}{\text{mol}} + 15{,}9994\ \frac{\text{g}}{\text{mol}} = 18{,}01528\ \frac{\text{g}}{\text{mol}}$$

If you take N_A entities (atoms, molecules) you get 1 mol

Multiply with the atomic/molecular masses: molar mass

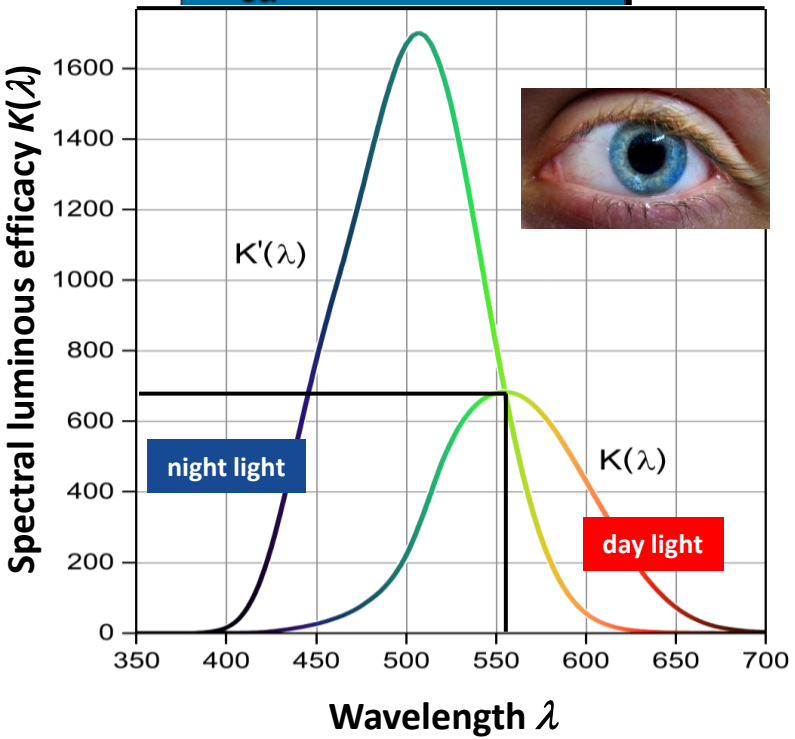
Defining Constants Creating the Units



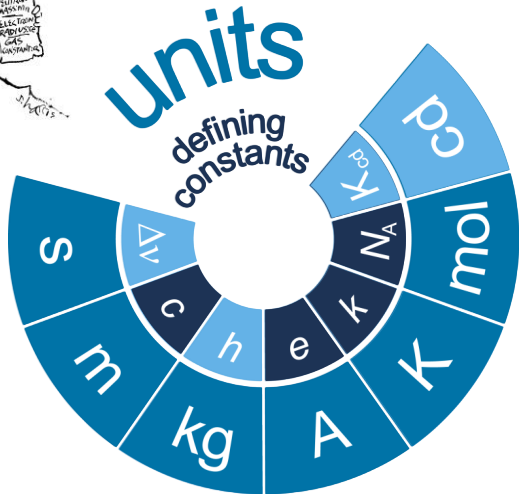
$K(\lambda) = K_{cd} \cdot V(\lambda)$

"K_{cd} brings humanity into metrology"

K_{cd} = 683 lm/W



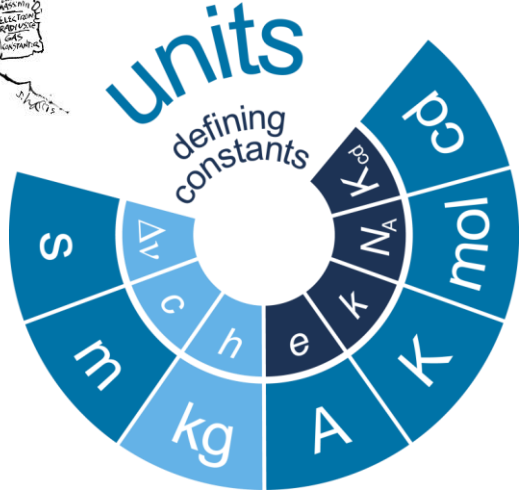
Revised International System of Units



A concept improved fundamentally!

- **Guarantees long-time stability**
- **A set of "defining constants" establish the units in general**

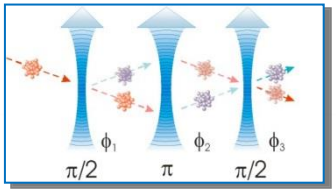
Revised International System of Units



A concept improved fundamentally!

- Guarantees long-time stability
- A set of "defining constants" establish the units in general
- Different realisations
- Realisation everywhere (Universe…)
  - Key comparisons: safer, less correlations
  - Atomic masses

"De Broglie"

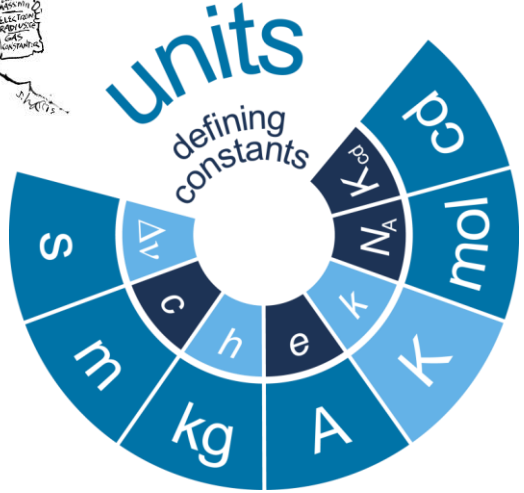


"Photon recoil"

"Silicon crystal"

"Kibble balance"

Revised International System of Units

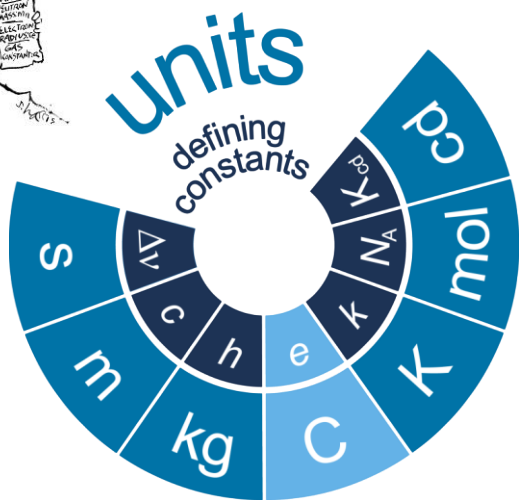


$$E = \frac{1}{2} k \ T$$

A concept improved fundamentally!

- **Guarantees long-time stability**
- **A set of "defining constants" establish the units in general**
- **Different realisations**
- **Realisation everywhere (Universe…)**
- **Often throughout the entire scale**
  - **Acoustic gas thermometry**
  - **Dielectric constant gas thermometry**
  - **Doppler thermometry**
  - **Noise thermometry**
  - **Radiation thermometry**

Revised International System of Units



$$R_K = \frac{h}{e^2} \approx 25\,813\ \Omega \Leftrightarrow R_{K-90}$$

$$K_J = \frac{2e}{h} \approx 483\,598\ GHz/V \Leftrightarrow K_{J-90}$$

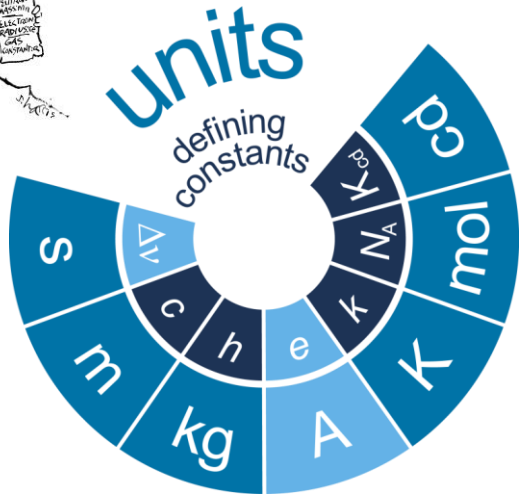
A concept improved fundamentally!

- Guarantees long-time stability
- A set of "defining constants" establish the units in general
- Different realisations
- Realisation everywhere (Universe…)
- Often throughout the entire scale
- Base units are only a convention

Direct realisation of

- the ohm
- the volt
- the ampere
- the coulomb

Revised International System of Units



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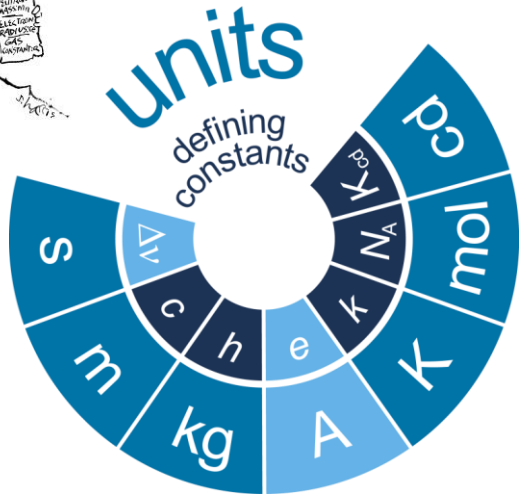
- Different realisations
- Realisation everywhere (Universe…)
- Often throughout the entire scale
- Base units are only a convention
- Electric units are "back in the SI"
- Consistency can be ensured
  - Si-kilogram ←→ Kibble balance
  - Quantum metrological triangle, …

Revised International System of Units

Tremendous benefits:



a “huge” change…

but “no” change!

A concept improved fundamentally!

- Guarantees long-time stability
- A set of “defining constants” establish the units in general
- Different realisations
- Realisation everywhere (Universe…)
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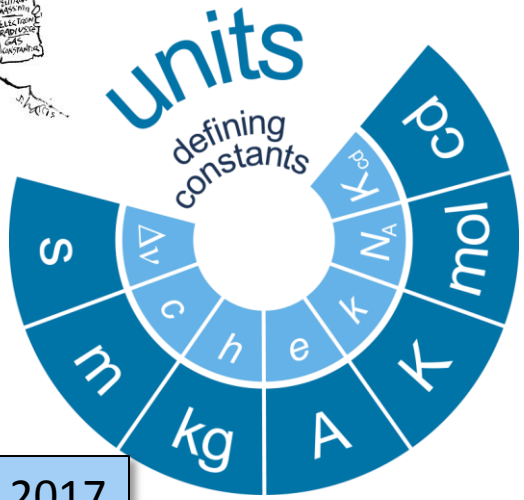
- Better experiment → better realization

Ensure continuity, harmonization, stability

Revised International System of Units

Establish the constants

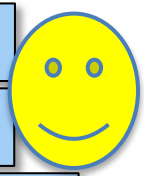


CODATA 2017

$u_{rel}(e) = 5.2 \times 10^{-9}$

$u_{rel}(k) = 3.7 \times 10^{-7}$

$u_{rel}(h,N_A) = 1.0 \times 10^{-8}$



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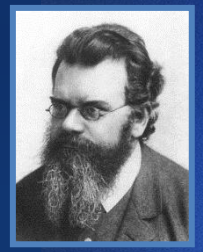
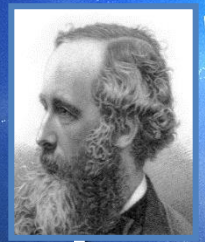
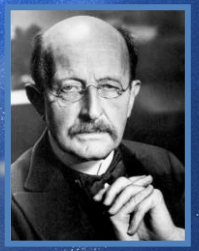
From Artefacts to the Quantum SI

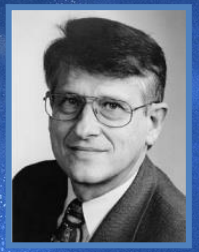
SI International System of Units

→ Please see the poster!









to underpin

…the 2nd Quantum revolution…

…innovation in science & industry

SI International System of Units

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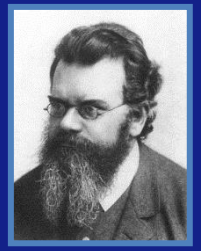

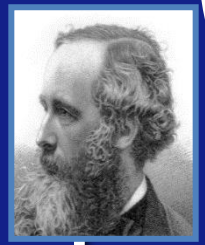
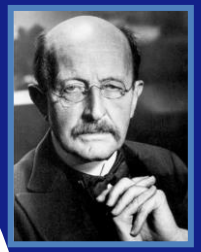

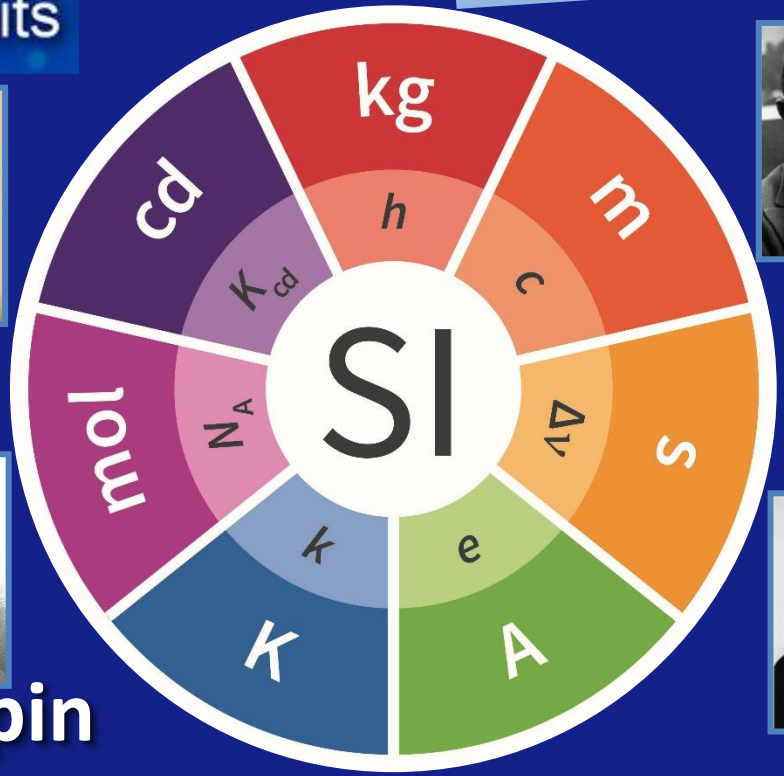

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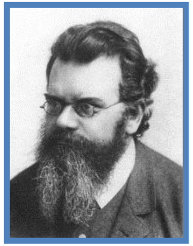

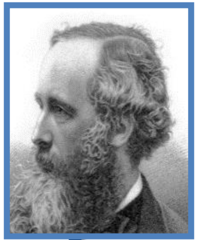

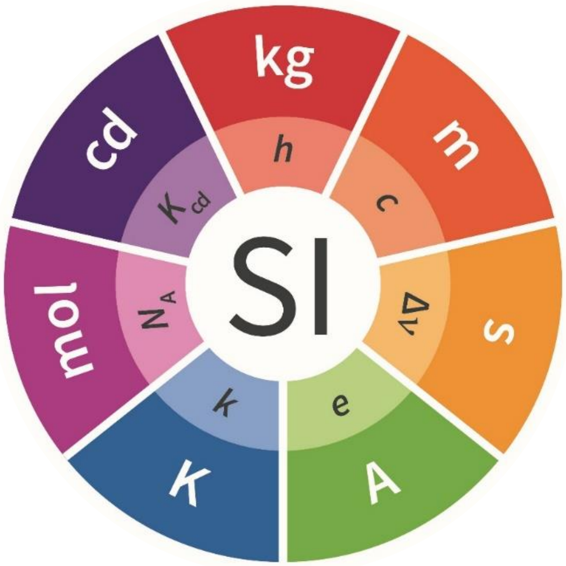

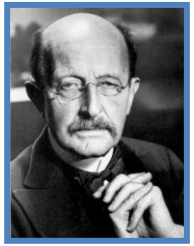

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