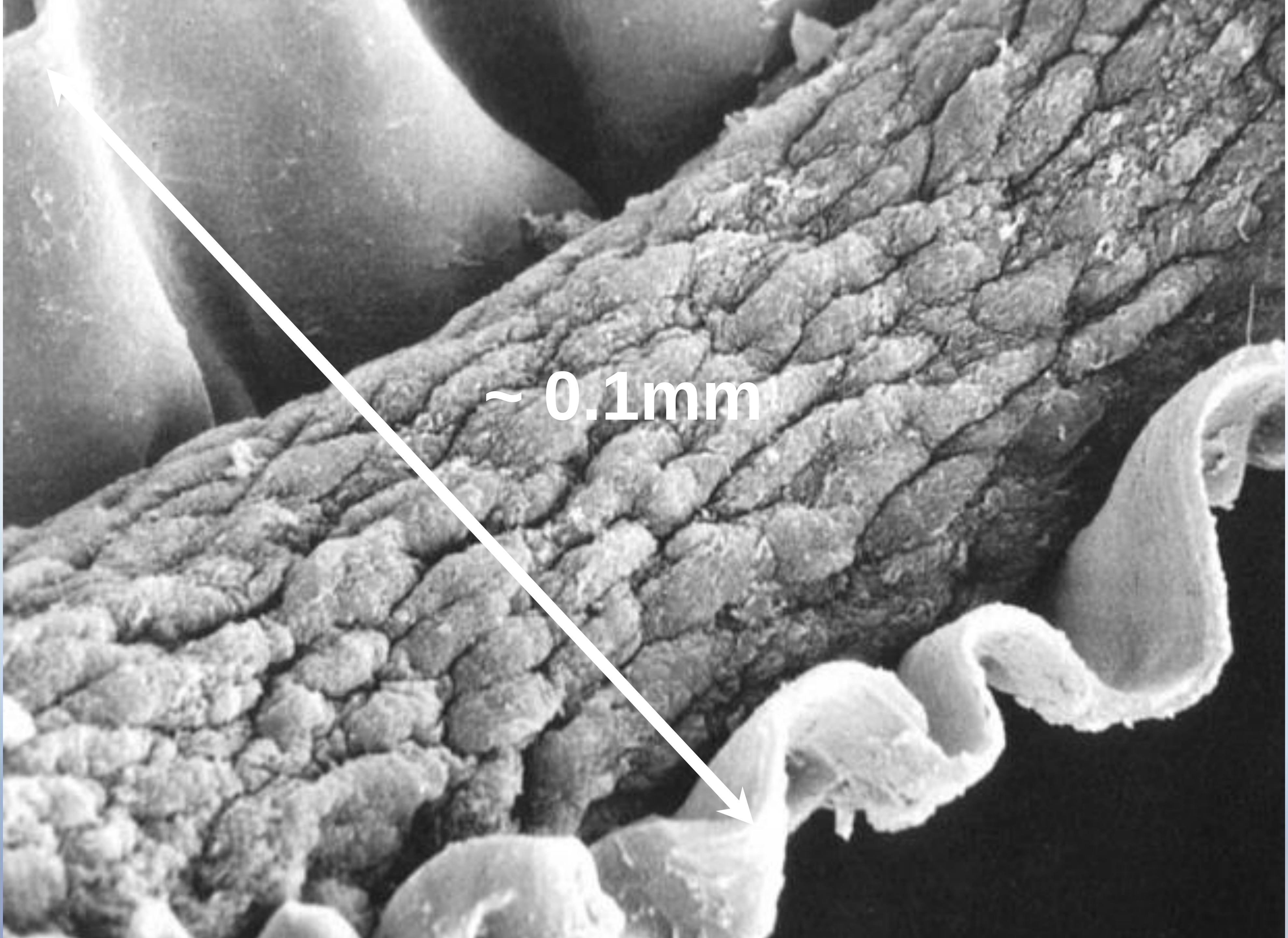
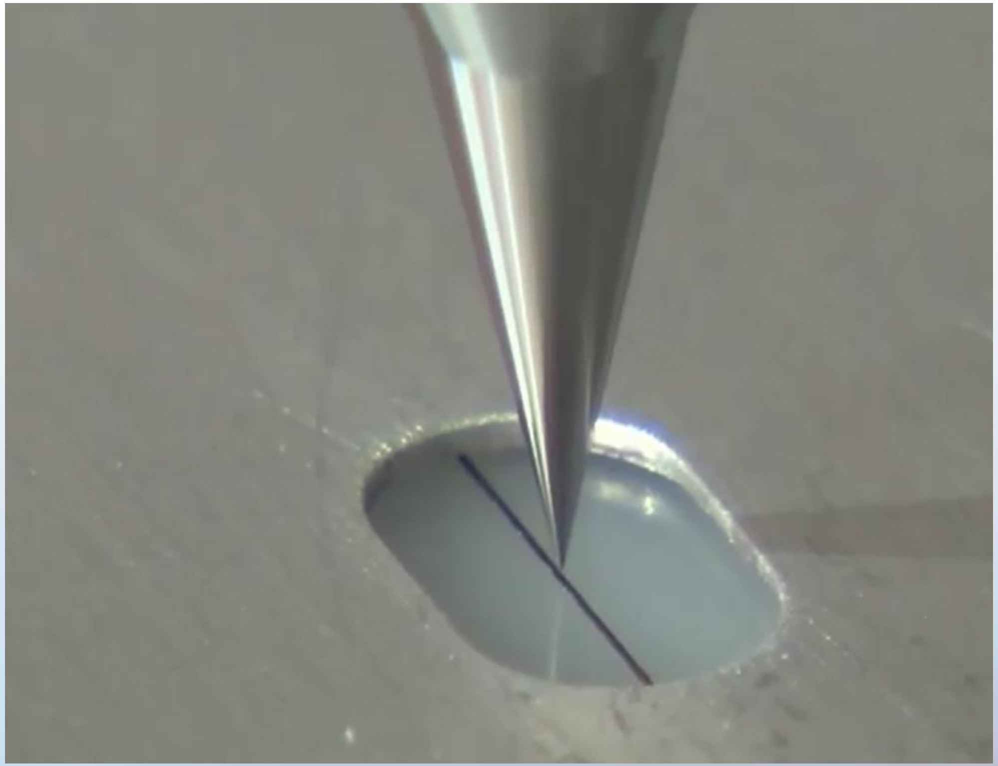
Introduction to Metrology

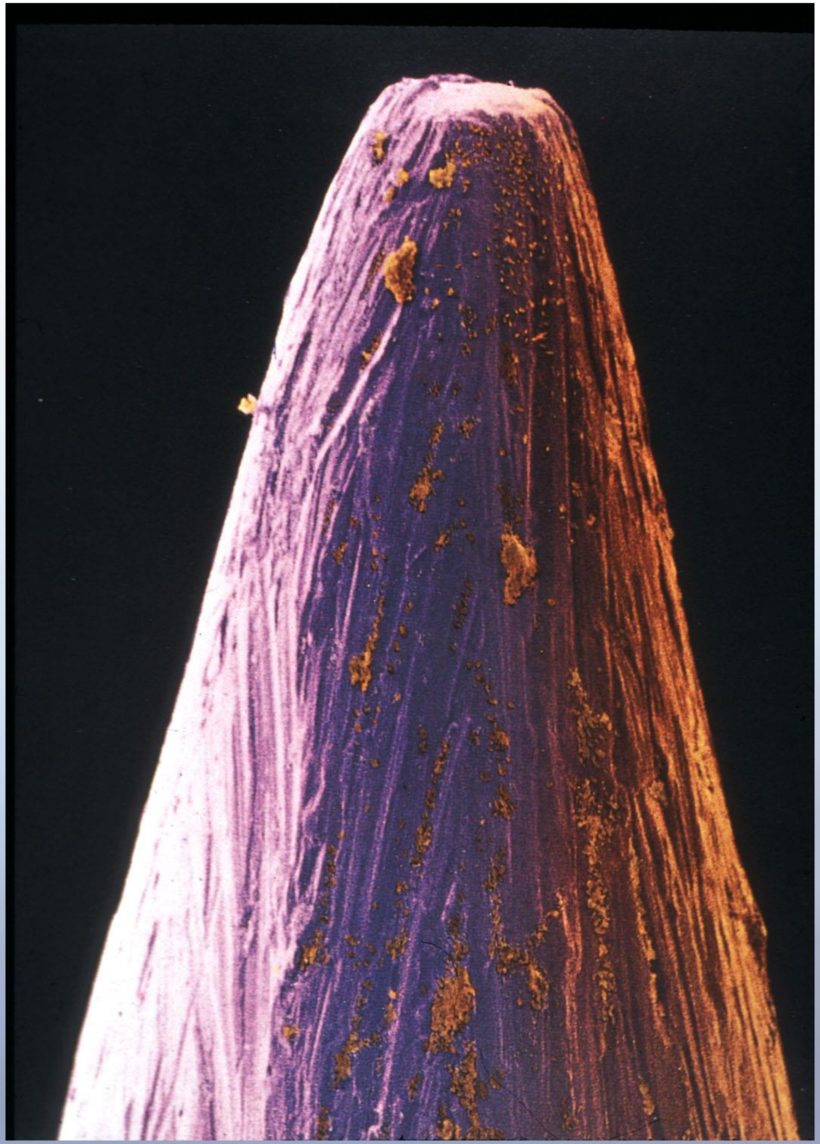
Paul Shore

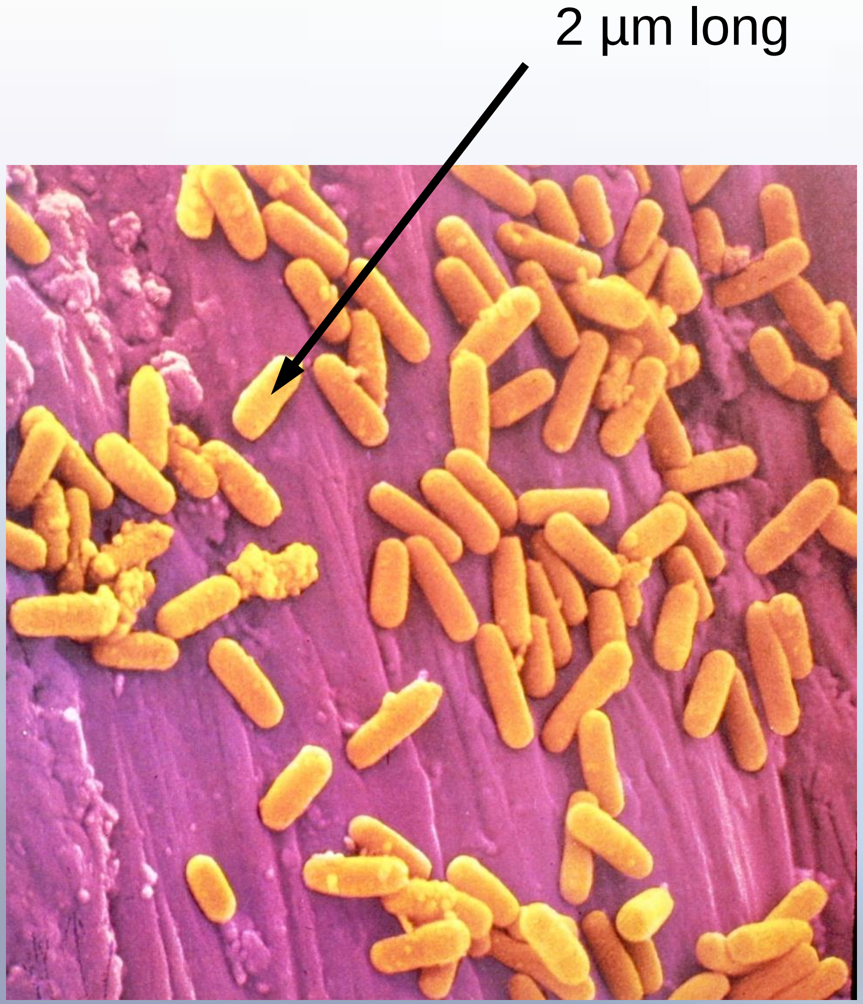
Previous roles
Head of Engineering, NPL, London ~ 7 years
Professor Precision Engineering, Cranfield, UK ~ 12 years
Head of Precision Technologies, SKF, Sweden ~ 7 years

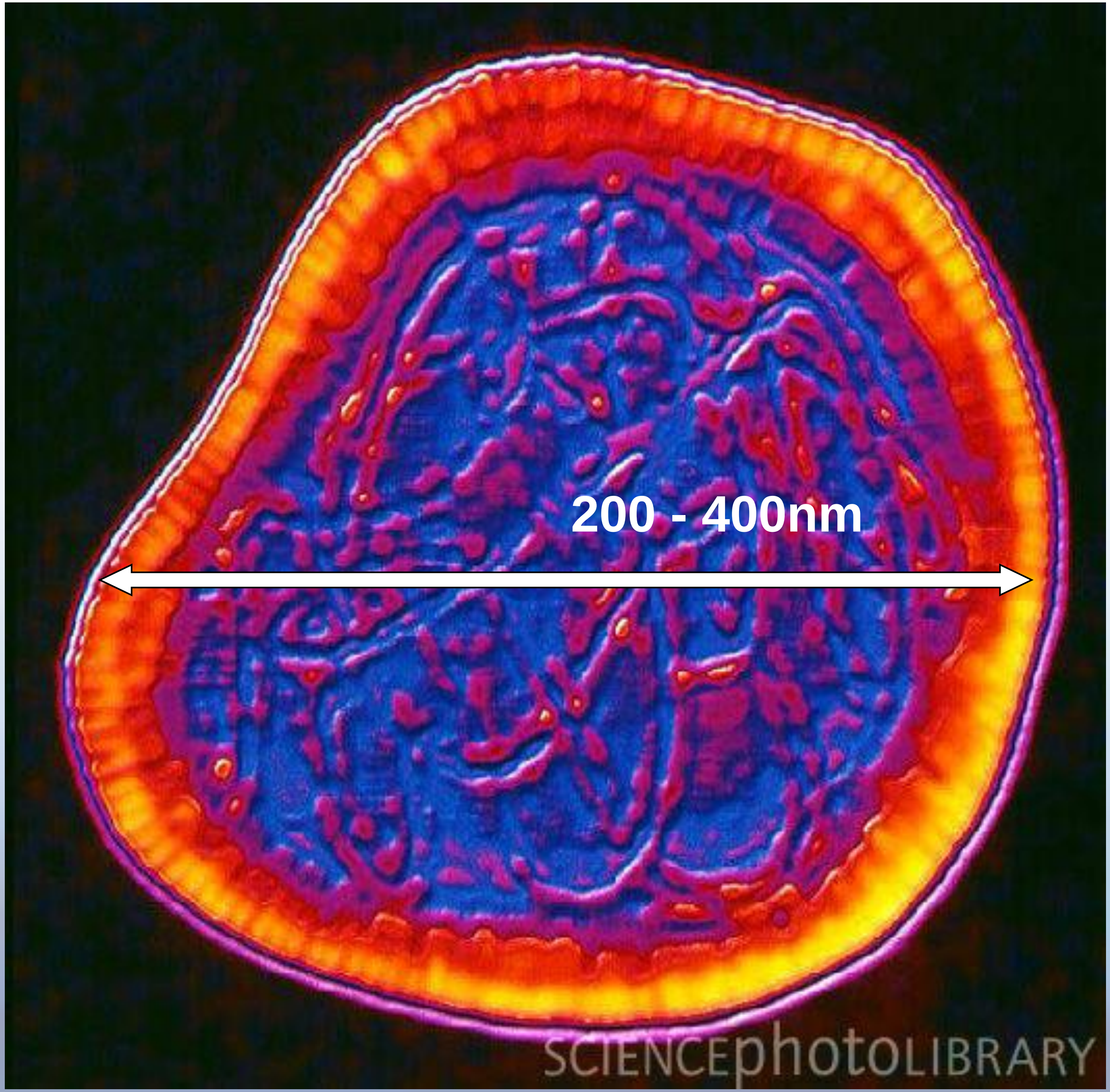

~ 0.1mm



Ref; NS Tool, Japan, 2023

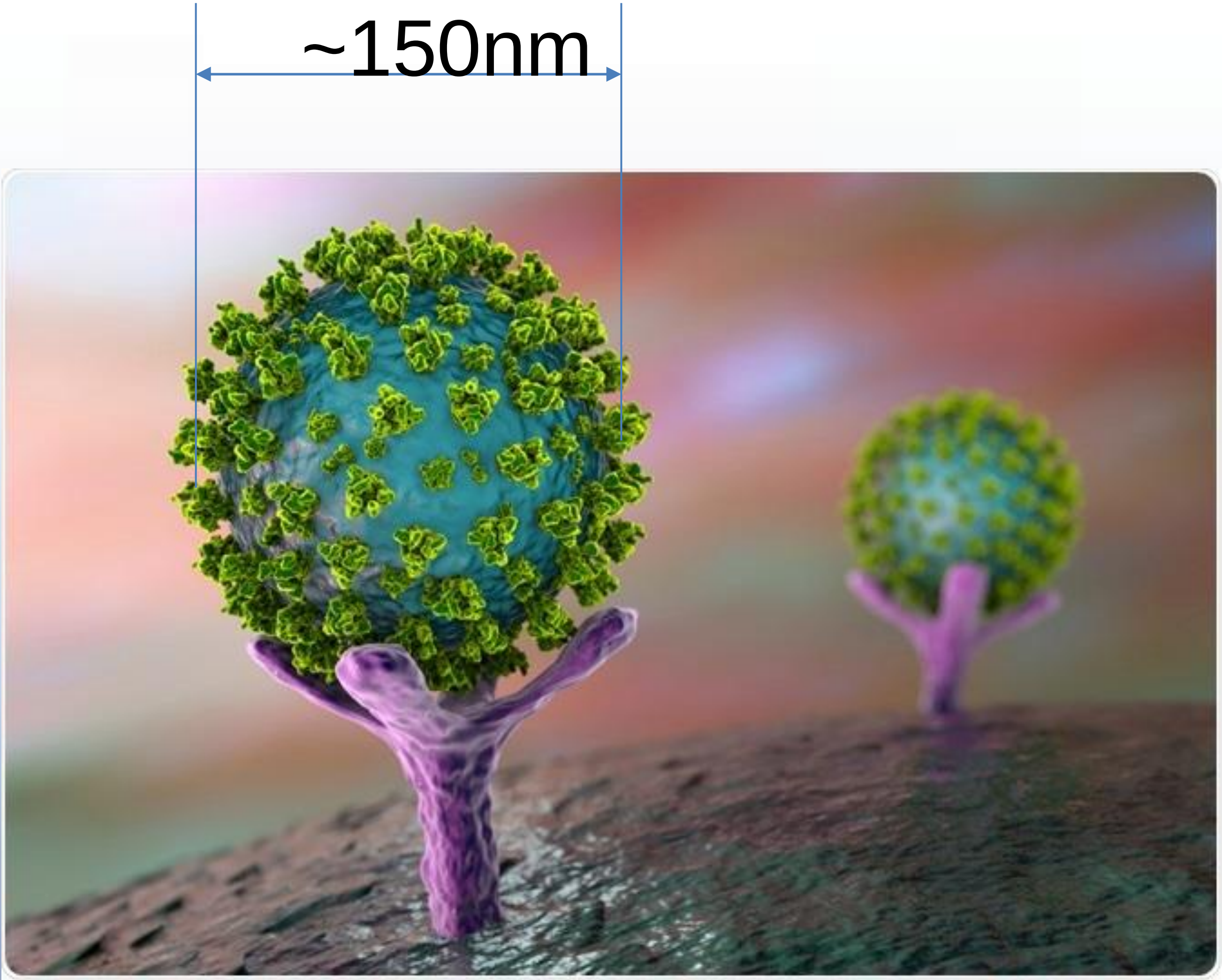


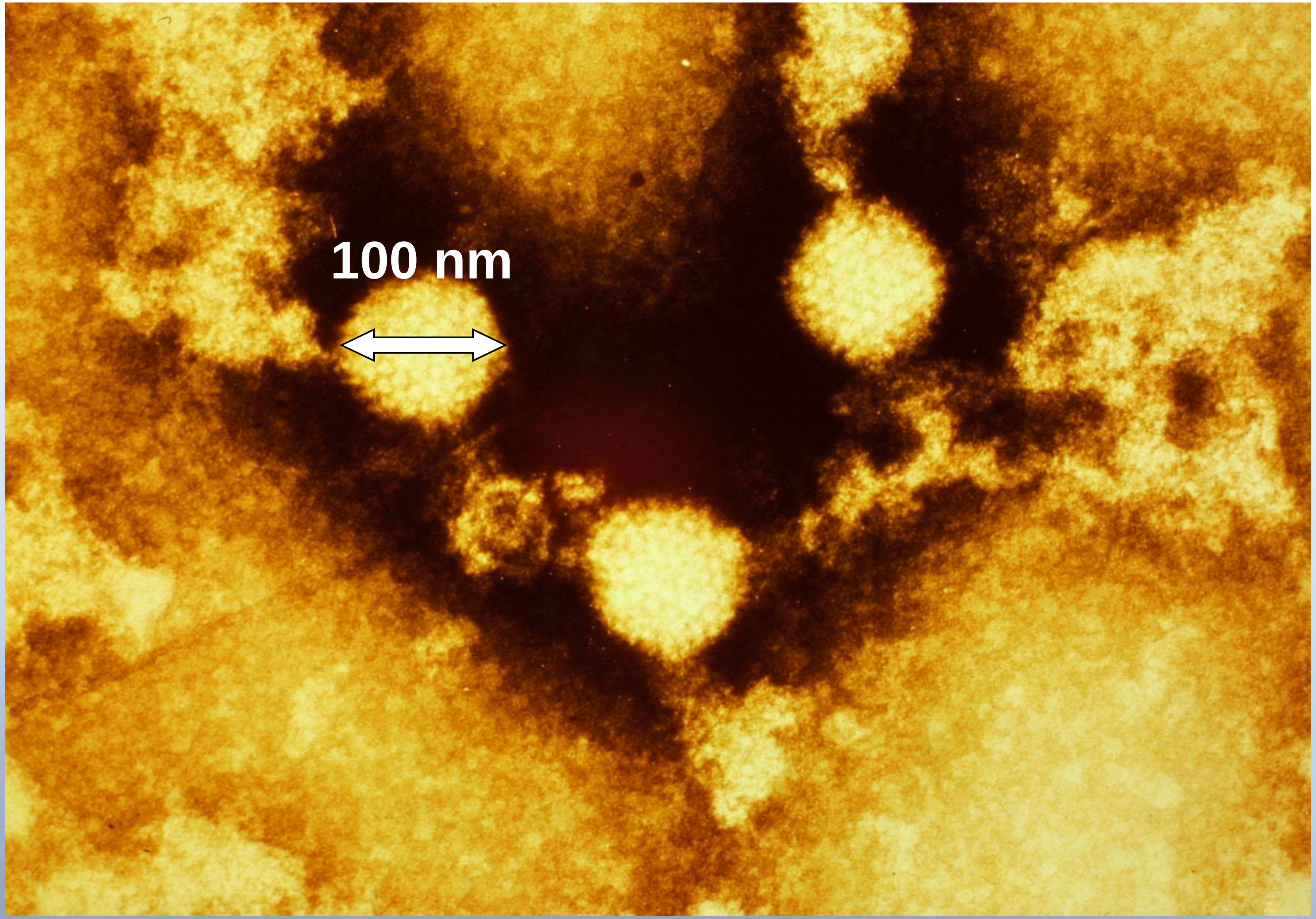

2 µm long


200 - 400nm
SCIENCEphotoLIBRARY

Credit: Kateryna Kon/Shutterstock.com

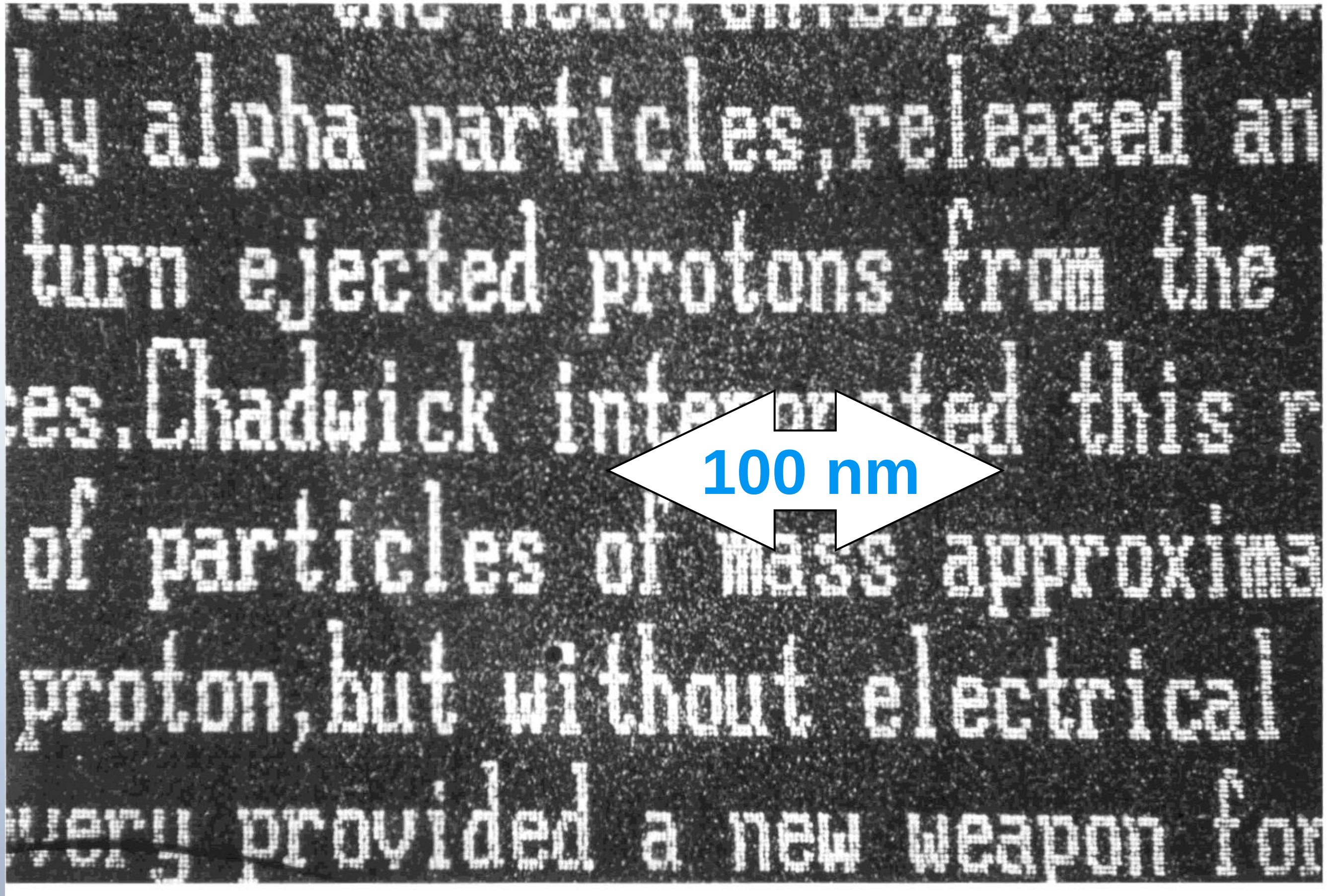
LOXHAM PRECISION




100 nm

Electron beam writing

Encyclopaedia Britannica on the head of a pin



Each letter is made of holes approximately 4nm diameter

C. Humpheys, 1992, Cambridge University

Nanotechnology "first concepts"

"There's plenty of room at the bottom"

- an invitation to enter a new field of physics

by Richard P Feynman

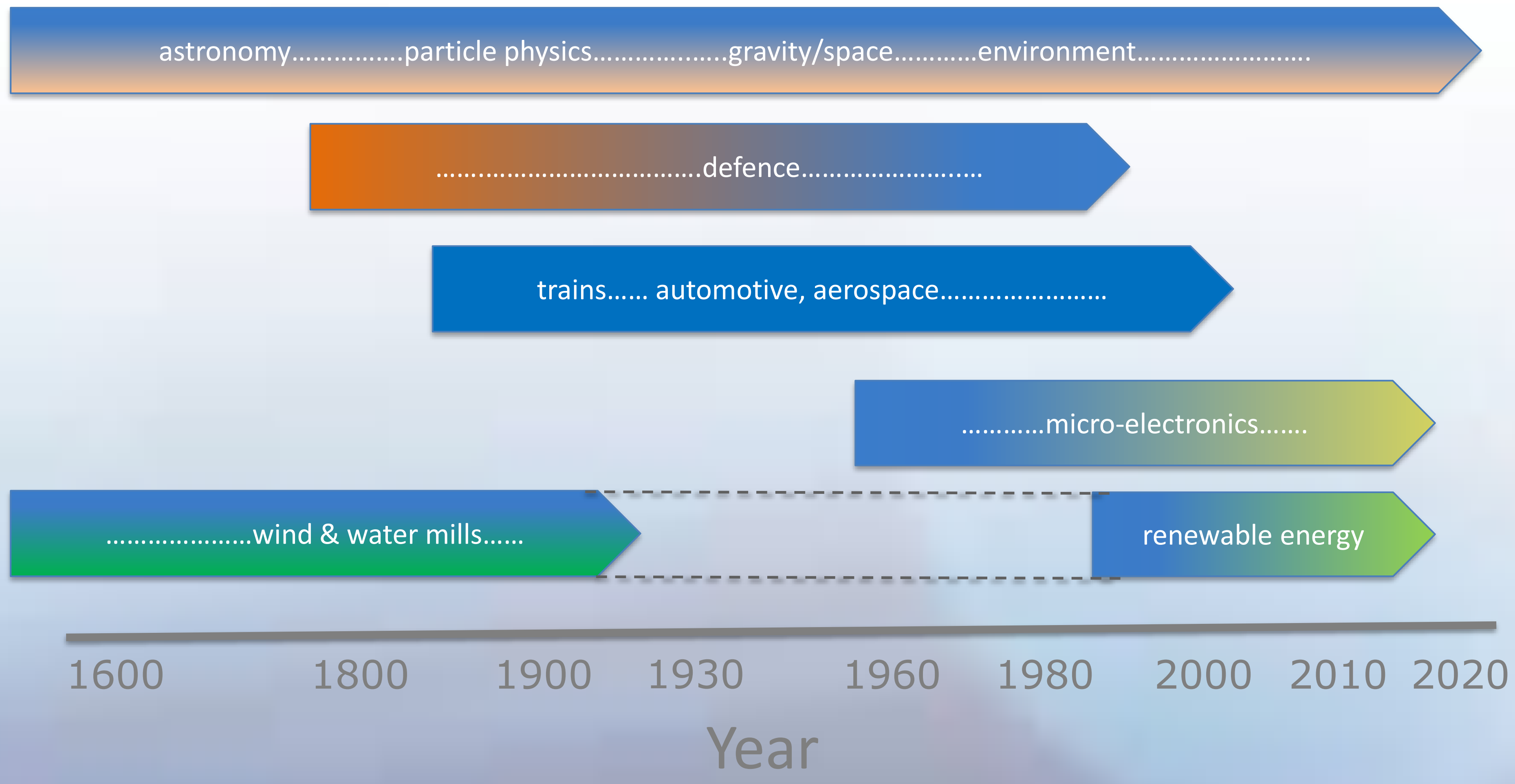
Talk given on the 20th December 1959 at annual meeting of the American Physical Society. Published in the February 1960 issue of Caltech's Engineering and Science Journal.

Discussed:

- Nanometre scale information storage by electron writing
- Integrated circuits for computing
- Machines for manipulation of atoms and molecules

http://www.nobel.se/physics/laureates/1965/feynman-bio.html

Drivers of manufacturing accuracy capability



Ref, Shore, Morantz, Phil. Trans. Royal Society 2011

This talk is based on knowledge and information
I was fortunate to obtain during from my time at the
UK's national measurement institute,
National Physical Laboratory.

Acknowledgements to Prof. Richard Brown, Head of Metrology
and Michael de Podesta, previous Principal Scientist, NPL

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UNIVERSITY OF SURREY

The Measure of All Things

Prof Richard Brown

Head of Metrology

National Physical Laboratory

Content

- Why accurate measurement matters
- How measurements are expressed
- Where our current measurement system came from
- How international agreement on units was achieved
- How our measurement system has evolved
  (& might change in future)

Measurement is ubiquitous, often unnoticed, but makes everything function

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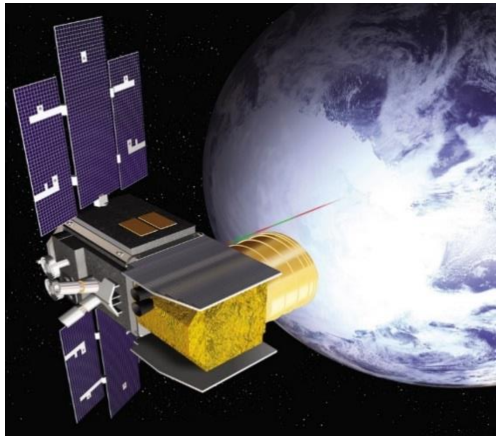






The language of measurement

Length of the table = 2 m

thing being measured

a number

a unit

Early unit 'standards'

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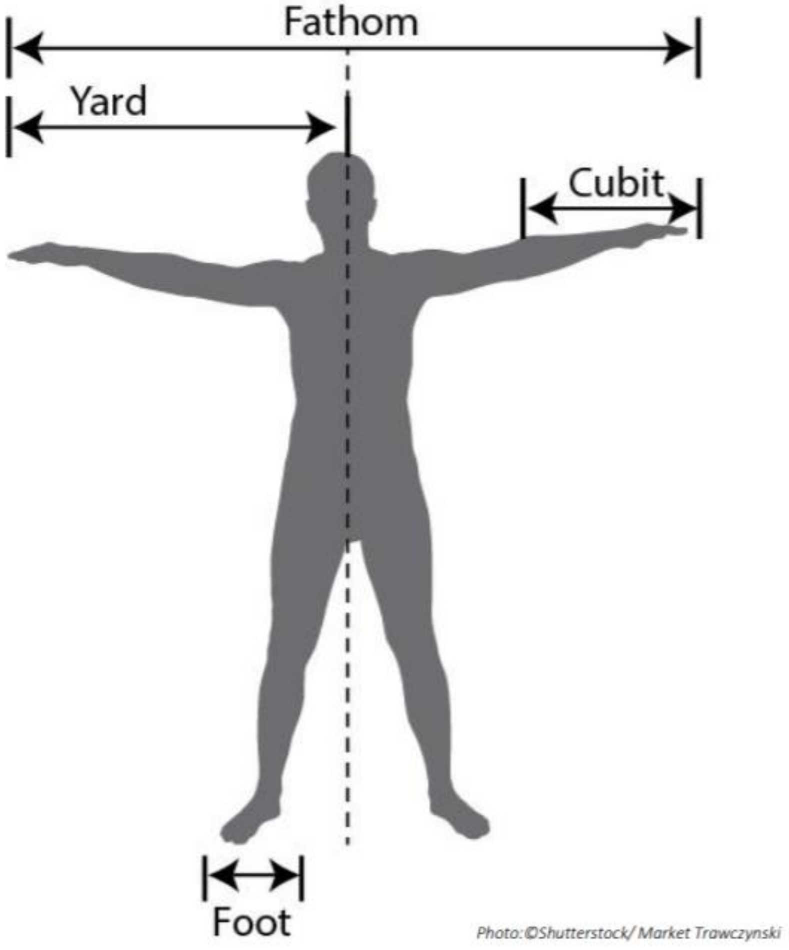
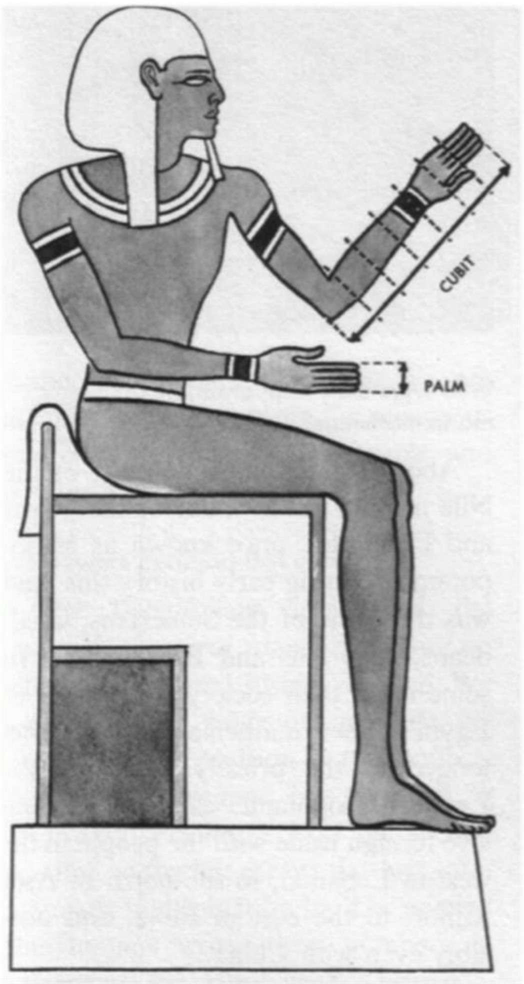


Convenient



Comparable

Convenient & comparable
…but not universal

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International agreement on units was needed

Key messages 1

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- All of science, technology, engineering, medicine, indeed all of life, relies on measurement
- It is accurate measurement that enables progress in science and society
- The system of measurement units and quantities we now rely on goes almost unnoticed – because it works so well
- This wasn't always the case – up until 150 years ago there was no agreement on the units we should use for measurement

How did we get to now?

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- After the French Revolution old units of measurement associated with the old regime were replaced by new units
- The meridional definition of the metre was soon embodied by a metre bar, 'mètre des Archives', in 1799

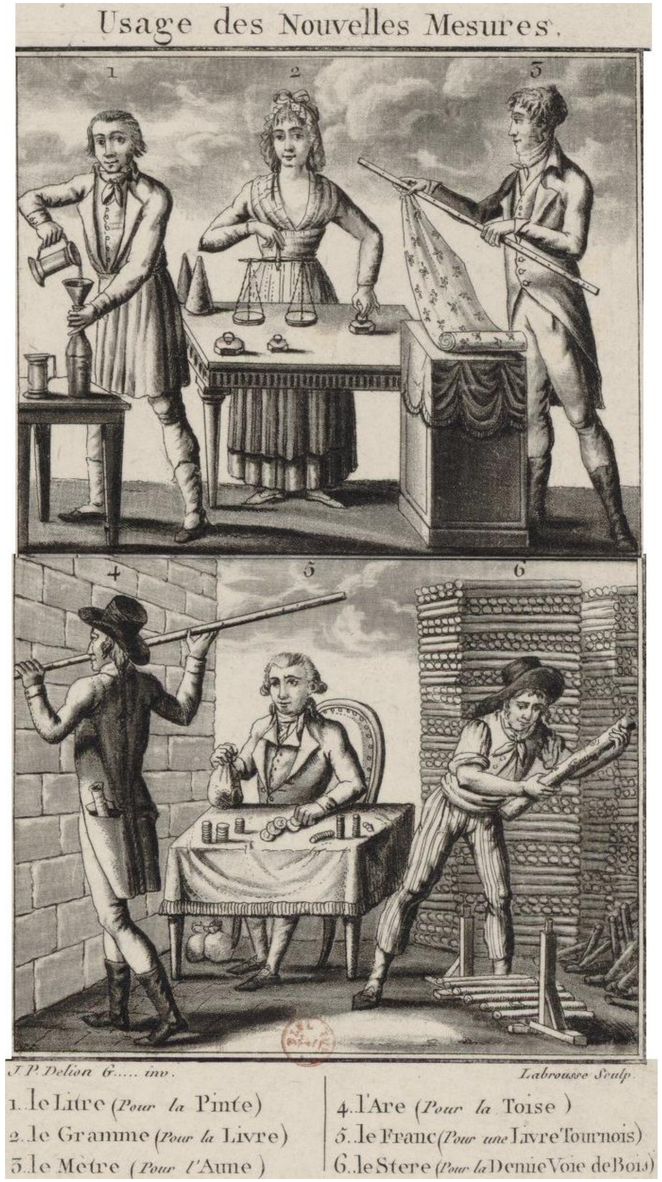
Prise du palais des Tuileries
Jean Duplessis-Bertaux, 1793

- The kilogram, based on the mass of water having a volume of one litre or one thousandth of a cubic metre was embodied by the 'kilogramme des Archives', in 1799
- Placed in the custody of the French Academy of Sciences
- By 1812, due to the unpopularity of the new metric system, France had reverted to using units similar to those of their old system
- By 1837 the metric system was re-adopted by France, not least because of growing use by the international scientific community

In 1794/5 the French government used a decimal clock – an unpopular change! (*The Measure of All Things, Alder*)

How did we get to now – part 2?

- As more countries adopted this ‘metric’ system there was a danger of lack of comparability, or rival systems emerging
- Prompted by the growth of international trade, the second industrial revolution, and the need to unify geodesic measurement, 17 governments signed “the Metre Convention” in 1875
- This diplomatic treaty established a permanent organizational structure for member governments to act in common accord on all matters relating to units of measurement
- Initially covering just mass and length standards, the coverage grew to encompass the current ‘International System of Units (SI)’



Woodcut dated 1800 illustrating the new decimal units which became the legal norm across all France on 4 November 1800

1875: The Metre Convention signed

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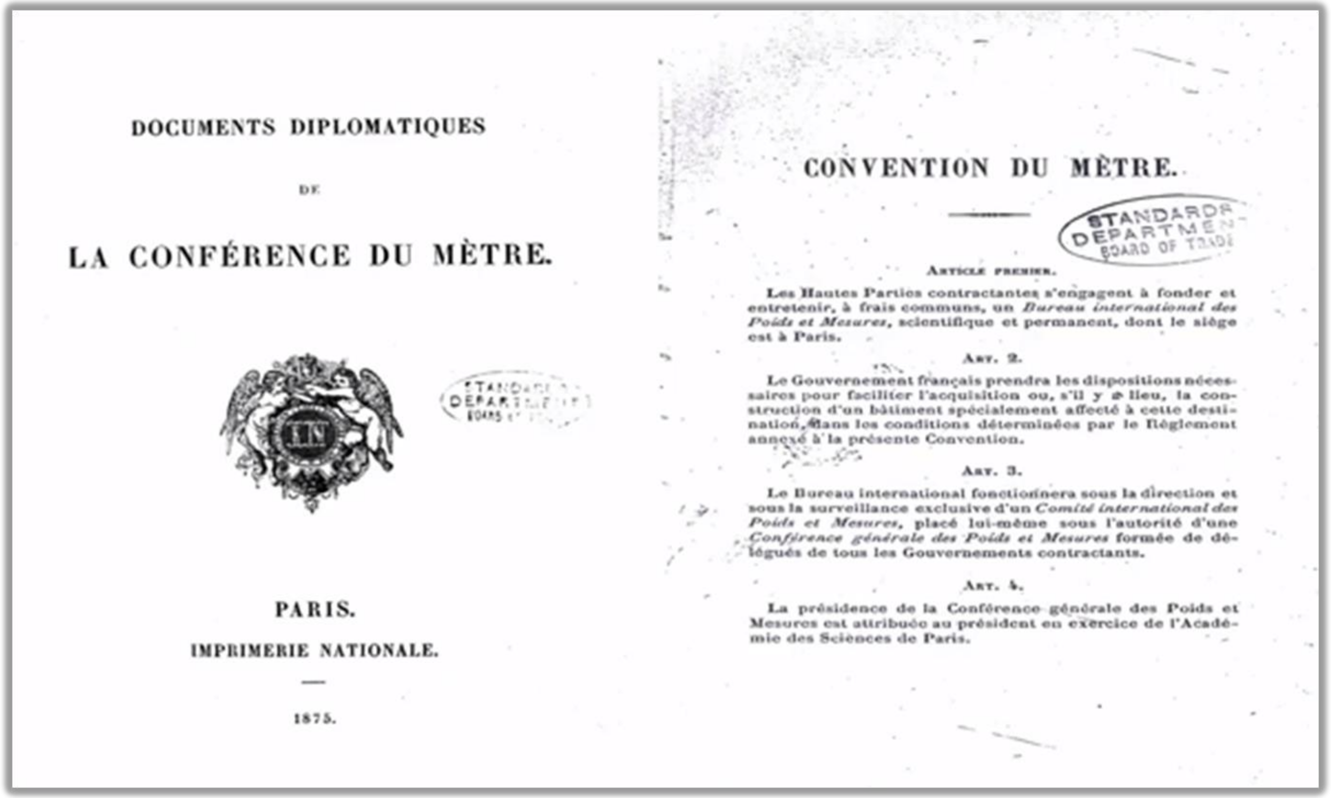


DOCUMENTS DIPLOMATIQUES

DE

LA CONFÉRENCE DU MÈTRE.

PARIS.

IMPRIMERIE NATIONALE.

1875.

CONVENTION DU MÈTRE.

STANDARDS DEPARTMENT BOARD OF TRADE

ARTICLE PREMIER.

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.

ART. 2.

Le Gouvernement français prendra les dispositions nécessaires pour faciliter l'acquisition ou, s'il y a lieu, la construction d'un bâtiment spécialement affecté à cette destination, dans les conditions déterminées par le Règlement annexé à la présente Convention.

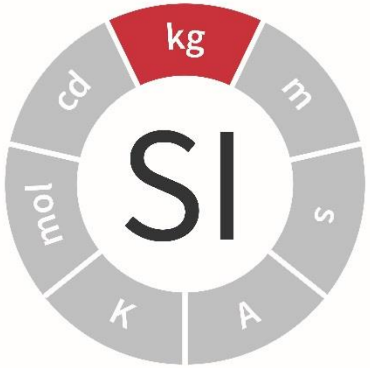
ART. 3.

Le Bureau international fonctionnera sous la direction et sous la surveillance exclusive 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.

ART. 4.

La présidence de la Conférence générale des Poids et Mesures est attribuée au président en exercice de l'Académie des Sciences de Paris.

1889: metre, kilogram & second agreed



1954: ampere, kelvin & candela

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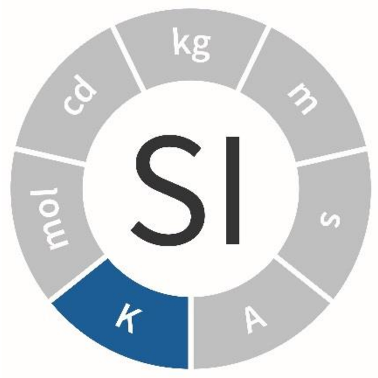
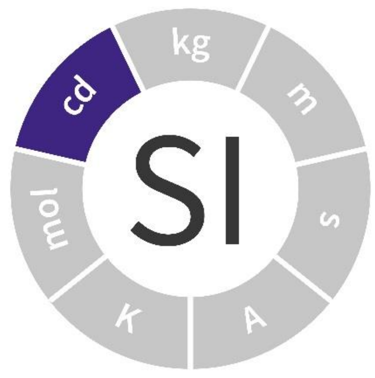
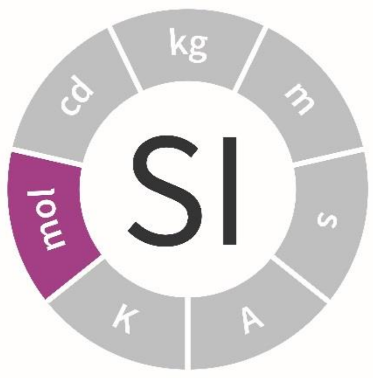
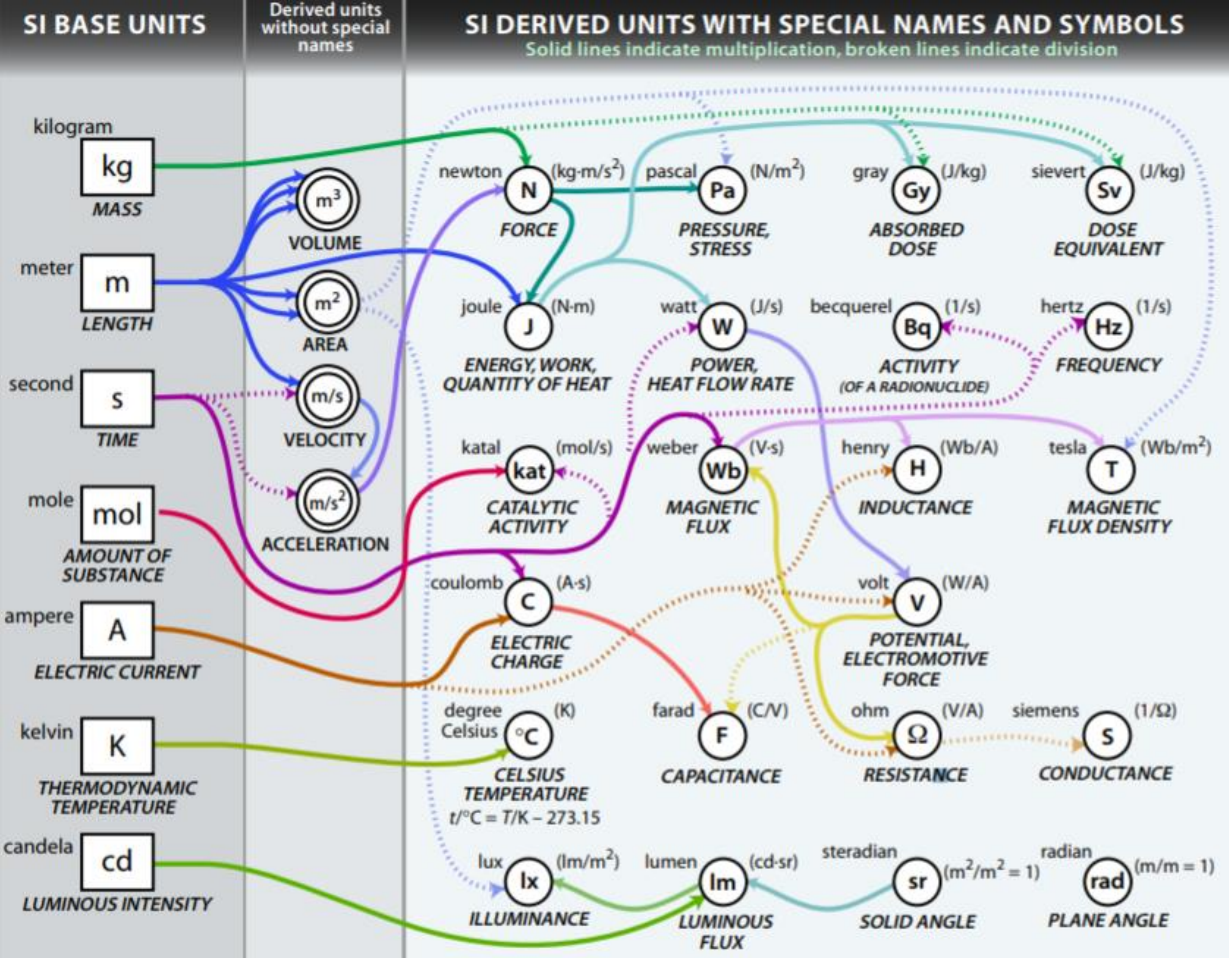




1971: mole



International System of Units (Système International d'Unités)



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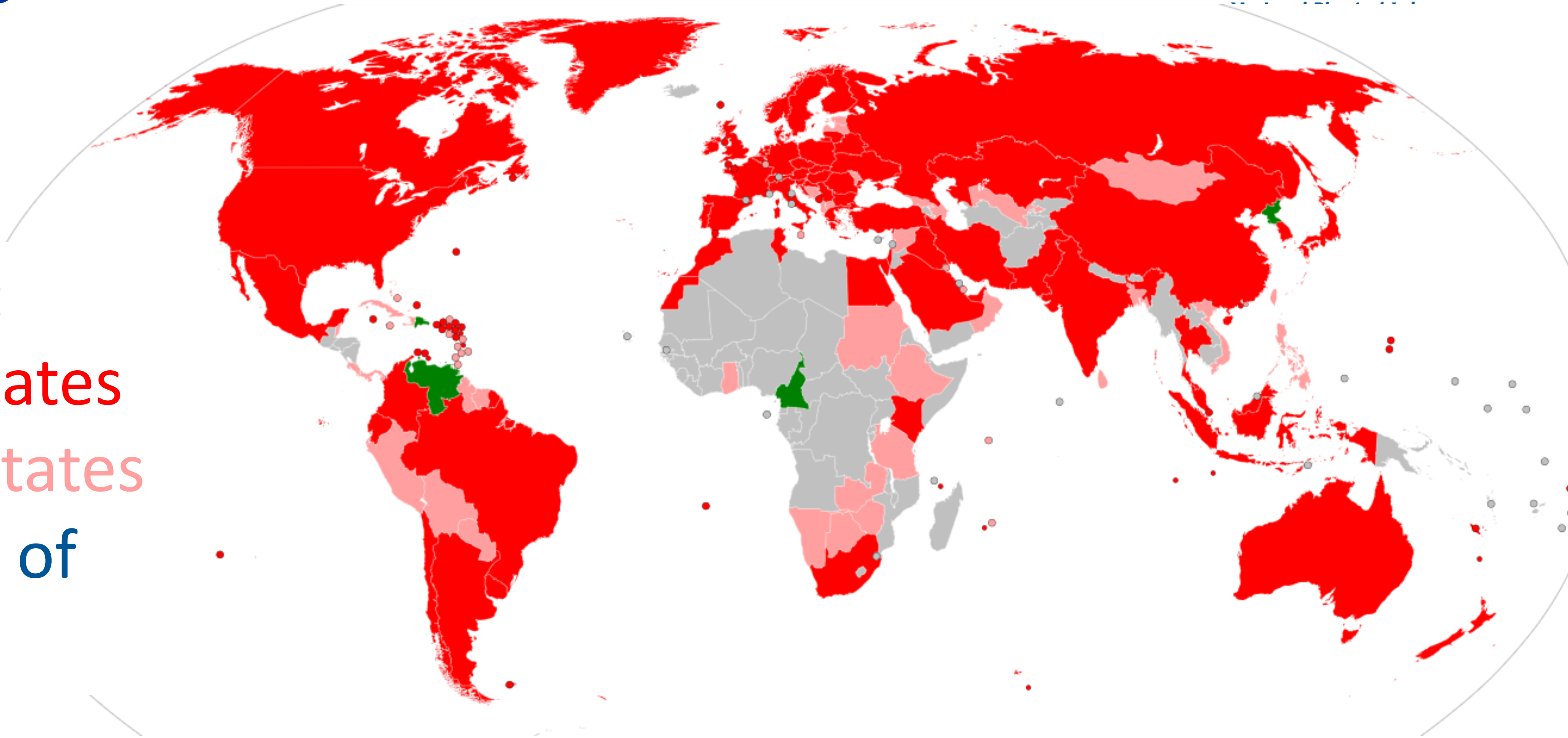
- Seven independent base units
- All other ‘derived units’ are made from combinations of these

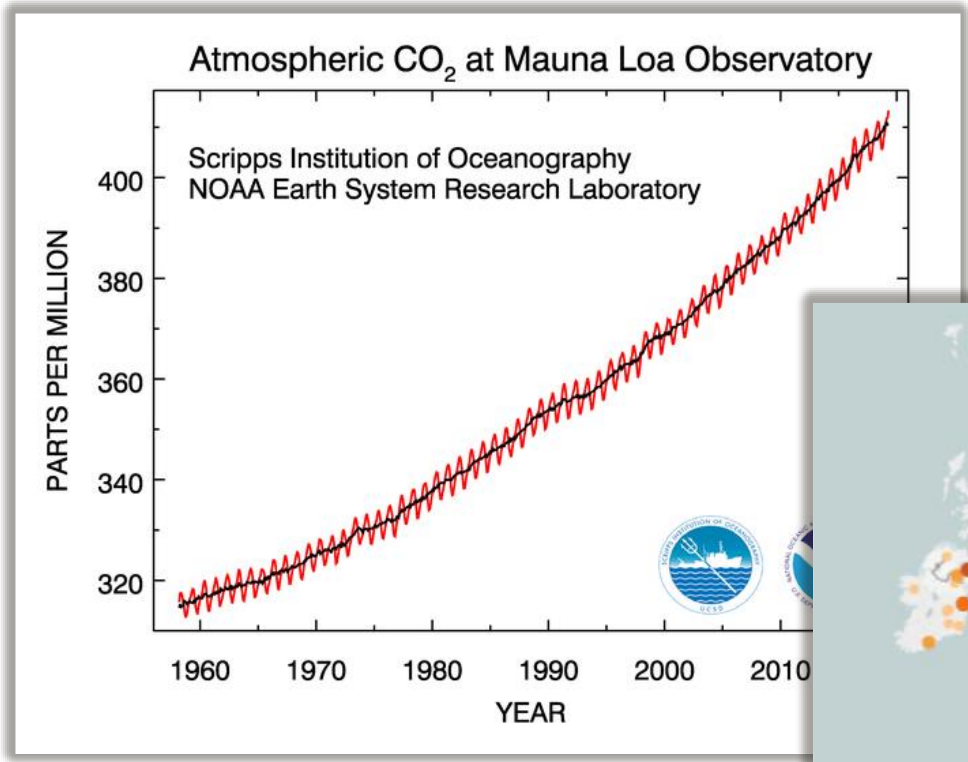
World-wide agreement



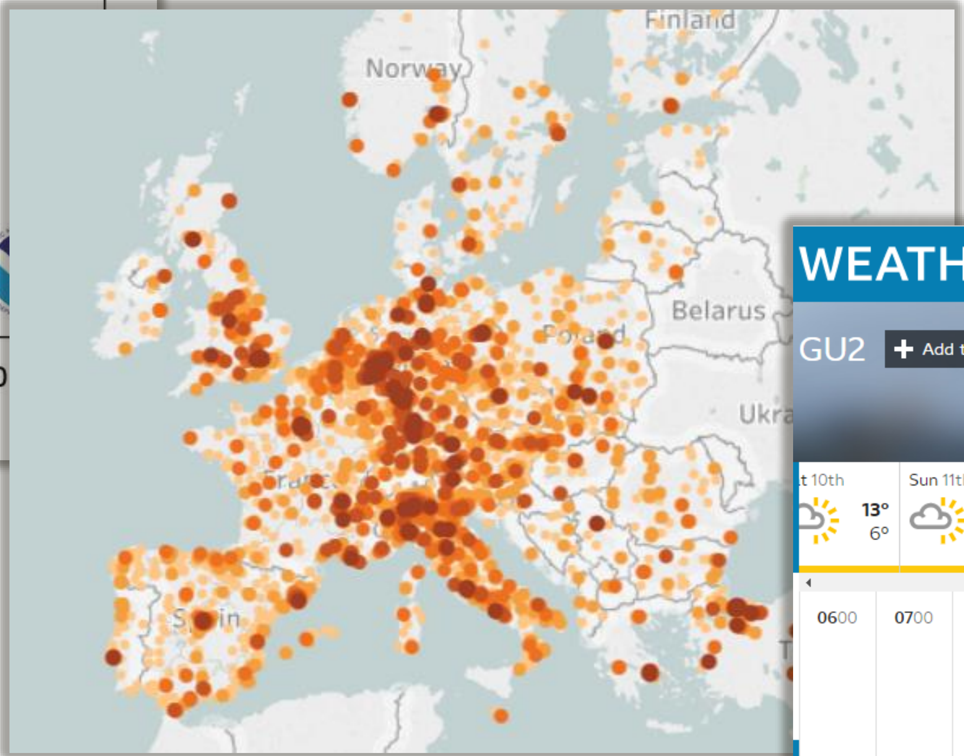
- October 2023:
  64 Member States
  36 Associate States
- Covering 98 % of global GDP

- National Metrology Institutes all around the world!
- Responsible for developing, improving and maintaining national measurement standards for these units

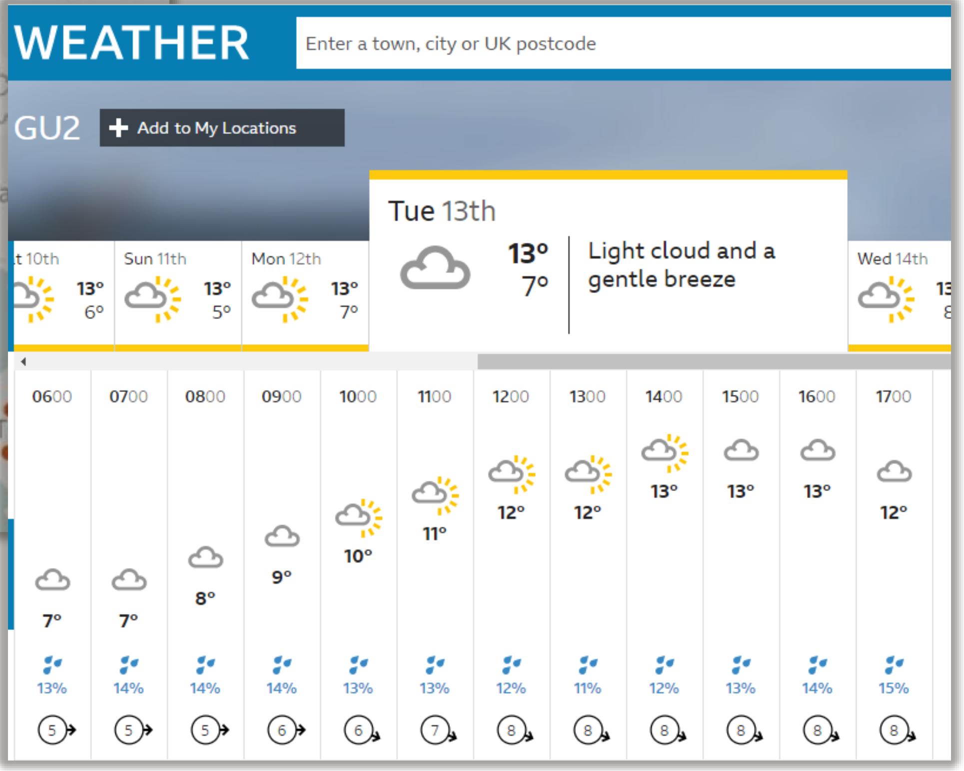
stable



comparable



universal



improving certainty in measurement

Key messages 2

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- Our current measurement system – the 'metric system' – rose from the ashes of the French revolution
- In 1875 the Metre Convention was signed between governments who agreed on the definition and size of key measurement units
- This system grew into the International System of Units (the SI) that we use today, founded on 7 independent base units
- A globally agreed system that confers on our measurements: stability, comparability and continuous improvement

Timeline of the SI

The SI constantly evolves unit definitions & realizations to meet user needs for accuracy

Resolution 6 of the 9th CGPM (1948)

The CIPM was tasked to make recommendations for a single practical system of units of measurement, suitable for adoption by all countries adhering to the *Metre Convention*

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

1971

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

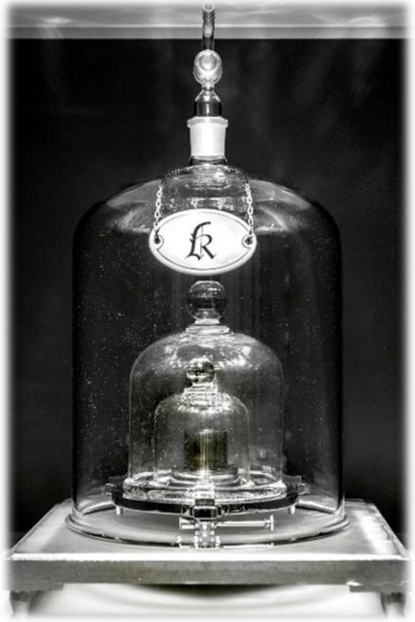
conventions for the **volt** and the **ohm** adopted

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

...and many smaller changes as well, except to the kg!

Measurement unit evolution

- We need to agree on something that is <u>'fixed'</u> – it has no uncertainty
- The agreement needs to be global
- There are three options:
  - Physical artefact
  - Material property
  - Constant of nature



Convenient

Unique artefact susceptible to change, damage or loss

Realisation in many locations

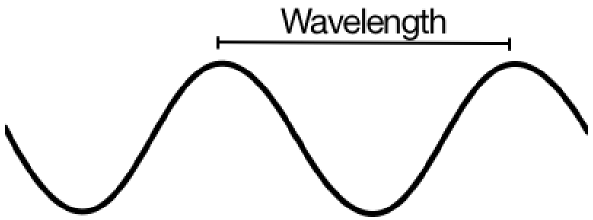
Depends on material purity & generally only one experiment

c

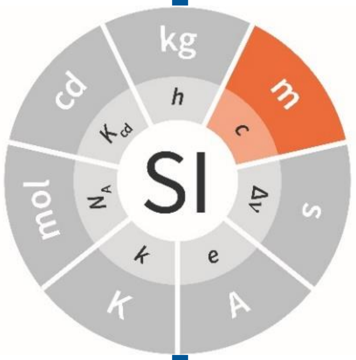
Realisation by many experiments

Experiments are challenging

Evolving units – the metre



Speed of Light = ***exactly***
299 792 458 m/s



Metre = distance travelled by light in ***exactly*** $^{1}/_{299792458}$ seconds

Physical artefact (1889) → Material property (1960) → Constant of nature (1983)

Key messages 3

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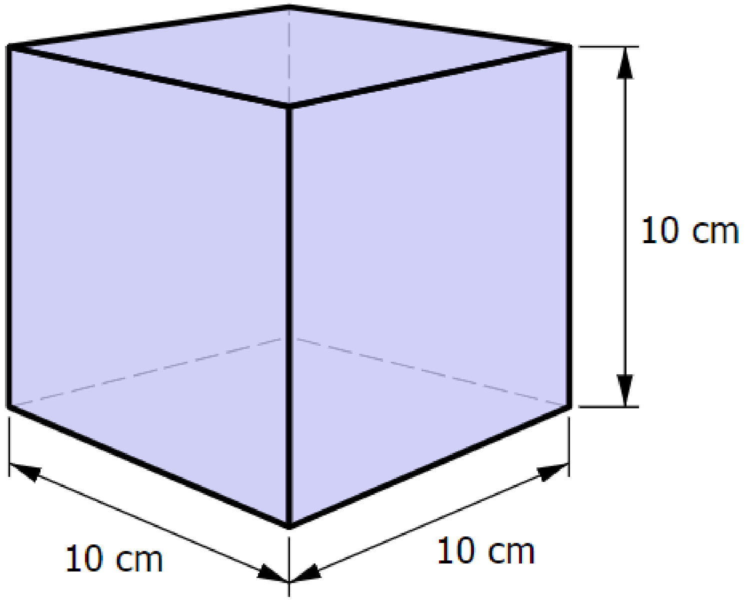
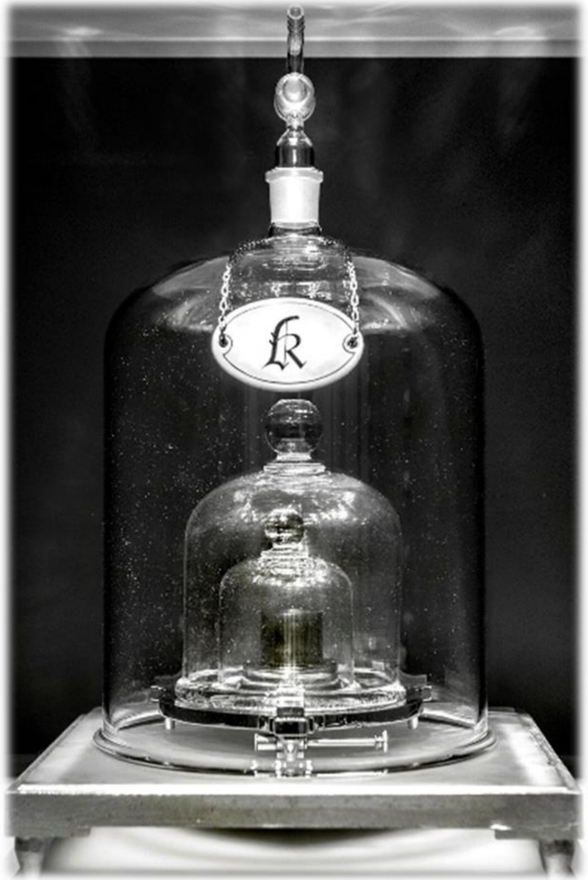
- Our system of 7 base units is a compromise between our perception of reality and practical usefulness
- The SI and the definition of base units has always evolved over time to meet the needs of end users
- Over time base units have transitioned from being based on physical artefacts → material properties → constants of nature
- This has happened in the past for the metre (using the speed of light) and the aim was for this to happen for all base units

Mass – the kilogram problem



Inconvenient artefact



Convenient but unique artefact susceptible to change

The kilogram problem: How was the international prototype of the kilogram (IPK) changing?

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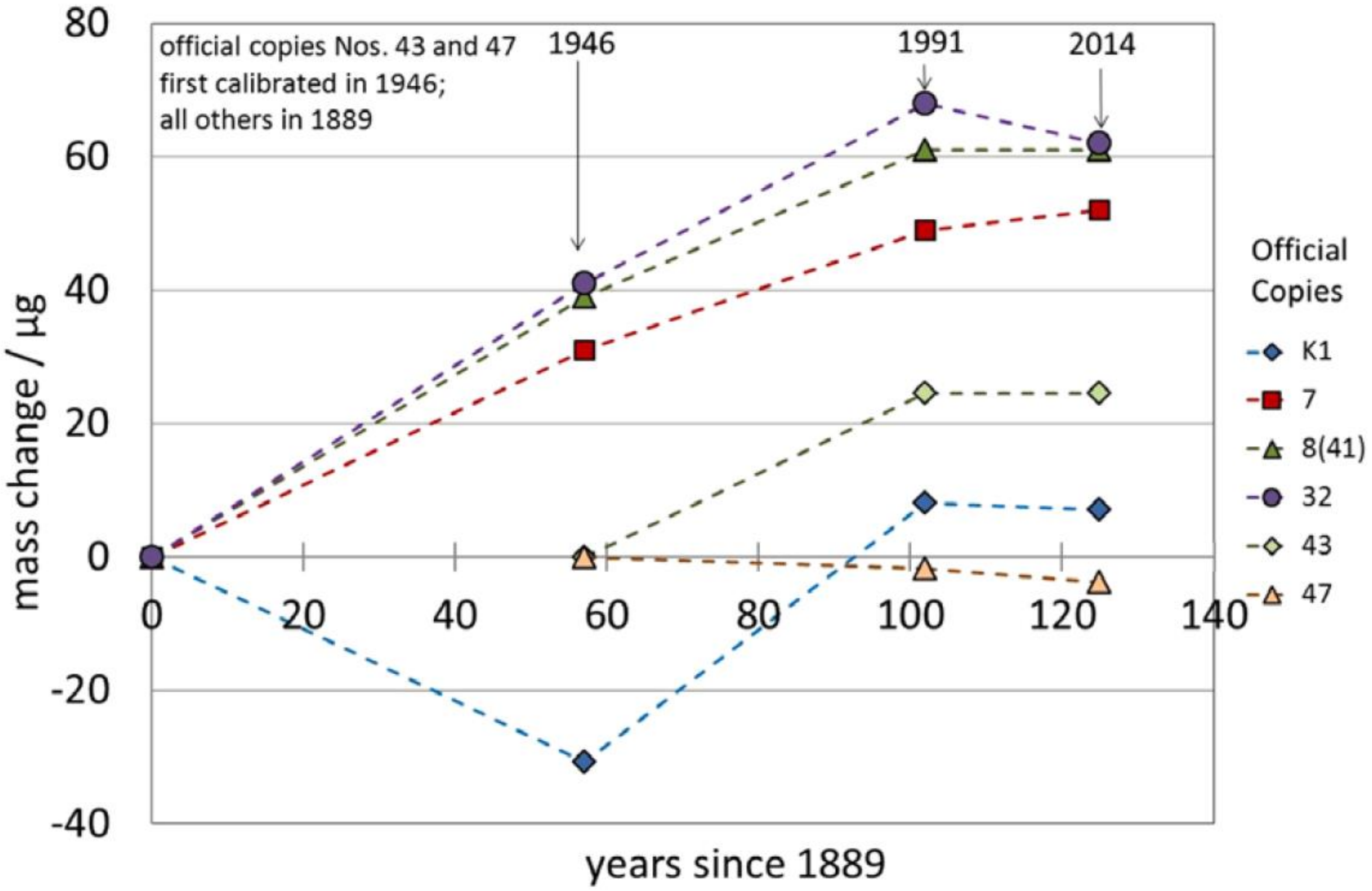


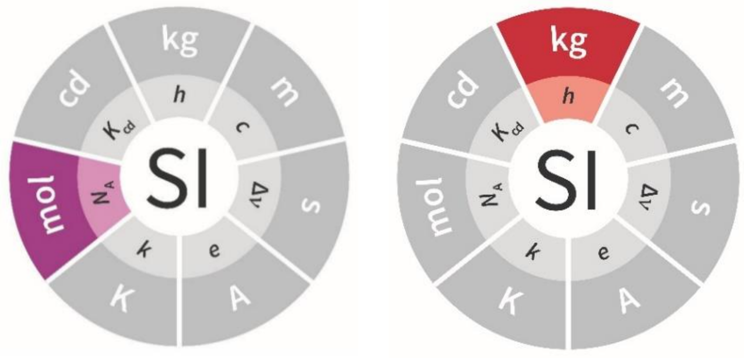
https://vimeo.com/270500374
2 minute trailor

https://www.pbs.org/video/the-last-artifact-bvn9ea/
50 minute film

Technological advances provide a solution

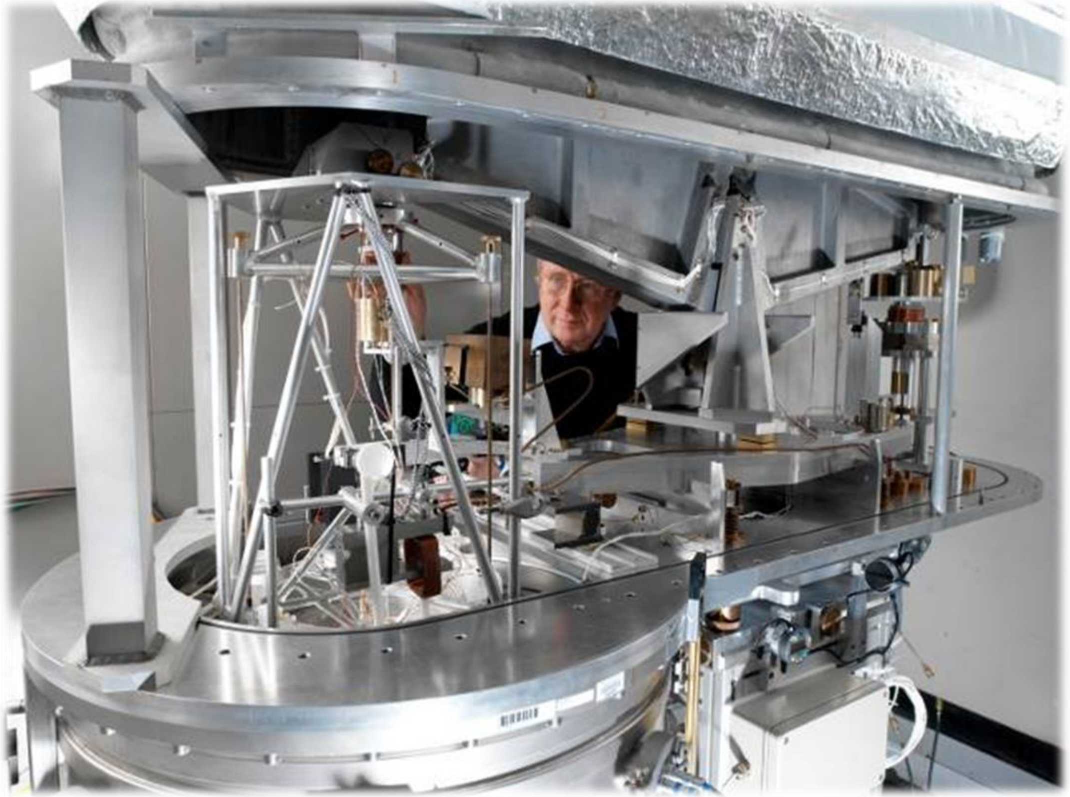
- Allowed a redefinition of the mole in terms of the Avogadro constant
- Allowed a redefinition of the kilogram in terms of Planck constant
- Provided confidence in the changes because these two, very different, experiments agreed

Counting atoms

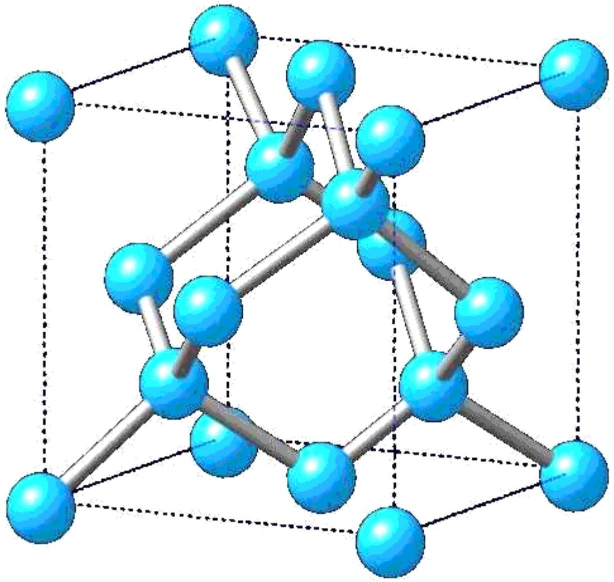


$$N_A h = \frac{A_r(e) c \alpha^2}{2R_\infty} M_u$$

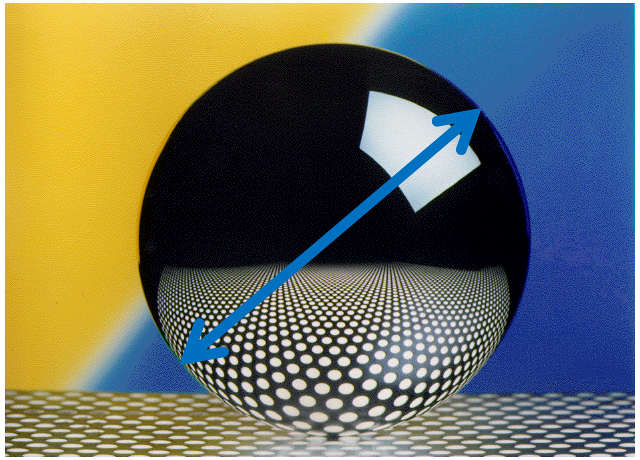
Balancing forces



Use of a silicon crystal!



1. Volume a_0^3 of the unit cell
2. Volume of an atom: $a_0^3/8$
3. Volume V of a sphere
4. Number N of the atoms



$$N_A = \frac{8\,V}{a_0^3} \cdot \frac{M_{mol}}{m_{sphere}}$$

The Kibble Balance

When balanced…

$$F_{down} = (M - X)g$$

$$F_{up} = BLi$$

$$\Delta M = \frac{BLi}{g}$$

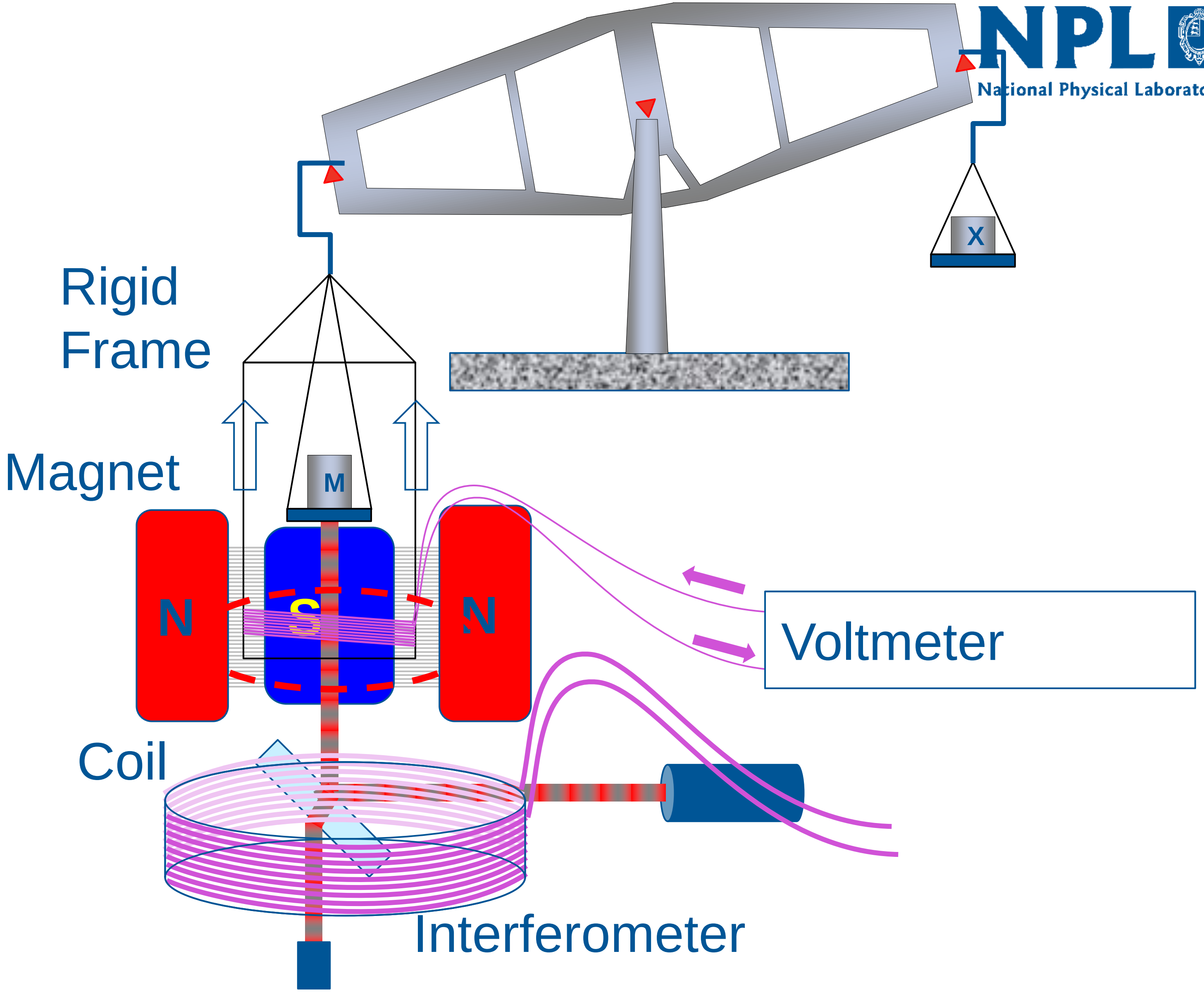
When falling…

$$V = BL \times speed$$

$$BL = \frac{V}{speed}$$

Combining…

$$\Delta M = \frac{Vi}{g \times speed}$$



The Kibble Equation

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$$\Delta M = \frac{V \times i}{g \times speed}$$

- Voltage, *V*, can be measured in terms of *h and e*
- Current, *i*, can be measured in terms of *h* and *e*
- *g* can be measured in the lab with gravimeter in terms of $\Delta\nu_{Cs}$ and *c*
- Speed is measured with the interferometer in terms of $\Delta\nu_{Cs}$ and *c*

Other terms already have fixed numerical values, or are closely related to *h*

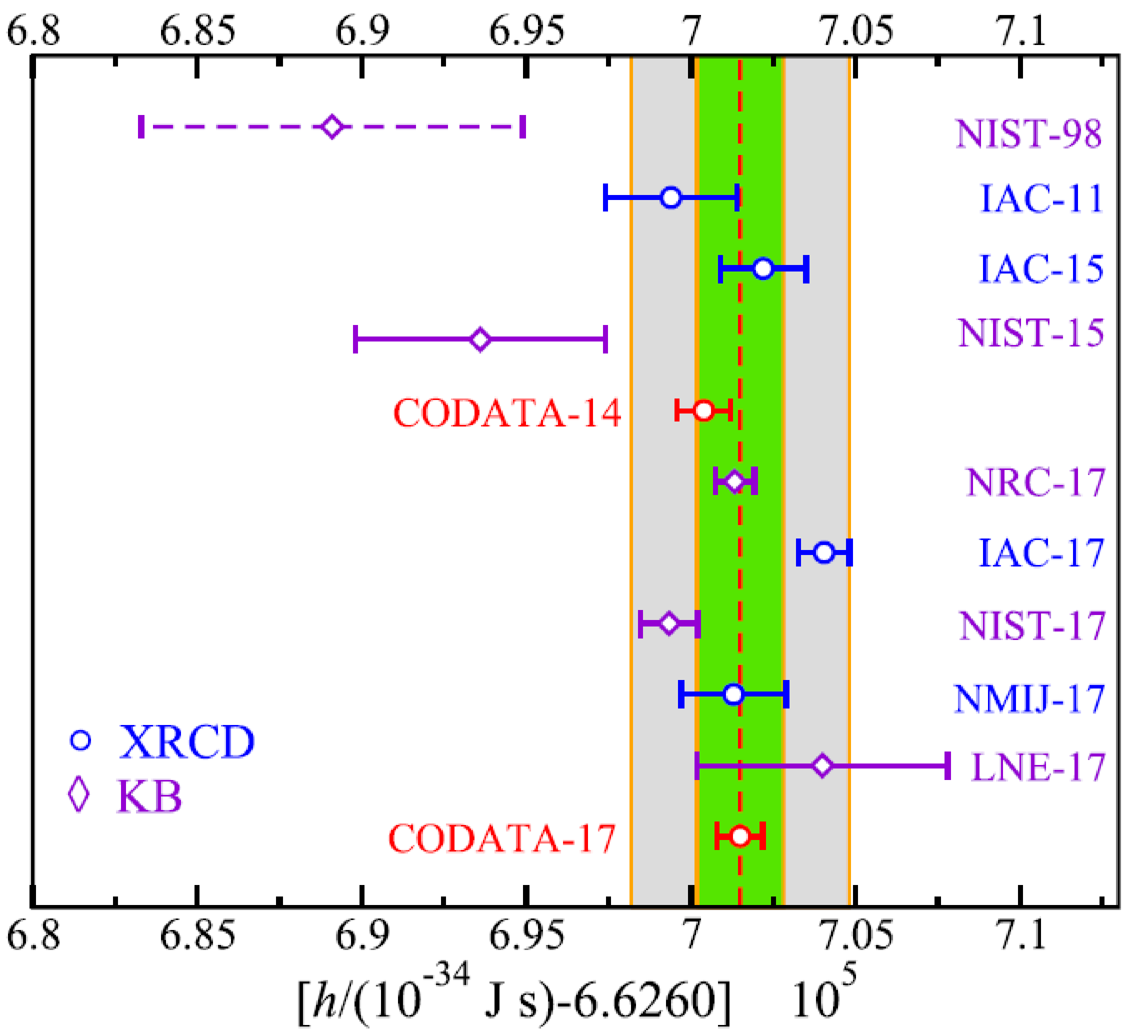

Figure 2. Values of the Planck constant h inferred from the input data in table 4, the CODATA 2014 value, and the CODATA 2017 value in chronological order from top to bottom (see table 10). Dashed values were not included in the final 2017 adjustment. The inner green band is ± 20 parts in 10^9 and the outer grey band is ± 50 parts in 10^9. KB: Kibble balance; XRCD: x-ray-crystal-density.

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How do we know when we've got there?

When the accuracy of the new experiments is such that we could start to determine changes in the mass of the IPK

Peter J Mohr *et al* 2018 *Metrologia* **55** 125

Key messages 4

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- The kilogram, the last base unit defined by a physical artefact, was a challenge to describe in terms of a constant of nature
- The solution was improvements in technology and the Kibble balance, which equates electrical and gravitational force
- This experiment was linked to the Avogadro experiment to count the atoms in a perfect sphere of ^{28}Si
- As a result both the kilogram and the mole could be redefined in terms of the Planck and Avogadro constants, respectively

Definitions

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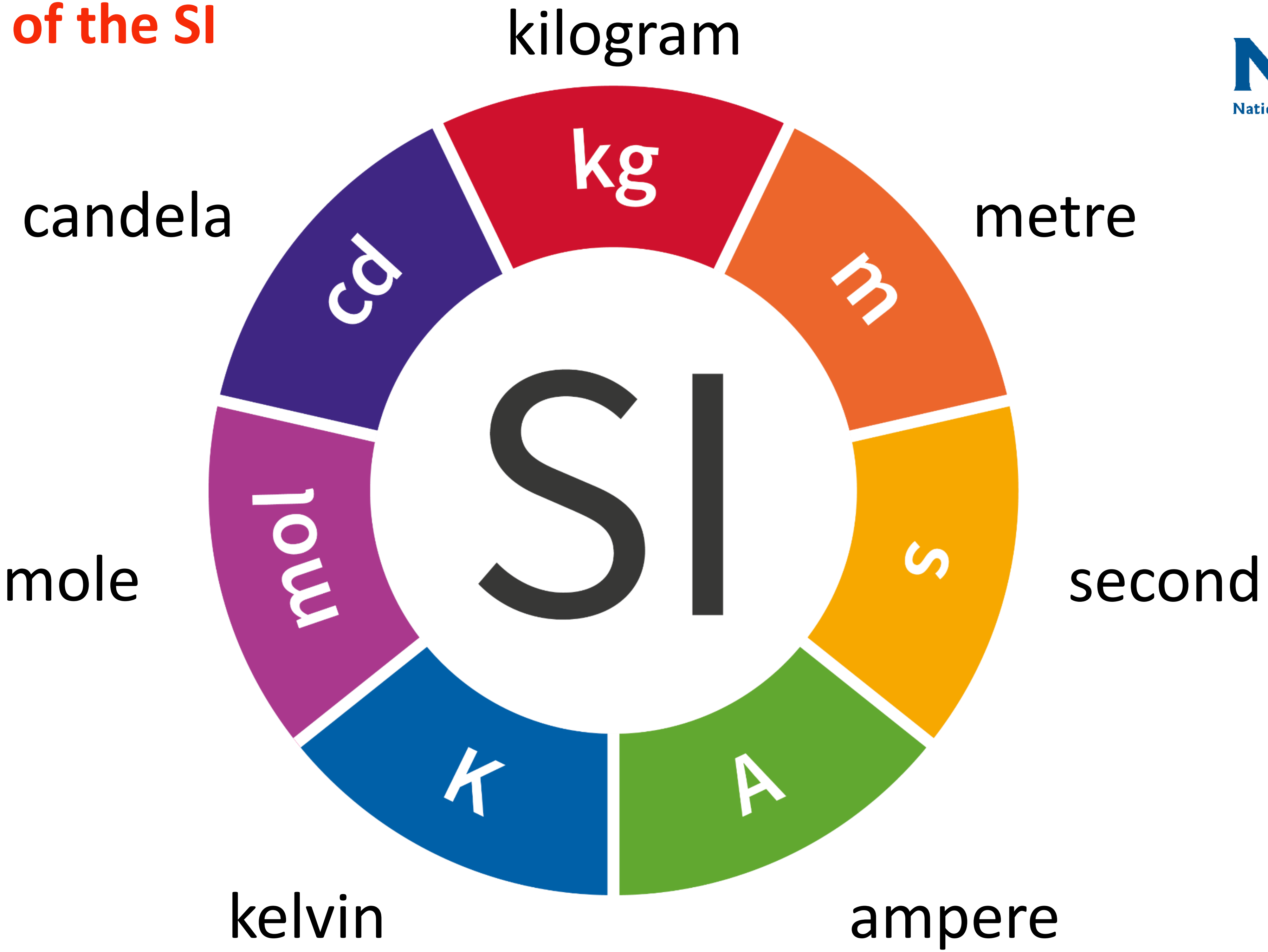
- Accuracy

  “the closeness of the agreement between the results of a measurement and the (conventional) true value of the measurand”, where International Standards represent the “truth”.

Base Units of the SI



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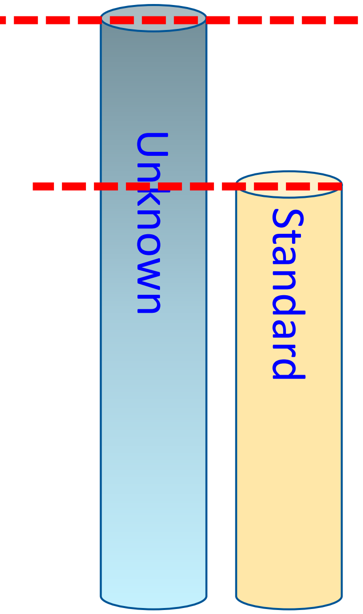
Measurement is…

Quantitative Comparison

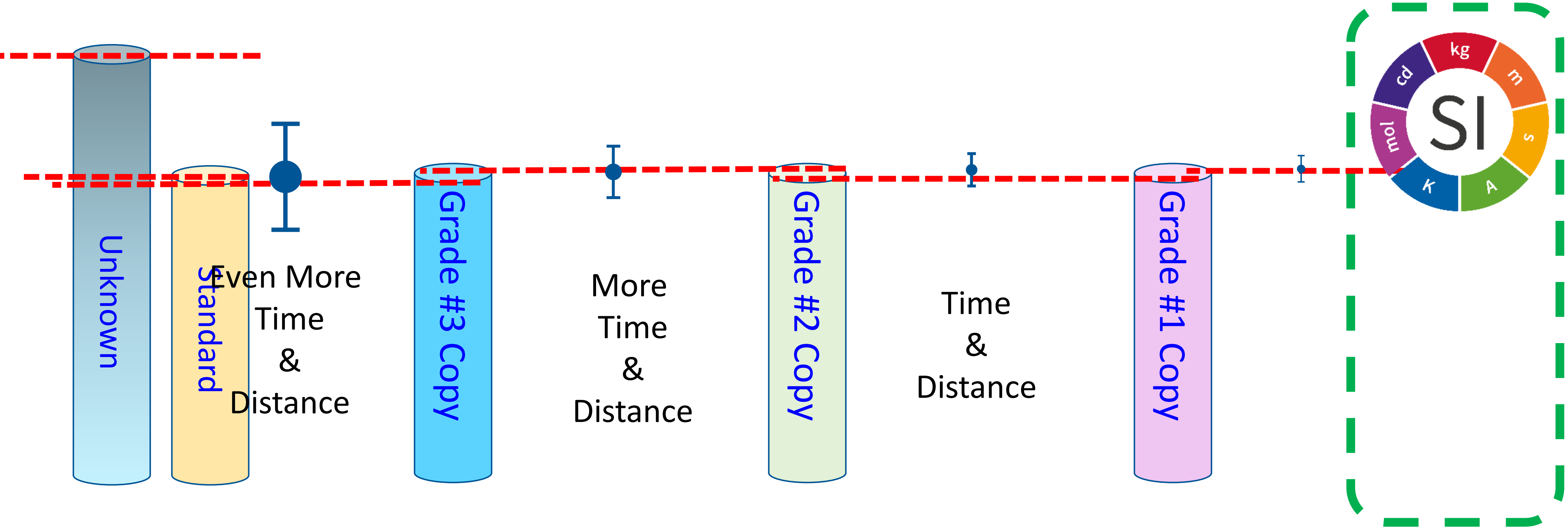


…of an unknown quantity with a standard quantity

After: M. de Podesta, NPL

Measurement is…

Quantitative Comparison



After: M. de Podesta, NPL

The Base Units of the SI

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Re-defining the base units of the SI?

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Why?

Measurement is…

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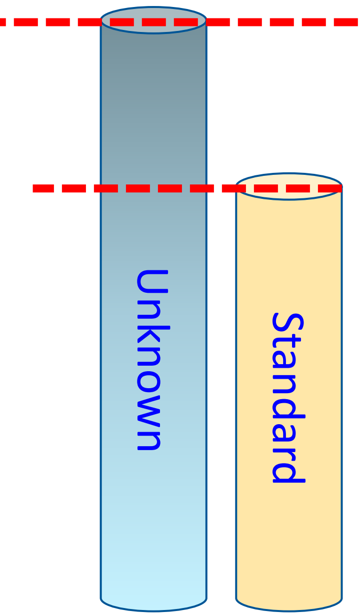
Quantitative Comparison



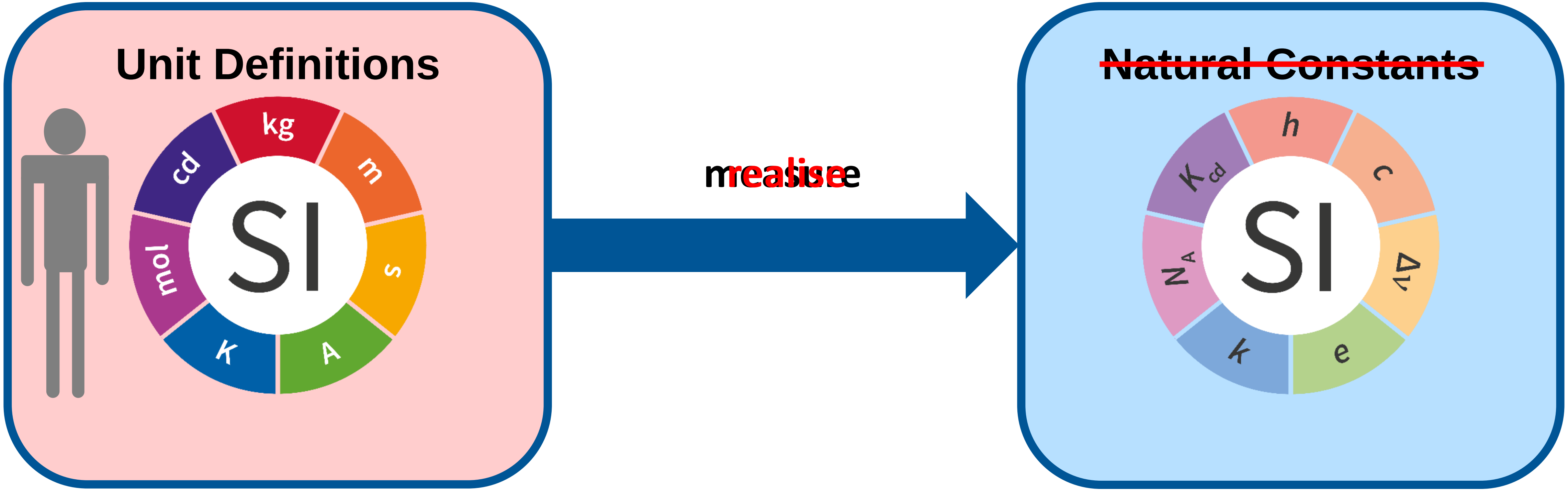
…of an unknown quantity with a standard quantity

Could we choose our standards more wisely?

After: M. de Podesta, NPL

SI Base Units and Natural Constants

Unit Definitions
in terms of



After: M. de Podesta, NPL

Measurement is…

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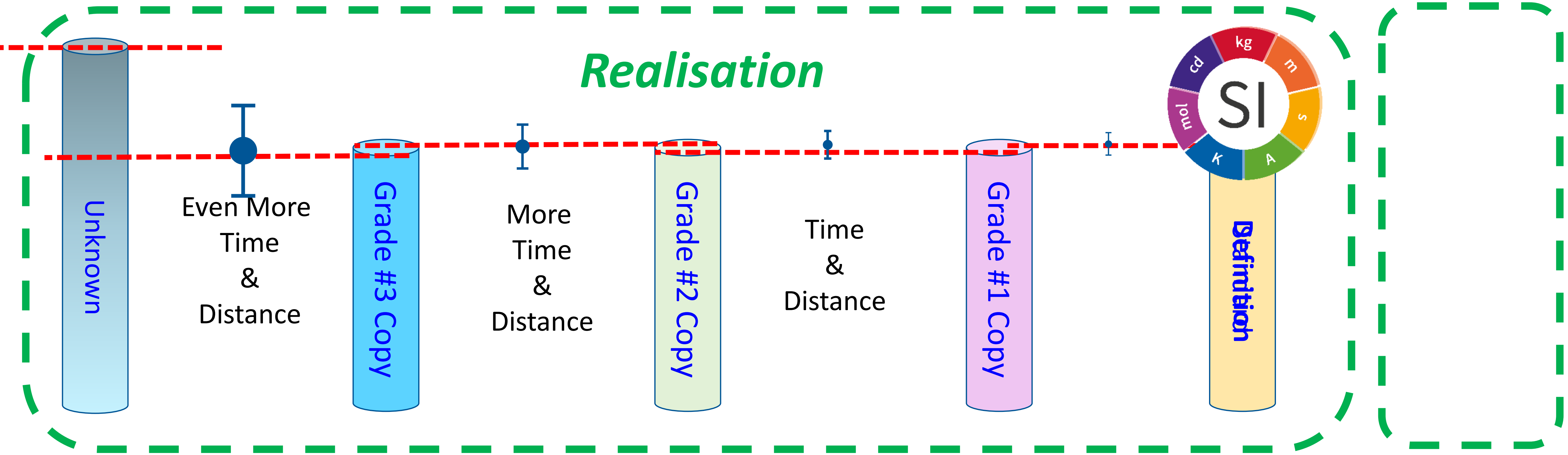
Quantitative Comparison



After: M. de Podesta, NPL

SI. The International System of Units

Administered from **BIPM**

- *International **Bureau** of Weights & Measures*

Run by

- *Inter*

Agenda

- *Gen*

DRAFT Resolution A: CGPM 2018

Should decide to make the change from 20th May 2019

Start	Measure	Measure	Measure	Measure	Measure	Measure	Measure	Measure	Measure	**STOP!**			
2007	2008	2009	2010	2011	2012	2013	2014	2015	2016	2017	2018	2019	

The New International System of Units

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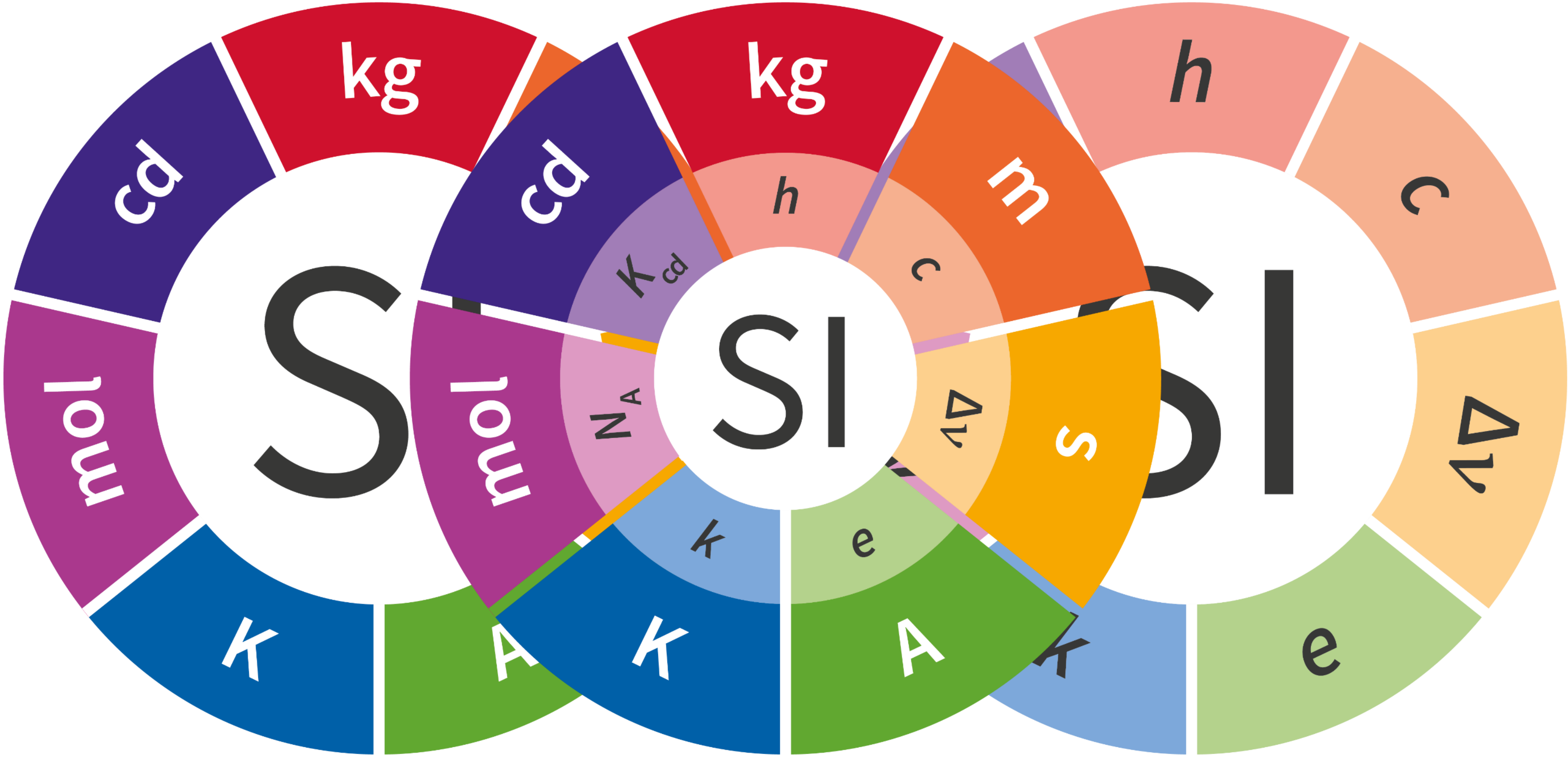

- The revised SI came into effect on 20 May 2019
- Definitions of the kilogram, mole, ampere & kelvin all changed
- Definitions of the metre, second & candela expressed differently
- The result of over thirty years of progress in metrology
- www.bipm.org/en/measurement-units/

The SI is now the system of units in which the following constants have these exact (numerical) values:

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

www.bipm.org/en/publications/si-brochure/

Definition of the kilogram

- 1889 - 2019

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

- 2019 onwards

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 kg m^2 s^{-1}, where the metre and the second are defined in terms of c and $\Delta \nu_{Cs}$.

Seven base units – *that are linked together*

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3 definitions based on fundamental (or conventional) constants:

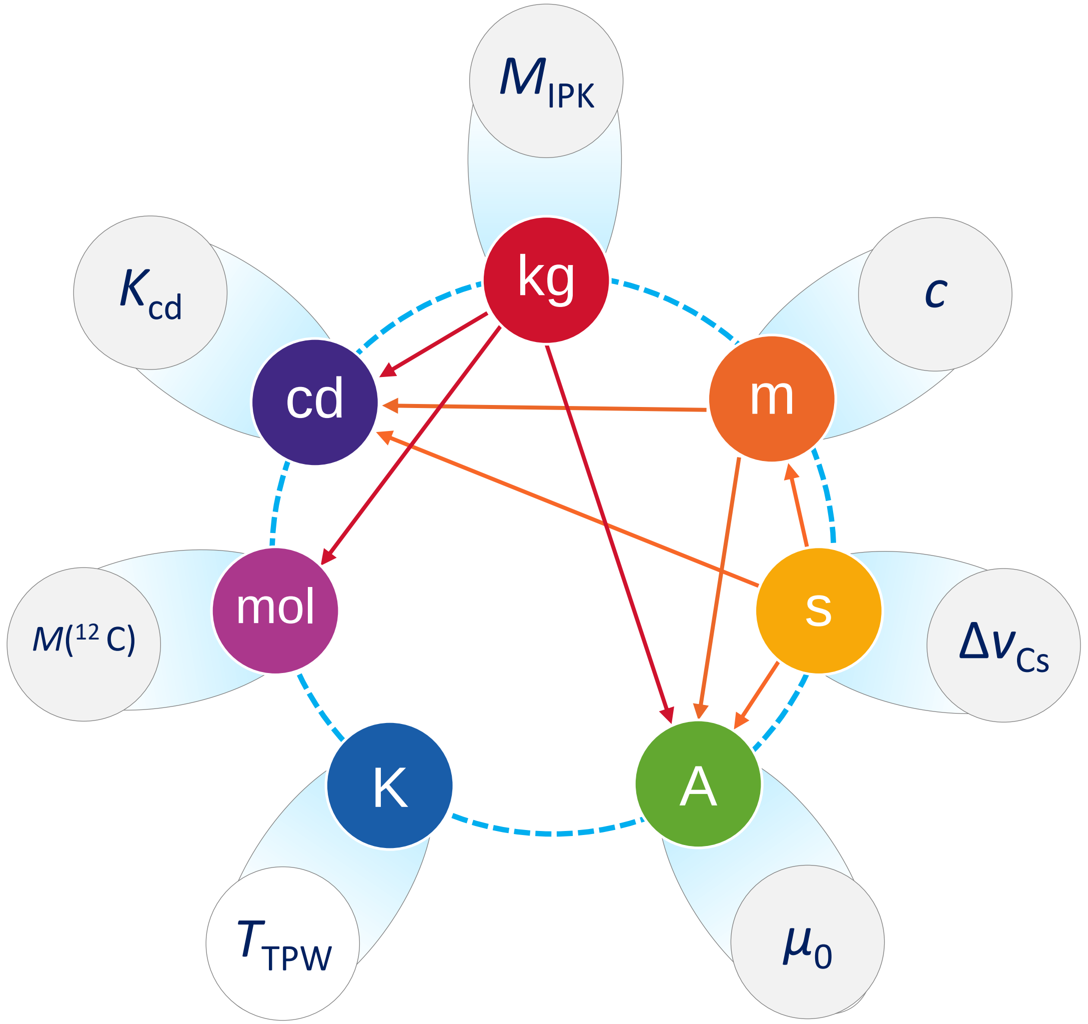
- metre (c)
- ampere (μ_0)
- candela (K_{cd})

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})



SI before May 2019

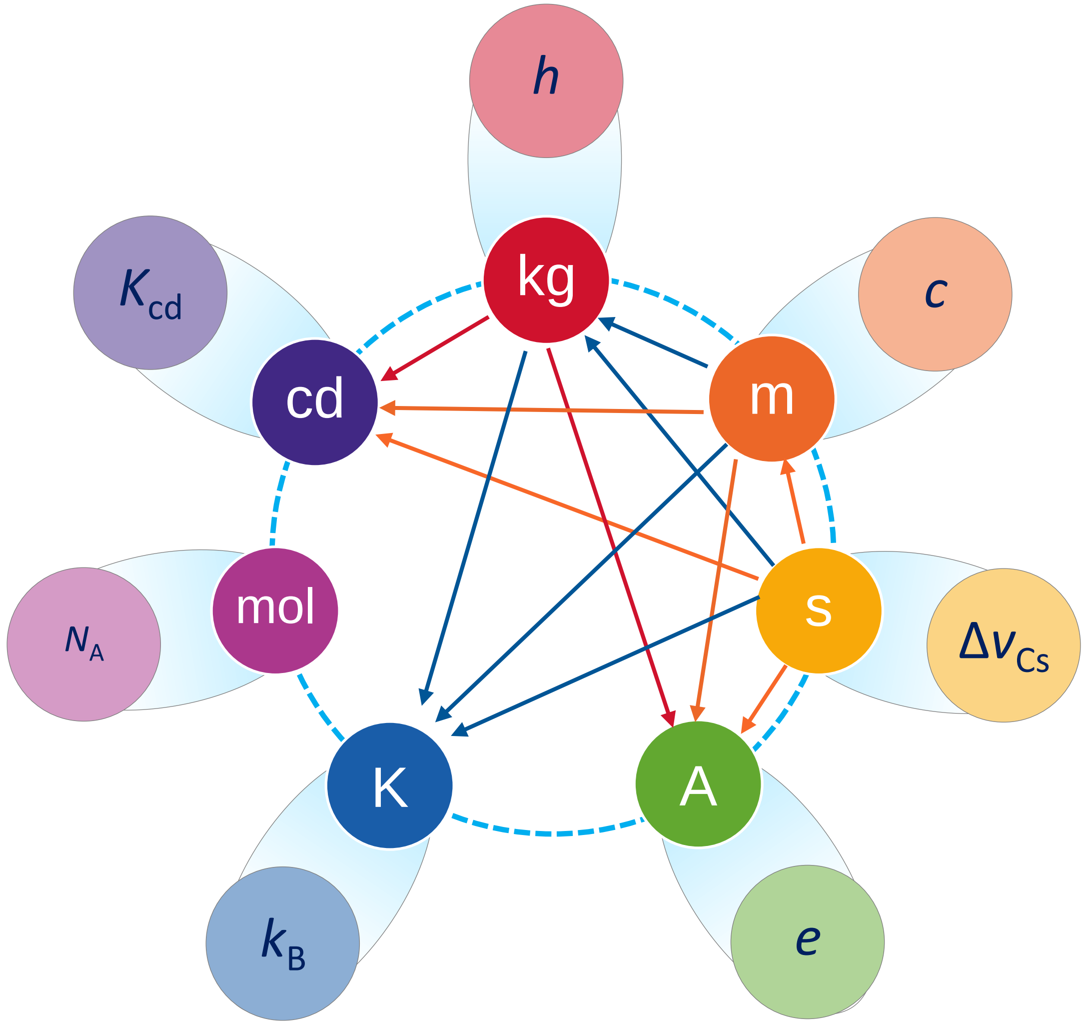
Seven base units – *same units, same size, now with different links*

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 ($\Delta\nu_{Cs}$)



SI after May 2019

SI Base Units and Defining Constants

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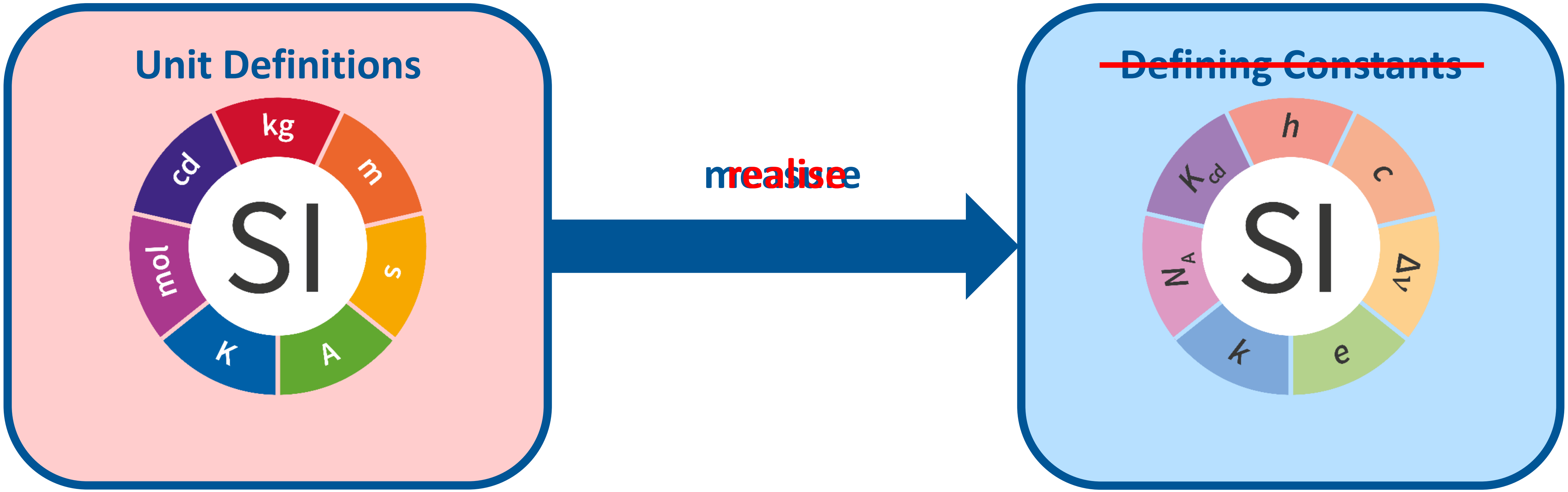
Unit Definitions in terms of



- 2019: Base unit definitions revised using ‘defining constants’
- Replaced less stable ‘artefacts’ and ‘material properties’
- Future-proofs our measurement system for decades

The future – quantum computing, 6G comms, smart cities, IoT

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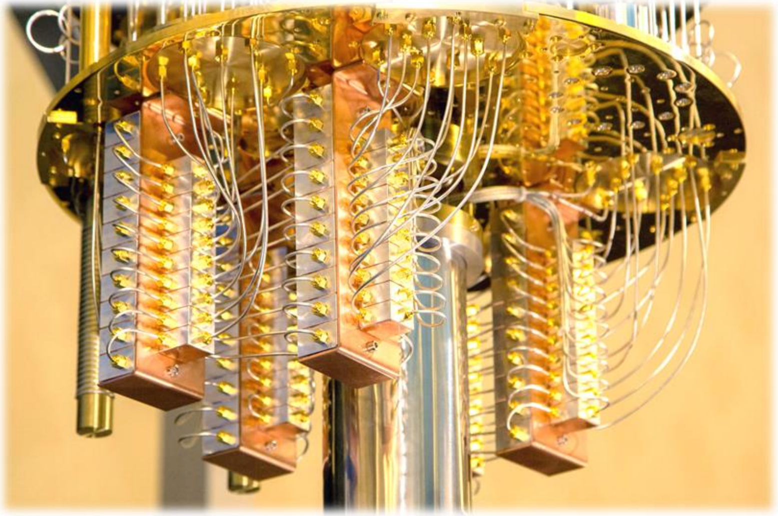


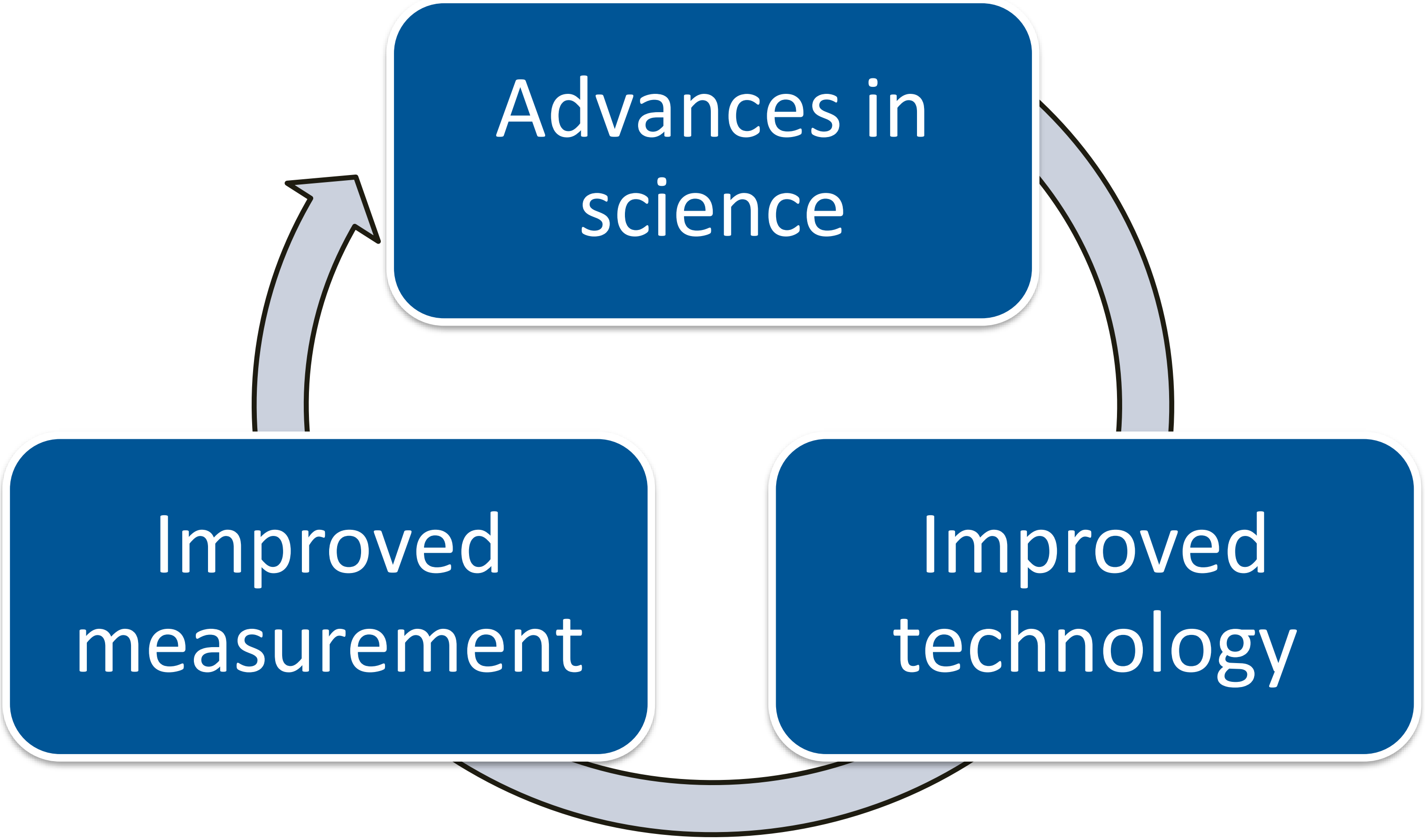
1980s

2020s

2060s ?

International System of Units: The Measure Of All Things

National Physical Laboratory



Key messages 5

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- The revised SI was introduced on 20 May 2019 (World Metrology Day) by unanimous agreement among Member States
- All base units remain the same and of the same size, but are now all defined in terms of constants of nature
- The SI is now future-proofed, allowing advances in technology to be realised directly as improvements in measurements
- The speed with which we can make use of future innovations depends on our ability to measure them accurately

What’s next for the SI?

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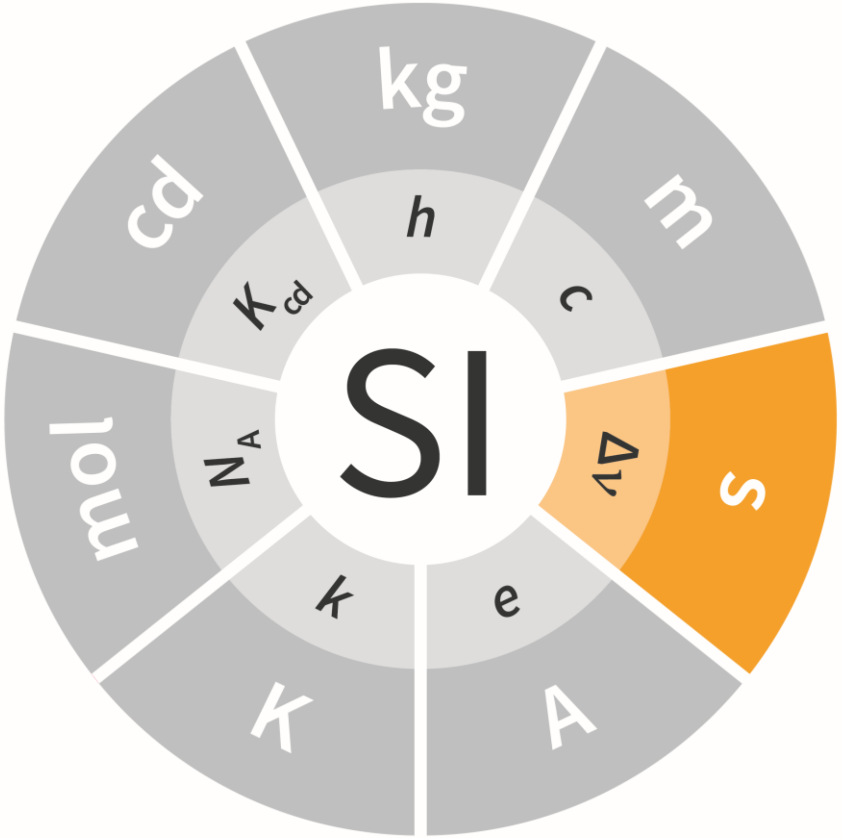
- Defining constants (h, c, N_A…)
- SI base units (m, s, mol…)
- SI derived units (m/s, m^3, N, W…)
- SI prefixes (M, k, µ, n…)



2022 : Extension to the range of SI prefixes

2030+ : Redefinition of the second

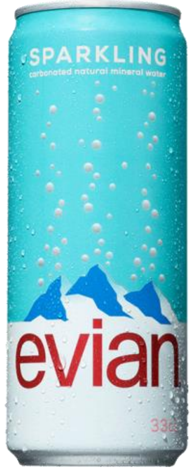
SI prefixes in everyday life

kilogram (kg)

kilowatt hour (kW h)

‘gigafactory’

millimetre (mm)



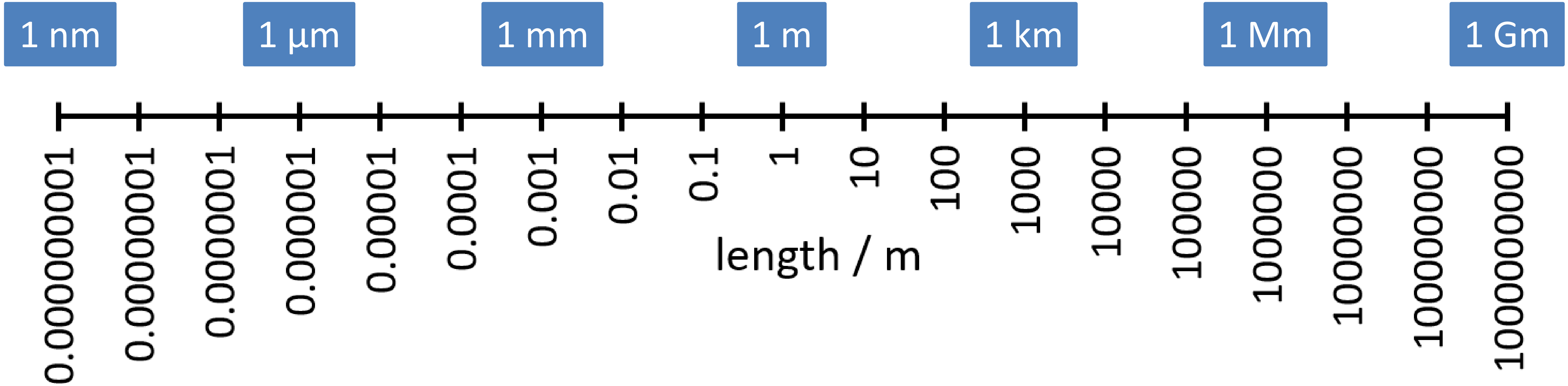
centilitre (cL)

‘micro scooter’

‘nanotechnology’

The complete set of SI units

- Includes the multiples and sub-multiples formed using SI prefixes
- SI prefixes allow use of SI units across a range of quantity sizes
- Essential characteristic of the SI as a unit system
- Fundamental for effective communication across disciplines



‘Human scale’ numerical values

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Ensures numerical value of the quantity remains on the ‘human scale’ between 1 and 100, making them easier to comprehend & communicate

“Amount fraction of sulfur hexafluoride (SF_6) in the atmosphere”

Decimal notation	Scientific notation	SI Prefix notation
0.000 000 000 011 mol/mol	**1.1×10^{-11} mol/mol**	**11 pmol/mol**
Hard to comprehend	Easier to comprehend	Easiest to comprehend

Data storage uses SI prefixes

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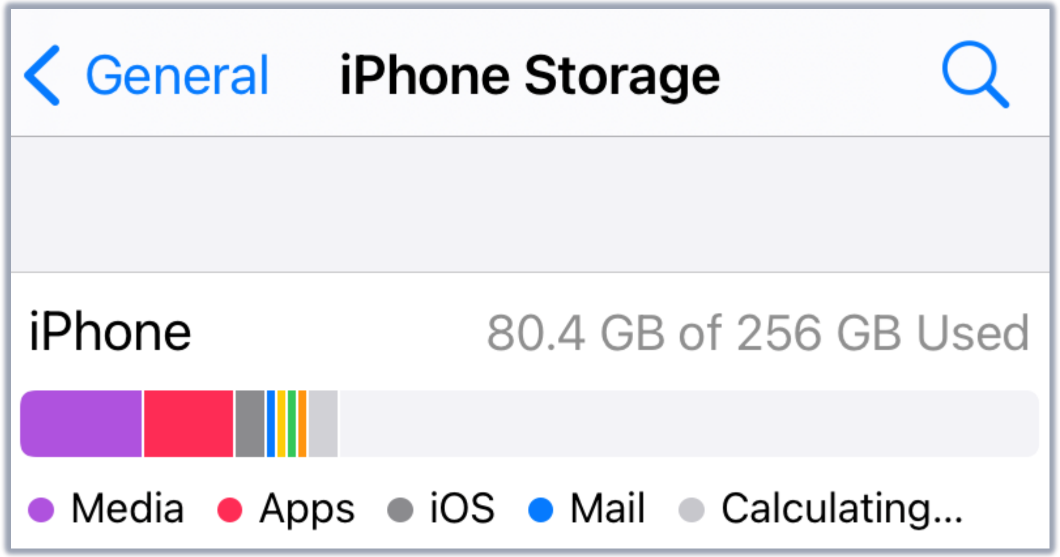

Today (5)

Convocation-EN .pdf	31/10/2022 08:46	Adobe Acrobat ...	199 KB
CGPM-2022-Participation-EN .pdf	31/10/2022 08:46	Adobe Acrobat ...	191 KB
Special-Procedure-EN .pdf	31/10/2022 08:46	Adobe Acrobat ...	109 KB
Draft-Resolutions-2022 .pdf	31/10/2022 08:46	Adobe Acrobat ...	516 KB
CGPM-2022-Letter-from-CIPM-President...	31/10/2022 08:47	Adobe Acrobat ...	174 KB

Acceleration in data produced from digitalisation, quantum computing, AI…

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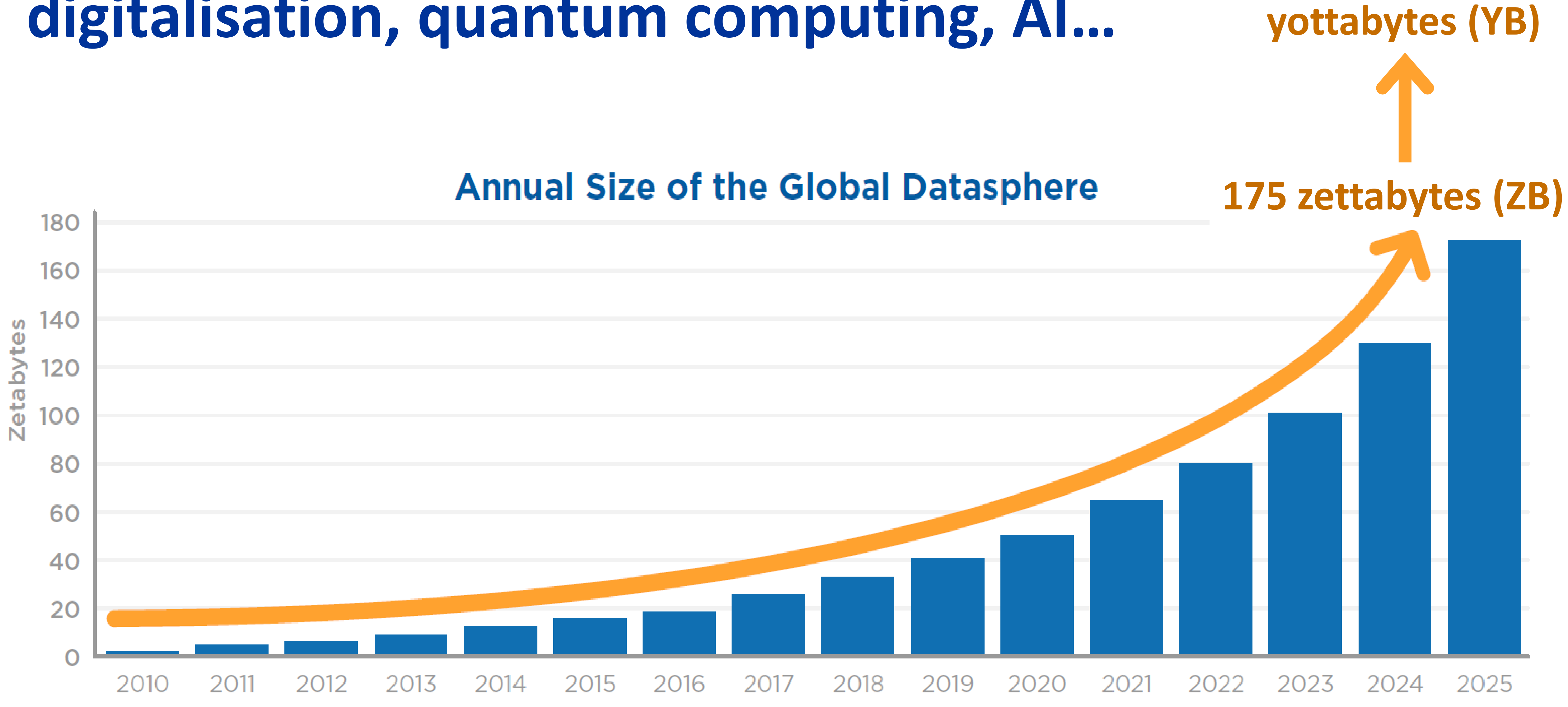

Source: Data Age 2025, sponsored by Seagate with data from IDC Global DataSphere, Nov 2018

New prefixes (added November 2022)

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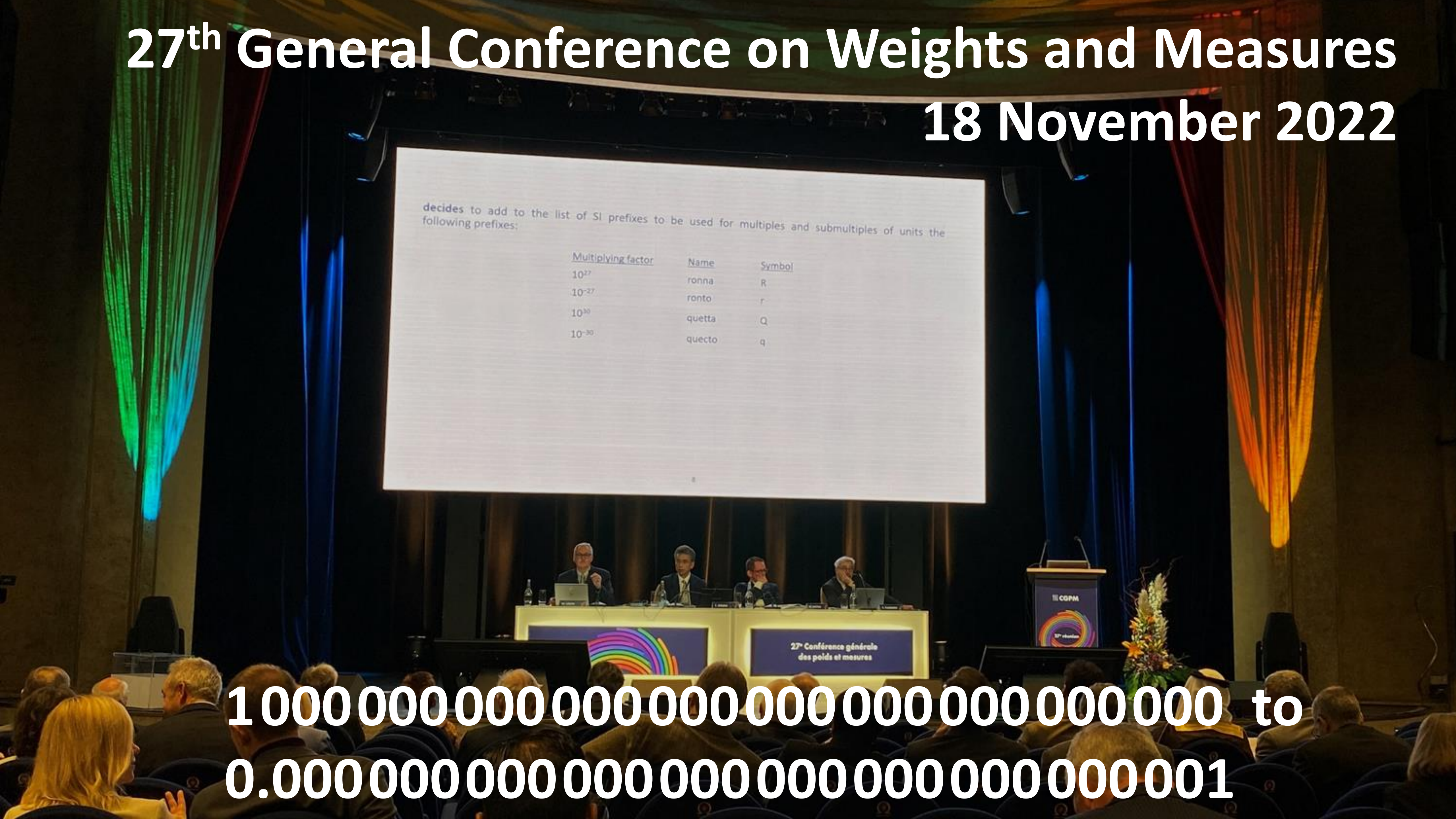
Multiplying factor	Name	Symbol
10^{27}	ronna	R
10^{-27}	ronto	r
10^{30}	quetta	Q
10^{-30}	quecto	q

27th General Conference on Weights and Measures
18 November 2022



1 000 000 000 000 000 000 000 000 000 000 to

0.000 000 000 000 000 000 000 000 000 001

Effective communication of scientific information

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Name	Symbol	Factor	Name	Symbol	Factor
quetta	Q	10^{30}	quecto	q	10^{-30}
ronna	R	10^{27}	ronto	r	10^{-27}
yotta	Y	10^{24}	yocto	y	10^{-24}
zetta	Z	10^{21}	zepto	z	10^{-21}
exa	E	10^{18}	atto	a	10^{-18}
peta	P	10^{15}	femto	f	10^{-15}
tera	T	10^{12}	pico	p	10^{-12}
giga	G	10^{9}	nano	n	10^{-9}
mega	M	10^{6}	micro	µ	10^{-6}
kilo	k	10^{3}	milli	m	10^{-3}
hecto	h	10^{2}	centi	c	10^{-2}
deca	da	10^{1}	deci	d	10^{-1}

- Useful, timely, low risk addition to the SI
- Essential for areas with a pressing need
- Remains optional for wider use
- Promotes effective, unified communication in science

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Science

Earth weighs in at si... new prefixes picked

Ronna, quetta, ronto and quecto adde... Units in first such change for more tha...

Ian Sample *Science editor*
@iansample
Fri 18 Nov 2022 19.13 GMT

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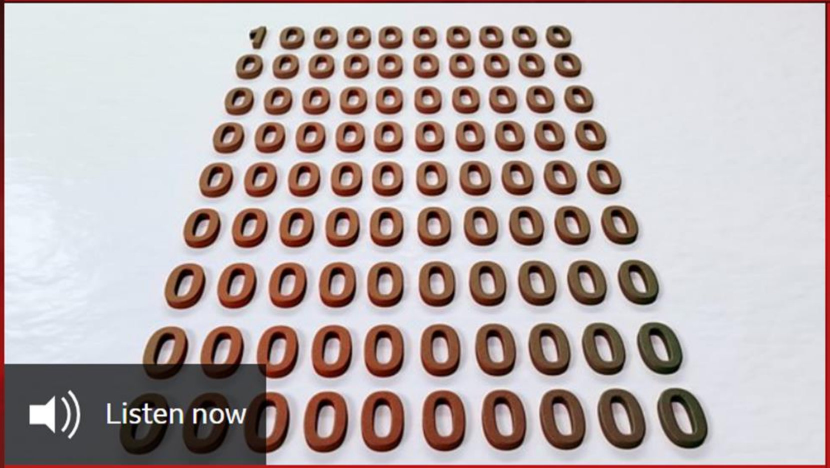

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...yottabytes in a ...e? Extreme numbers get ...s

...drove the need for prefixes that denote 10^{27} and 10^{30}.

The Washington Post
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...ghs 6 ronnagrams. ...an?

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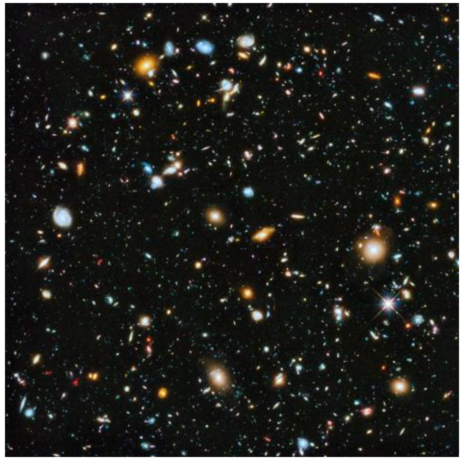
Ronnametres an... joined the ranks ...

New prefixes in the International Syst... in ronto and quecto for tiny numbers and ronna and quetta for very large numbers, like the amount of data on internet servers

PHYSICS 17 November 2022 , updated 18 November 2022

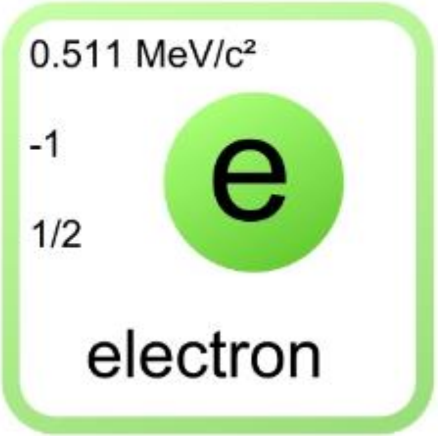
By Alex Wilkins

Mass = 1.9 Qg

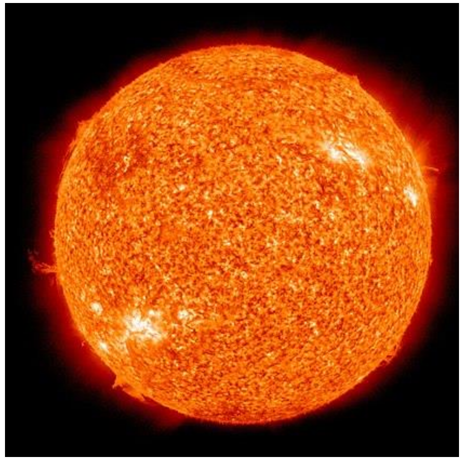


Diameter = 0.88 Rm

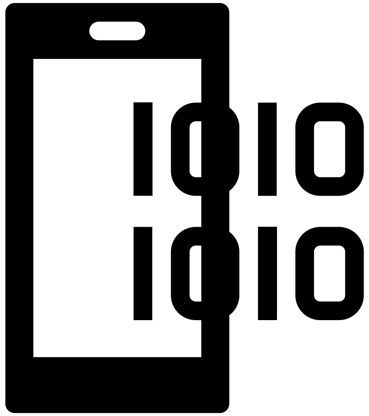
Mass = 6.0 Rg



Mass = 0.91 rg



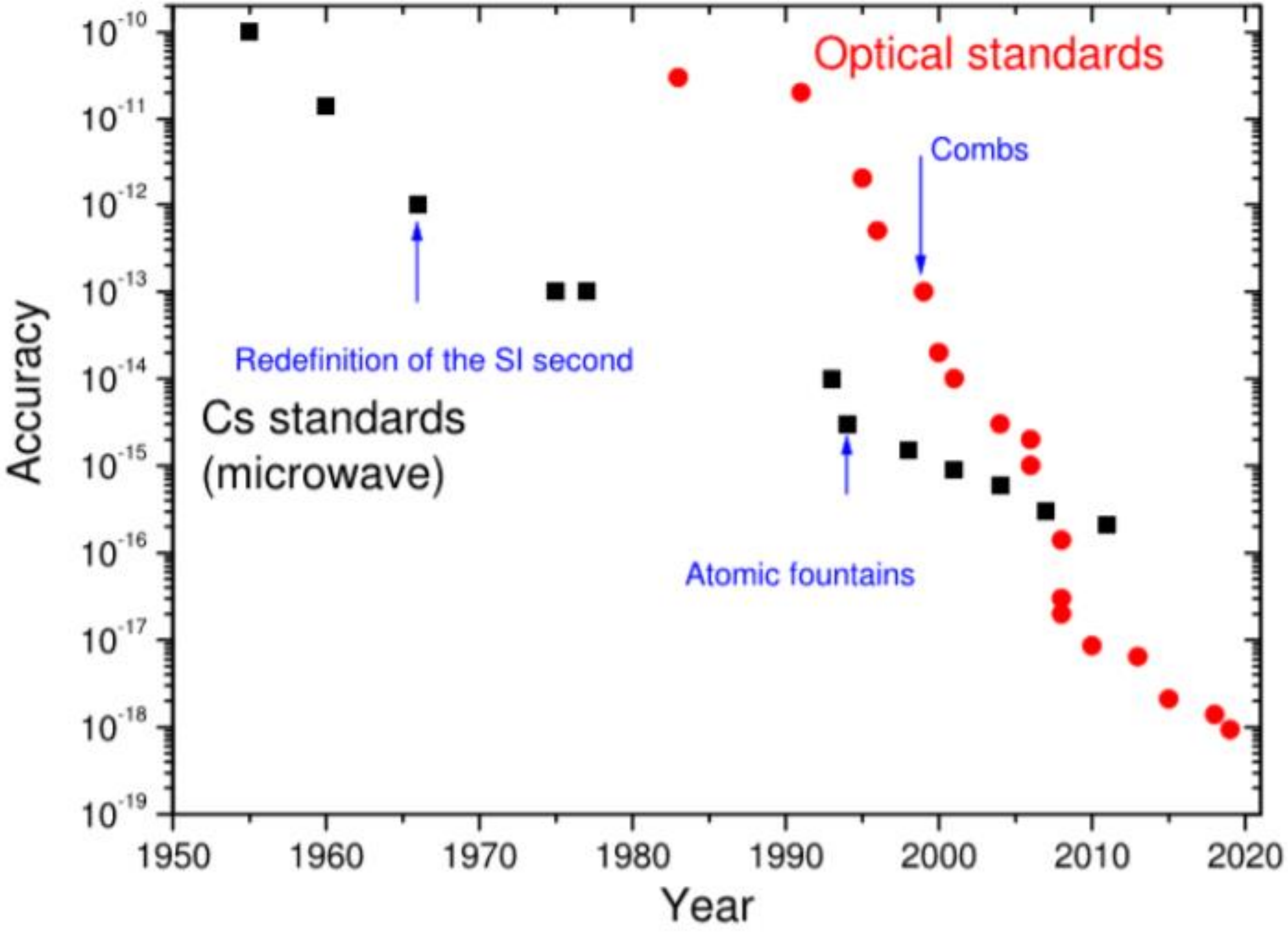
Daily energy output = 33 QJ



Mass = 10 qg

What’s next for the second?

- It is likely that the unit of time will continue to relate to an atomic property
- Optical clocks are already more ‘accurate’ that the current Cs microwave clock definition
- Current limiting factor is decision over atom/ion to use, and ability to compare across locations
- Roadmap for redefinition of second in 2030??



The SI is an essential part of modern society!

Any questions?