The SI from Platinum to Planck: *The biggest revolution in metrology since the French Revolution*

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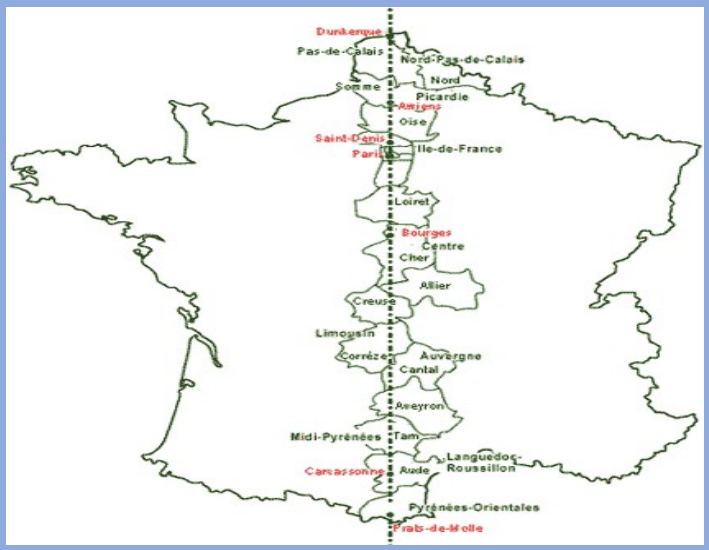
PML

A Brief Review: From the Origin of the Metric System to the Modern SI

Origin of the Metric System

Now known as International System of Units (SI)

- Adopted by Intl. committee on *December 10, 1799*
  Basic principles: Decimalization, open access, *based on nature*
- Treaty of Meter signed May 20, 1875 (U.S.:1878)
- Originally *only* weights (kg) and measures (m)
- Amended in 1921 to add:
  - Coordinating and establishing electrical units
  - Duty to determine the ***physical constants***
- The CGPM in 1954 *adopts 6 base units* (*meter, kilogram, second, ampere, Kelvin,* and *candela*) giving rise to the modern SI – mole added in 1971
- In 1960 adopts the name "*Système International d'Unités*" (SI)



Survey of the Meridian, Dunkirk to Barcelona 1792–1799

Bureau International des Poids et Mesures: BIPM

Dawn of the New Metrology Era

- Timeline of some major metrology advances
- *A few months ago* mass measurement still depended on a single chunk of metal — *Le Grand K*
- But this changed . . .

1799 Metric System

1875 Treaty of the Meter

1889 Base units –m, kg, s

1954 A, K , cd

1967 Second = Cs 133 hyperfine frequency

1971 Mol added as base unit

1983 Meter= c in vacuum

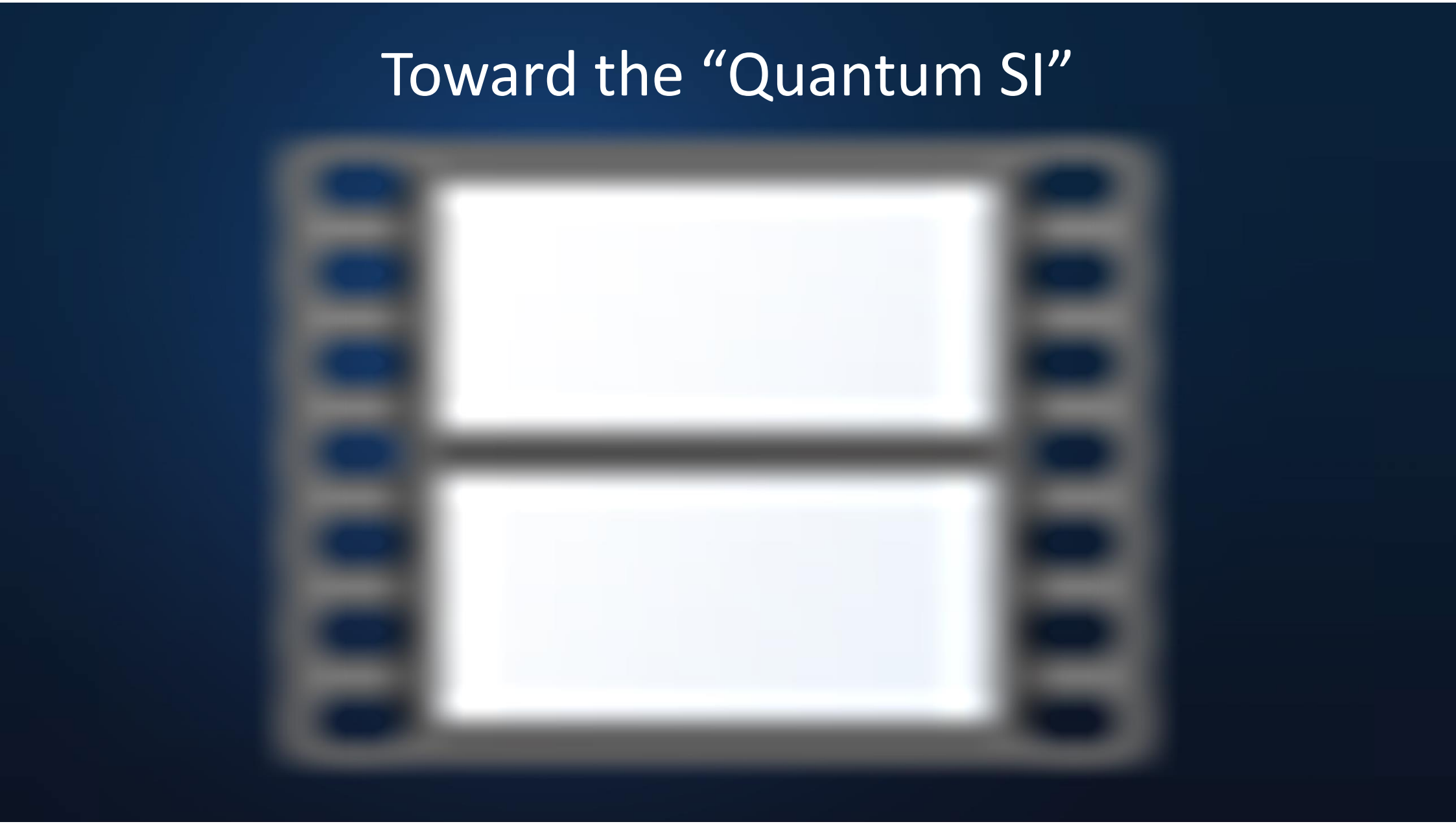
2019 Constant based SI

Credit Left: PM:/NIST Credit Right: Wikimedia Creative Commons/Airair

The Système International d'Unités: SI

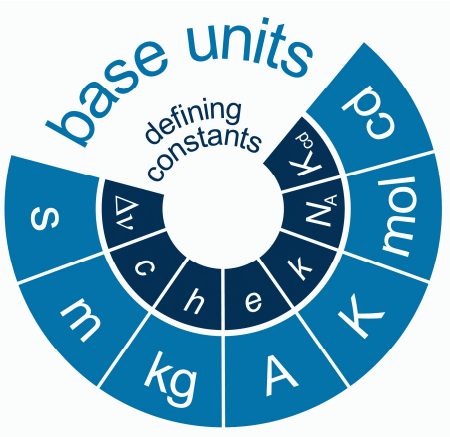
Today, the base units of the International System of Units are defined by the fixed values of fundamental constants of nature.

Toward the “Quantum SI”



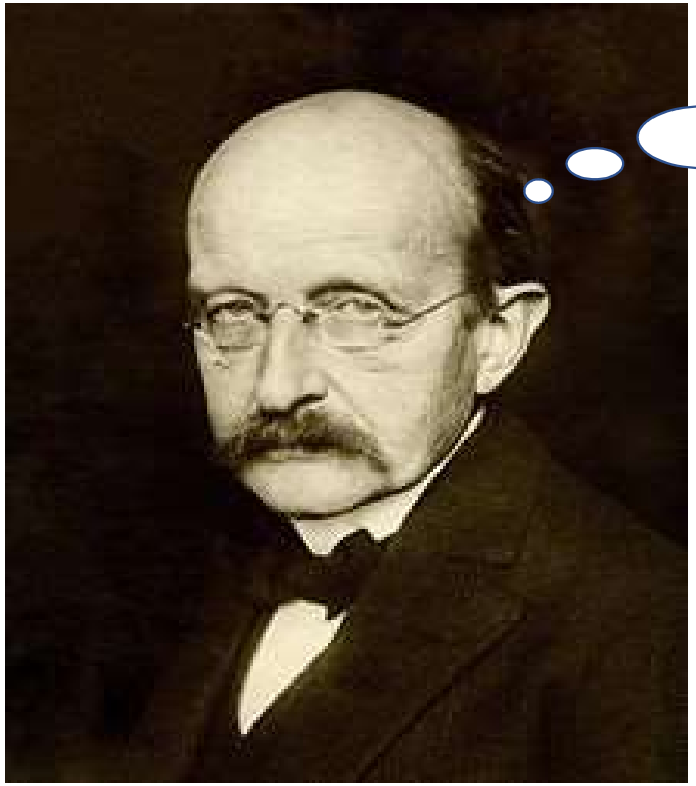
Comparing the Old and Quantum SI

Old SI		"Quantum" or Modern SI	
Base quantity	**Base unit**	**Base quantity**	**Defining Constant**
Time	second (s)	Frequency	$\Delta\nu(^{133}Cs)_{hfs}$
Length	meter (m)	Velocity	c
Mass	kilogram (kg)	Action	h
Electrical Current	ampere (A)	Electric Charge	e
Therm. Temperature	kelvin (K)	Heat Capacity	k
Amount of Substance	mole (mol)	Amt of Substance	N_A
Luminous intensity	candela (cd)	Luminous intensity	K_{cd}



From: D. Newell, "*A more fundamental International System of Units*," *Physics Today* **67(7),** July 2014.

How new of an idea is the Modern SI?



The two constants [h,k]…which occur in the equation for radiative entropy ***offer the possibility of establishing a system of units for length, mass, time, and temperature*** which are ***independent of specific bodies or materials*** and which necessarily maintain their meaning for all time and for all civilizations*, even those which are extraterrestrial and non-human.

-- Max Planck, 1900

*Planck uses language similar to that used by the Marquis de Condorcet when he transferred the original French length and mass standards to the Archives de la Republique in 1799. More on the new SI can be found in Dave Newell's Physics Today article, July, 2014.

The Modern SI or SI

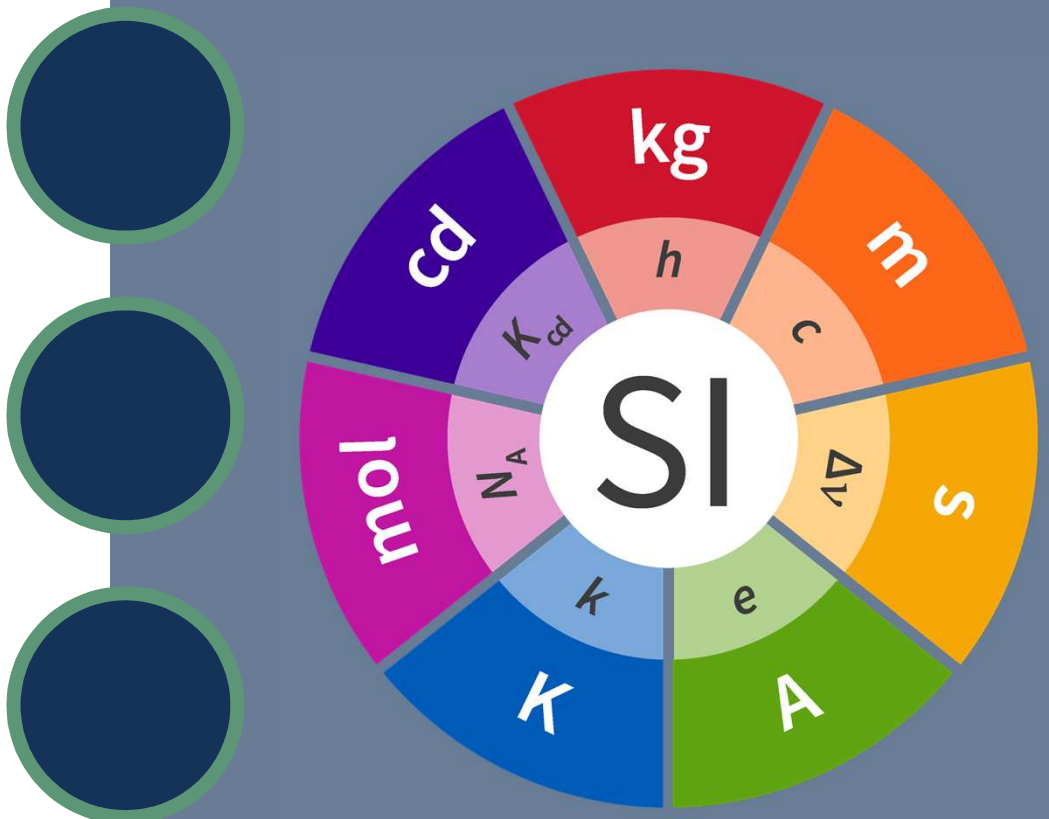
The French revolution brought us the metric system, with metres as the measure of length, and kilograms as the measure of mass.

The *Convention du Metre* brought us an international agreement about the units.

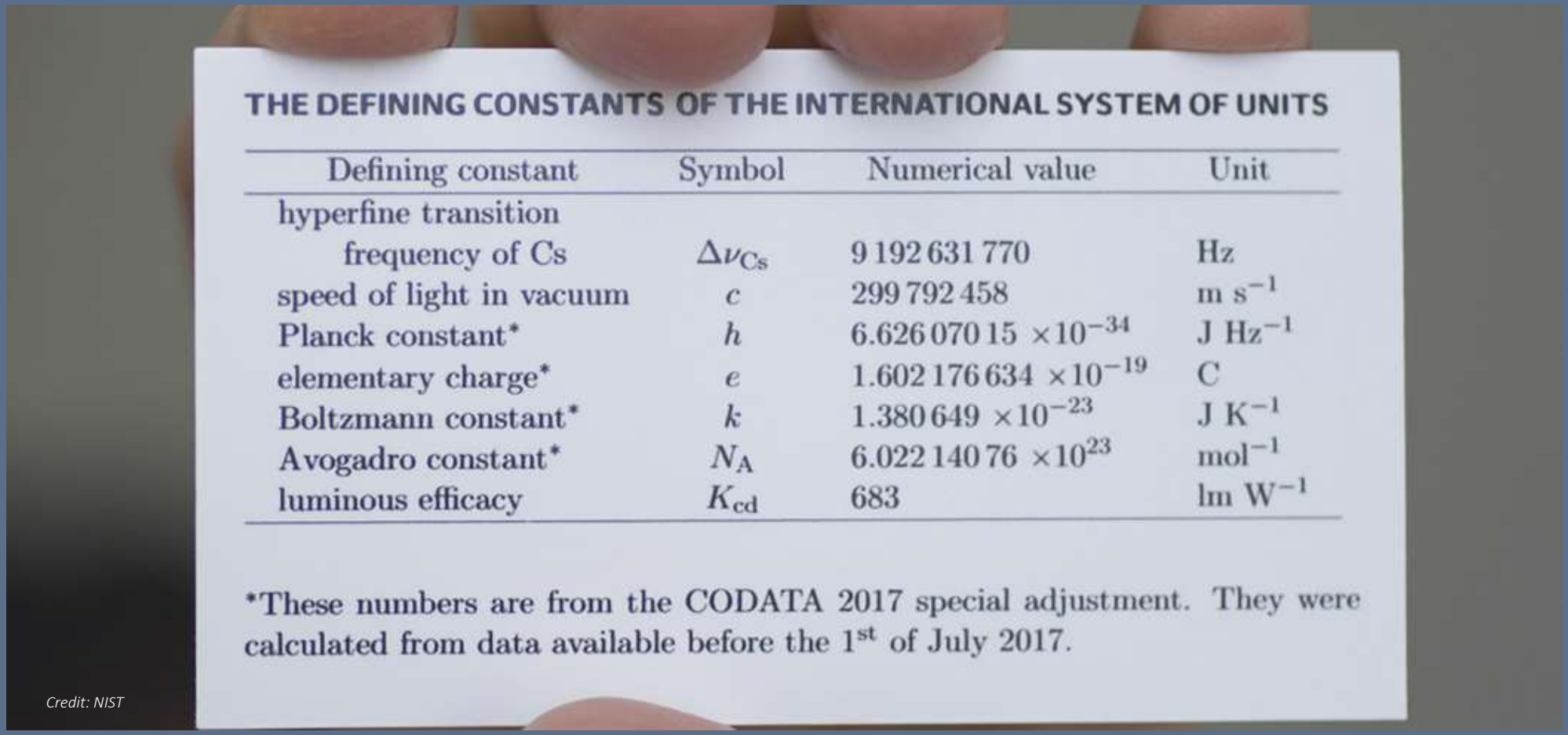
On 20 May 2019 (the anniversary of the signing of the 1875 Convention du Metre), we *enjoyed* the biggest revolution in measurement units since the French Revolution.

The New Système Internationale

All of the base units of the International System of Units will be defined by fixing the values of fundamental constants of nature.



The Defining Constants of the New SI



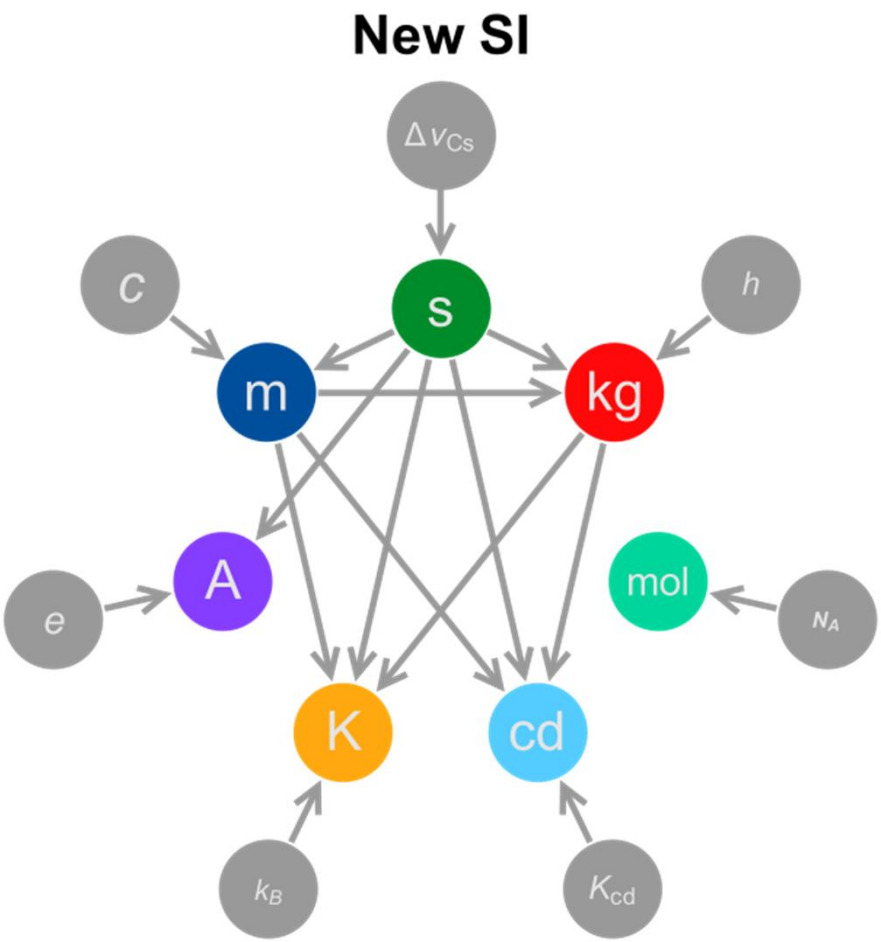
THE DEFINING CONSTANTS OF THE INTERNATIONAL SYSTEM OF UNITS

Defining constant	Symbol	Numerical value	Unit
hyperfine transition frequency of Cs	$\Delta\nu_{Cs}$	9 192 631 770	Hz
speed of light in vacuum	c	299 792 458	m s^{-1}
Planck constant*	h	$6.626\,070\,15 \times 10^{-34}$	J Hz^{-1}
elementary charge*	e	$1.602\,176\,634 \times 10^{-19}$	C
Boltzmann constant*	k	$1.380\,649 \times 10^{-23}$	J K^{-1}
Avogadro constant*	N_A	$6.022\,140\,76 \times 10^{23}$	mol^{-1}
luminous efficacy	K_{cd}	683	lm W^{-1}

*These numbers are from the CODATA 2017 special adjustment. They were calculated from data available before the 1st of July 2017.

Credit: NIST

Quantum SI



Traceability directly to the SI

Zero-length traceability chain

Democratizing Metrology

Realizing the Dream

À tous les temps, à tous les peuples.

For all times, for all peoples.

Direction Générale des Entreprises : Photo

Length Metrology: Example of moving toward a Constant Based System

Ancient Length Standards

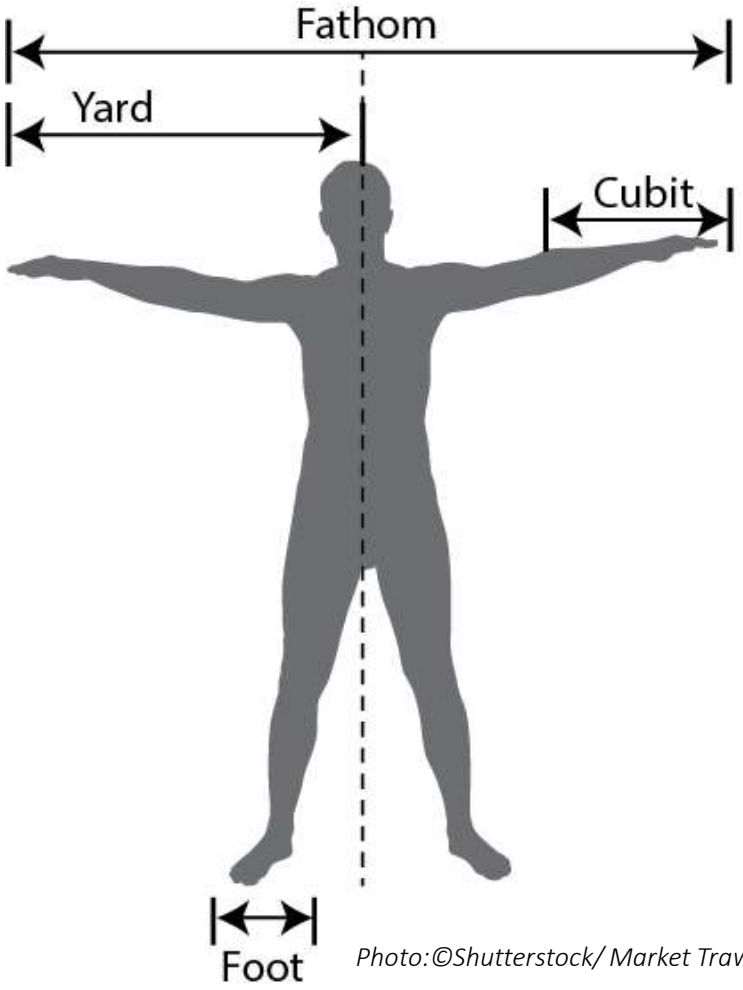


Photo:©Shutterstock/ Market Trawczynski

The early approach to length used the human body as the standard.

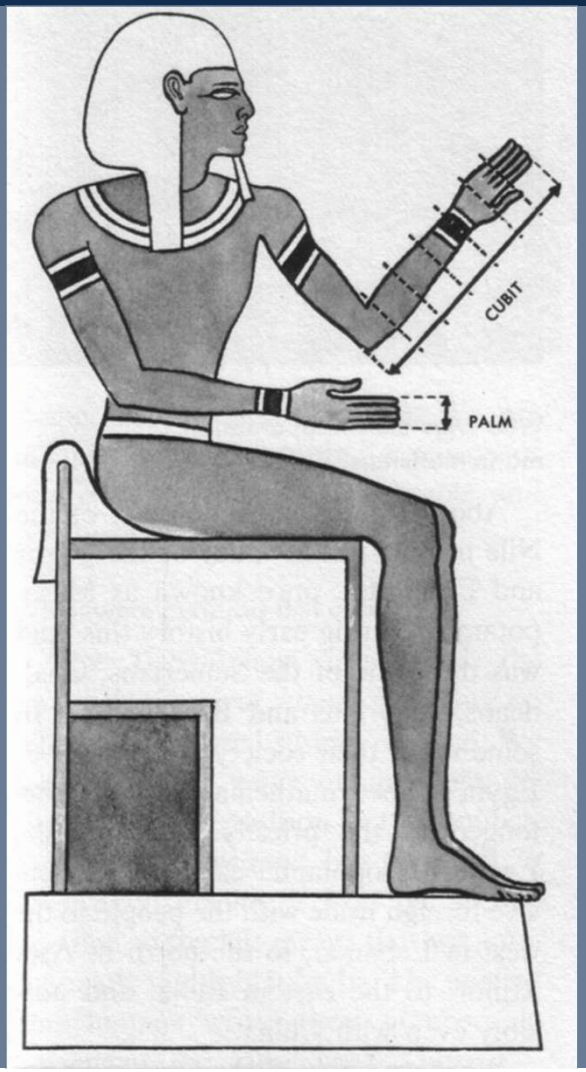
Ancient Length Standards

This was convenient, but not very consistent.

(A short fabric merchant might be selling you a smaller length of fabric than you had expected.)

Ancient Length Standards

One solution was to use a particular body—that of the king or pharaoh—as the standard.



Ancient Egyptian Approach

- Surprisingly modern
- Royal Egyptian cubit, based on the size of the Pharaoh's forearm and hand, was embodied as an artifact.
- Primary cubit in granite
- Secondary cubits in wood
- Recalibration each month
- Death penalty for noncompliance

Base lines of pyramid consistent to 0.025%; square to 12 arcsec

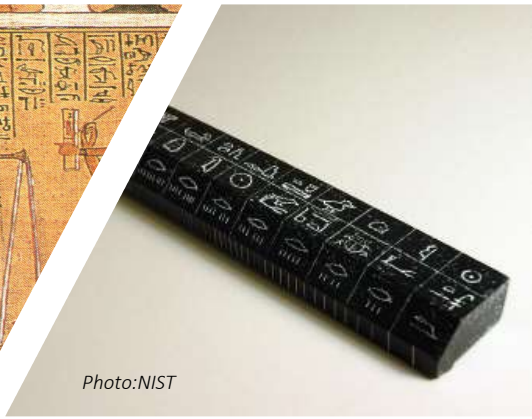


Photo:NIST

Ancient Length Standards

Photo:©Stephan Schlamminger, used by permission

- Standard fathom, foot and cubit fixed into the wall at the city hall of the city of Regensburg.

- These standards were different from those of surrounding Bavaria—a vexing, but common problem.

The Revolutionary Metre

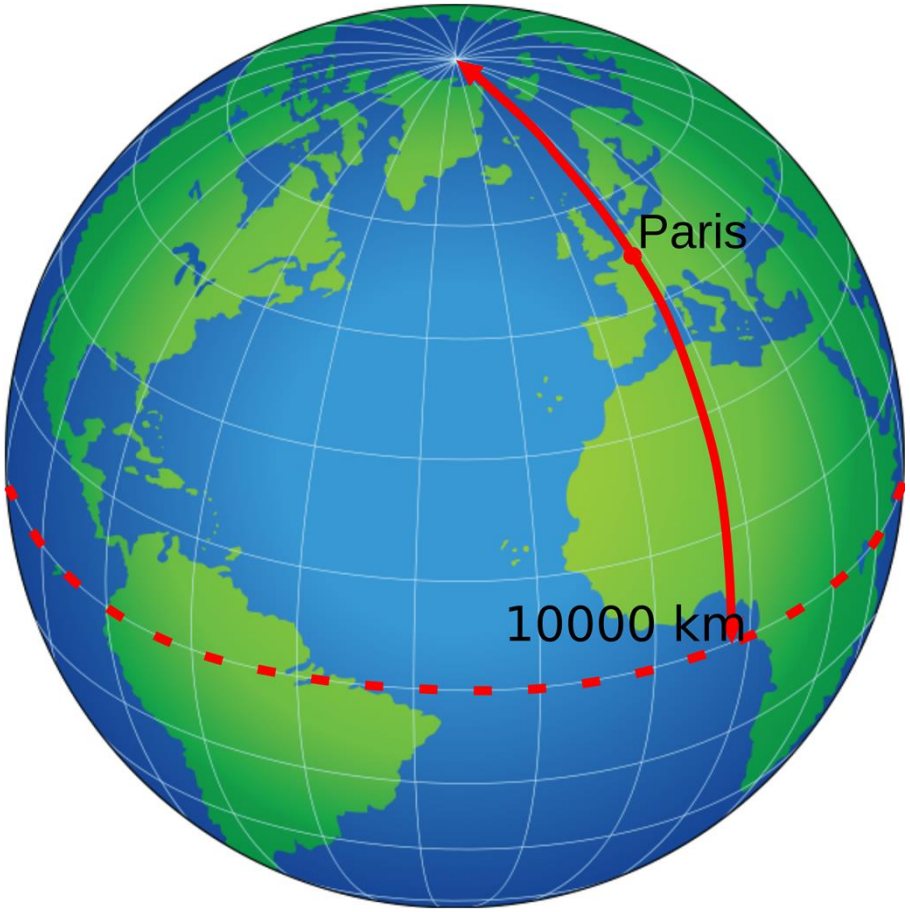


Photo: U.S. Government

The metric system came into being, during the French Revolution (ca. 1791) based on the metre and kilogram and *natural philosophy*.

The metre was to be **"the measure of all things,"** and was (in the spirit of equality and fraternity) to be available to everyone.

The metre is **1/10 000 000 of the distance from the equator to the pole** along a meridian passing through Paris.

The Metre Archived

The earth as a definition of the metre was clear, and more stable (and global) than the Pharaoh's forearm, or a city-specific standard, but it was hardly more convenient.

The meridian definition of the metre was used to create an artifact end-standard—the "metre of the archives."

This was very much in the spirit of the Egyptian cubit, where the definition of length was a primary-standard artifact, against which secondary, working standards were calibrated.

The New Metre

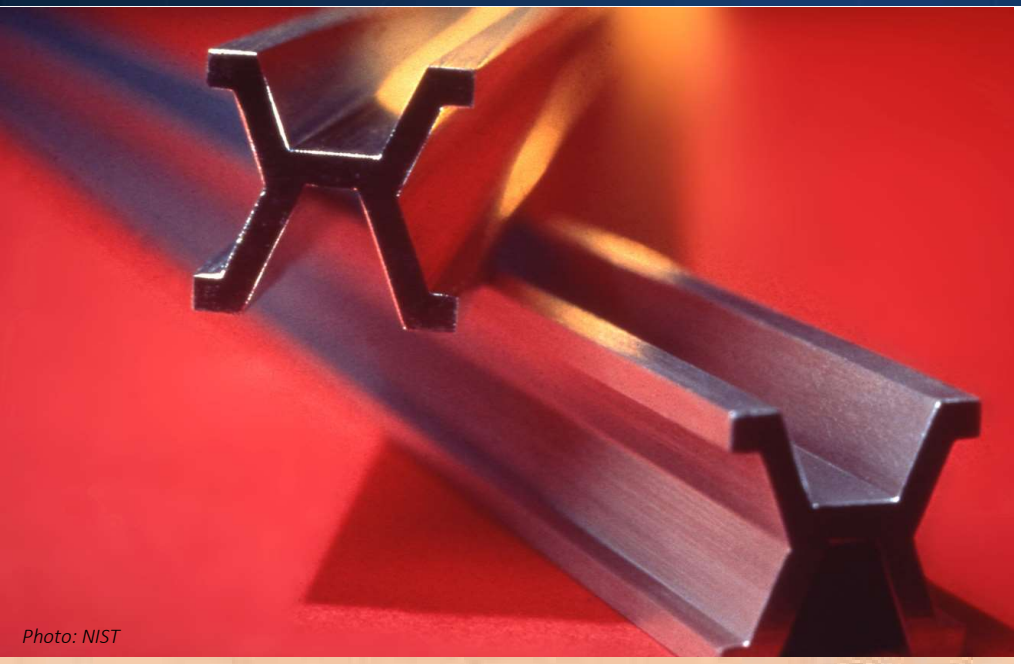
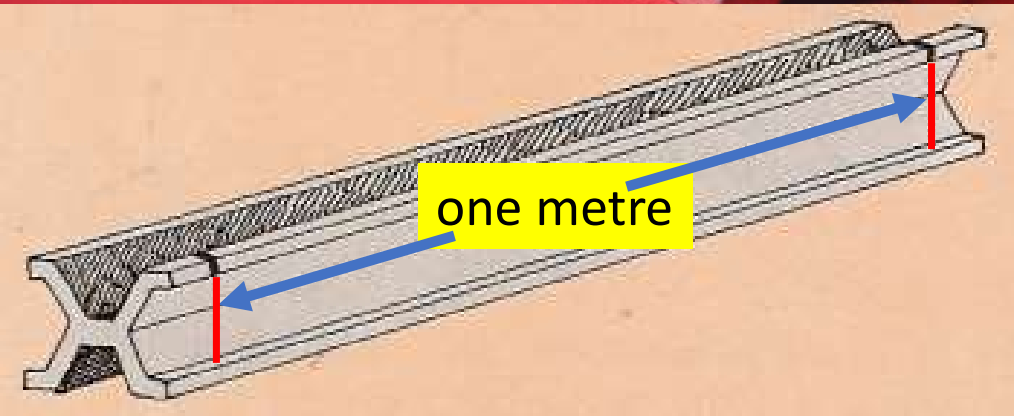


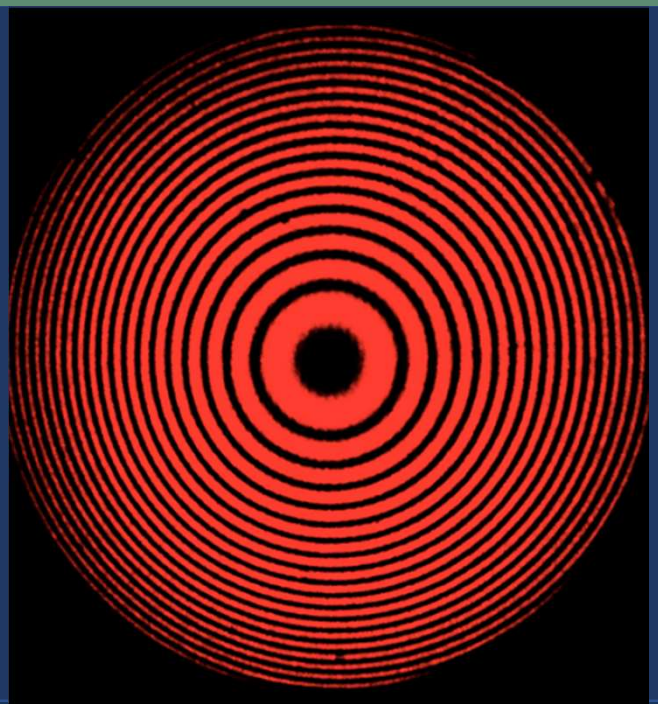
Photo: NIST

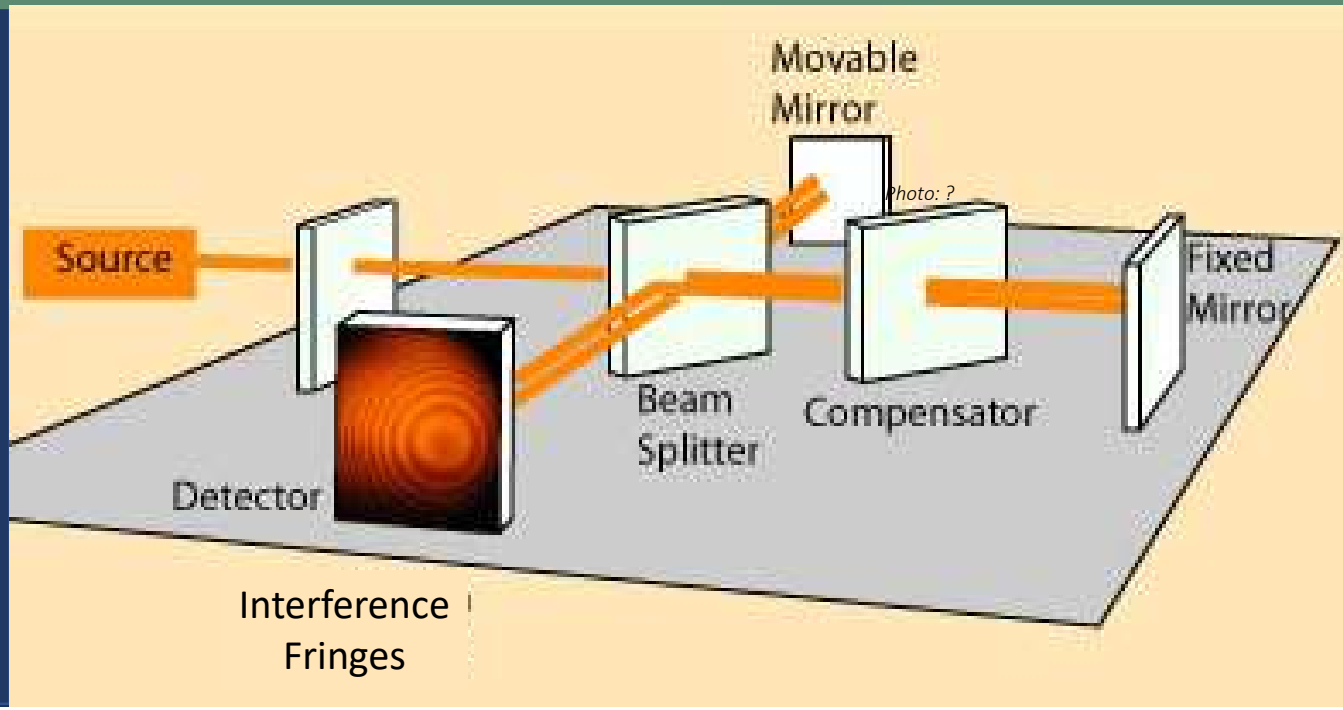


Following the famous 1875 Convention du Metre (the International Treaty of the Metre), the metre of the archives was replaced with a line standard, the International Prototype of the Metre.

Light for Length

Soon, the distance between two scratches became inadequate as a standard, and people used the wavelength of light as a de facto standard.





The Krypton Metre

Photo: NIST

- So, in 1960 *(the year the laser was invented)*, the metre was re-defined as a certain number of wavelengths of light from a krypton lamp.
- But soon, the purity of that light from krypton was found to be insufficient for the accuracy of measurements people were making with laser light

Laser-Light Length

Laser light as a de facto length standard

By the 1970s, almost everyone was using an iodine-stabilized He-Ne laser as an ***unofficial*** standard of length. Such lengths were **NOT in SI metres**.

The metre needed to be re-defined.

The obvious choice:

Define the metre in terms of an I_2-stabilized He-Ne laser.

The brilliant choice:

Define the speed of light.

A Brilliant, BEAUTIFUL Definition of the Metre

NIST

The metre is the length of the path travelled by light in vacuum during a time interval of 1/299,792,458 second.

This effectively **DEFINES** the speed of light, and given:

$$\lambda f = c$$

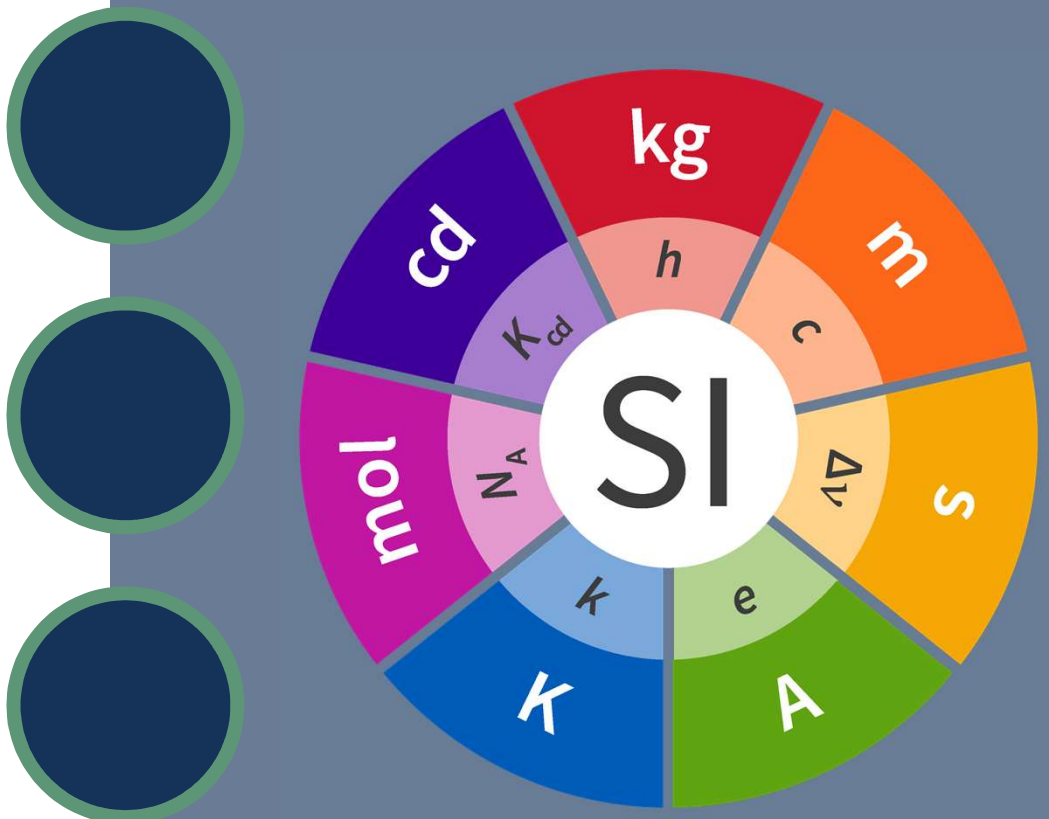
If we know the frequency ***f*** of any light, we know its wavelength λ.

This definition incorporates improvements in lasers and frequency measurements.

17th CGPM 1983

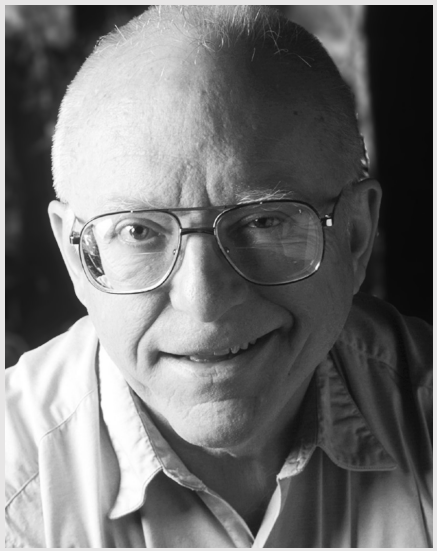
Why is this Beautiful?

- According to the *original wishes* of the founders of the metric system it is *now based* on nature.
- The current definition was reaching its technical limitations of 1 part in 10^7 or 100 nm in a meter.
- It provided a path to get away from scaling.
- It provided numerous ways of measuring from time-of-flight to interferometry.
- And



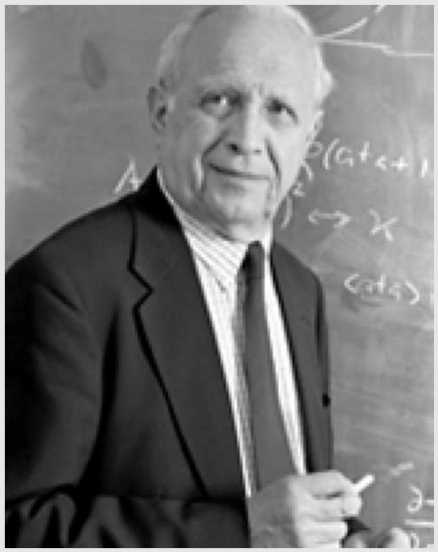
The 2005 Nobel Prize In Physics

The 2005 Nobel to Jan Hall and Ted Hänsch was for dramatic improvements in measuring the frequency of light.



John “Jan” Hall
Photo: NIST

Theodor W. Hänsch
Photo: Courtesy Theodor Hänsch



Roy J. Glauber
Photo: J. Reed

Beautiful Definitions

The definition of the metre is both brilliant and beautiful.

Last November, the CGPM voted to bring this same beauty to the kilogram and the rest of the SI.

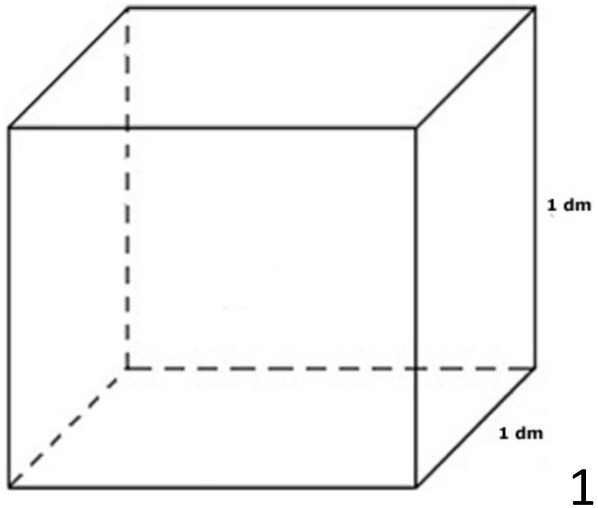
Why and How?

A *Brief* History of Mass

Ancient Mass Standards

In ancient Babylonia and elsewhere, manufactured objects were the mass standards.

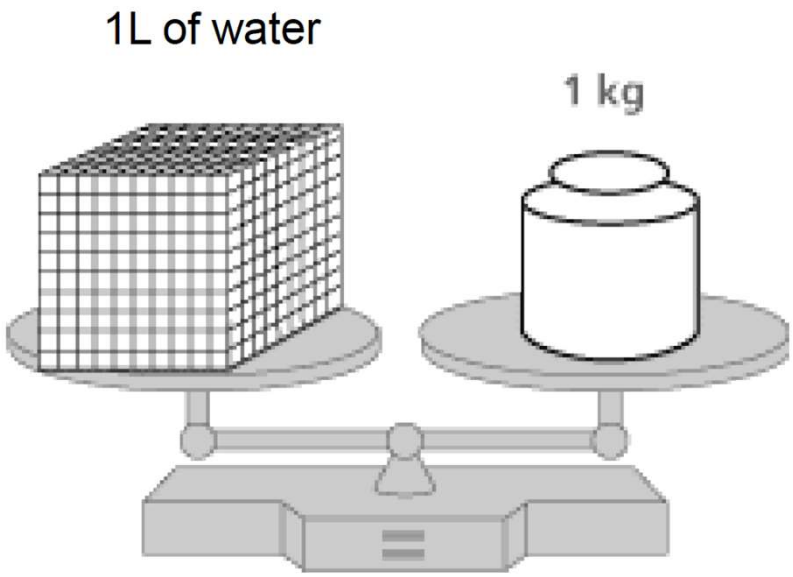
Revolutionary Mass Standard



1 dm

1 dm

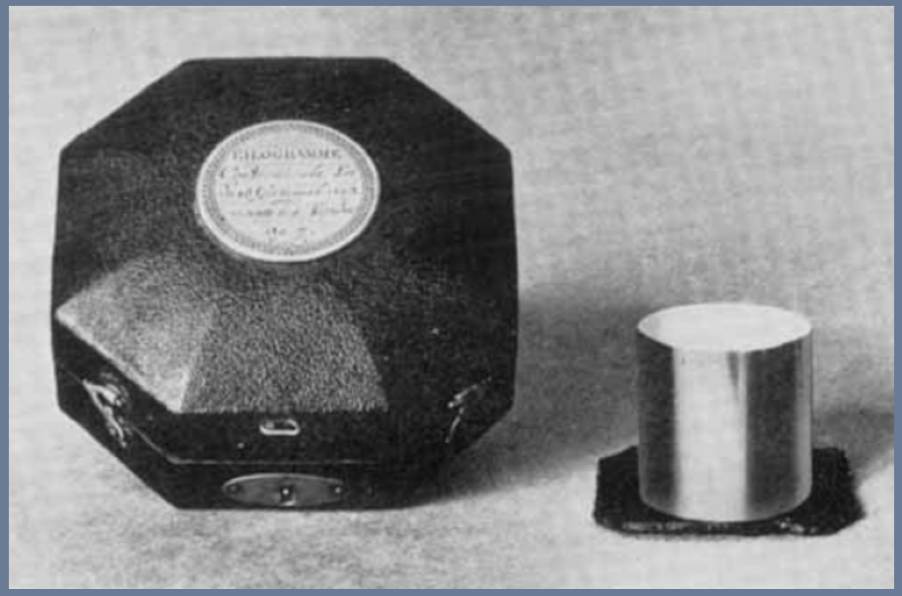
1 dm = 0.1 m



In the French metric revolution, ca. 1793, the kilogram was defined as the mass of a cubic decimetre (a litre) of water.

From Water to a New Artifact

The water definition of the kilogram was difficult to use. So, a platinum artifact became the kilogram of the archives—a return to the ancient practice.



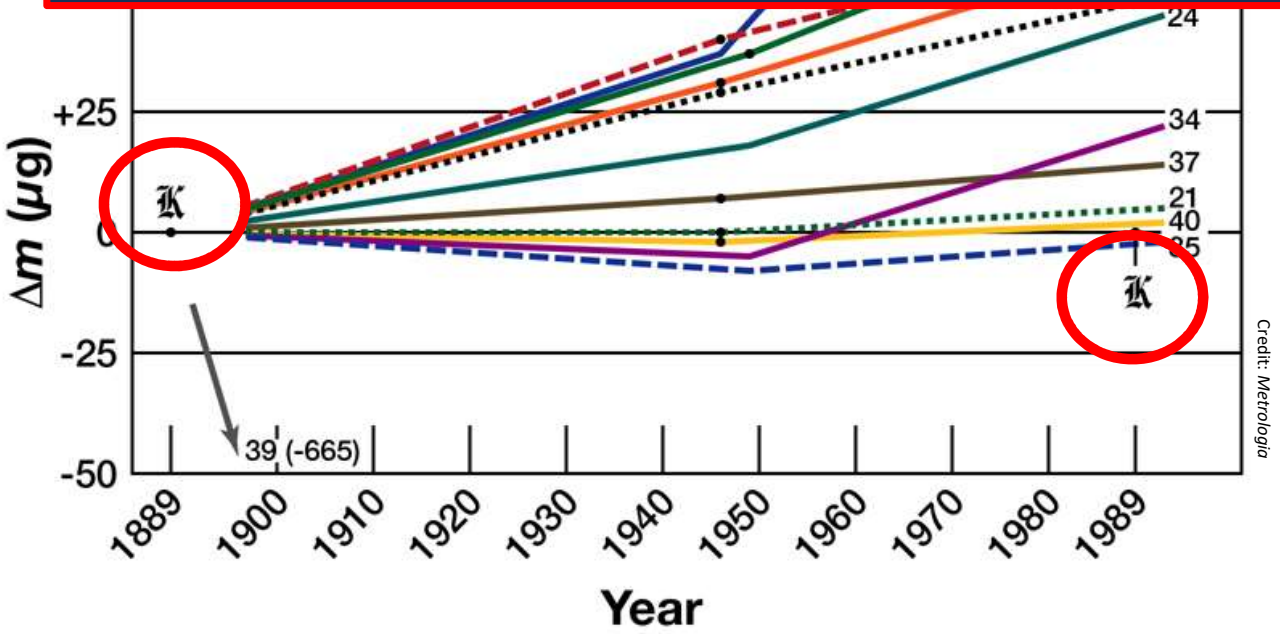
F. J. Smith, *Platinum Metals Rev.*, 1973, 17, (2), 66. ©Johnson Matthey Plc.

International Prototype Kilogram (IPK)

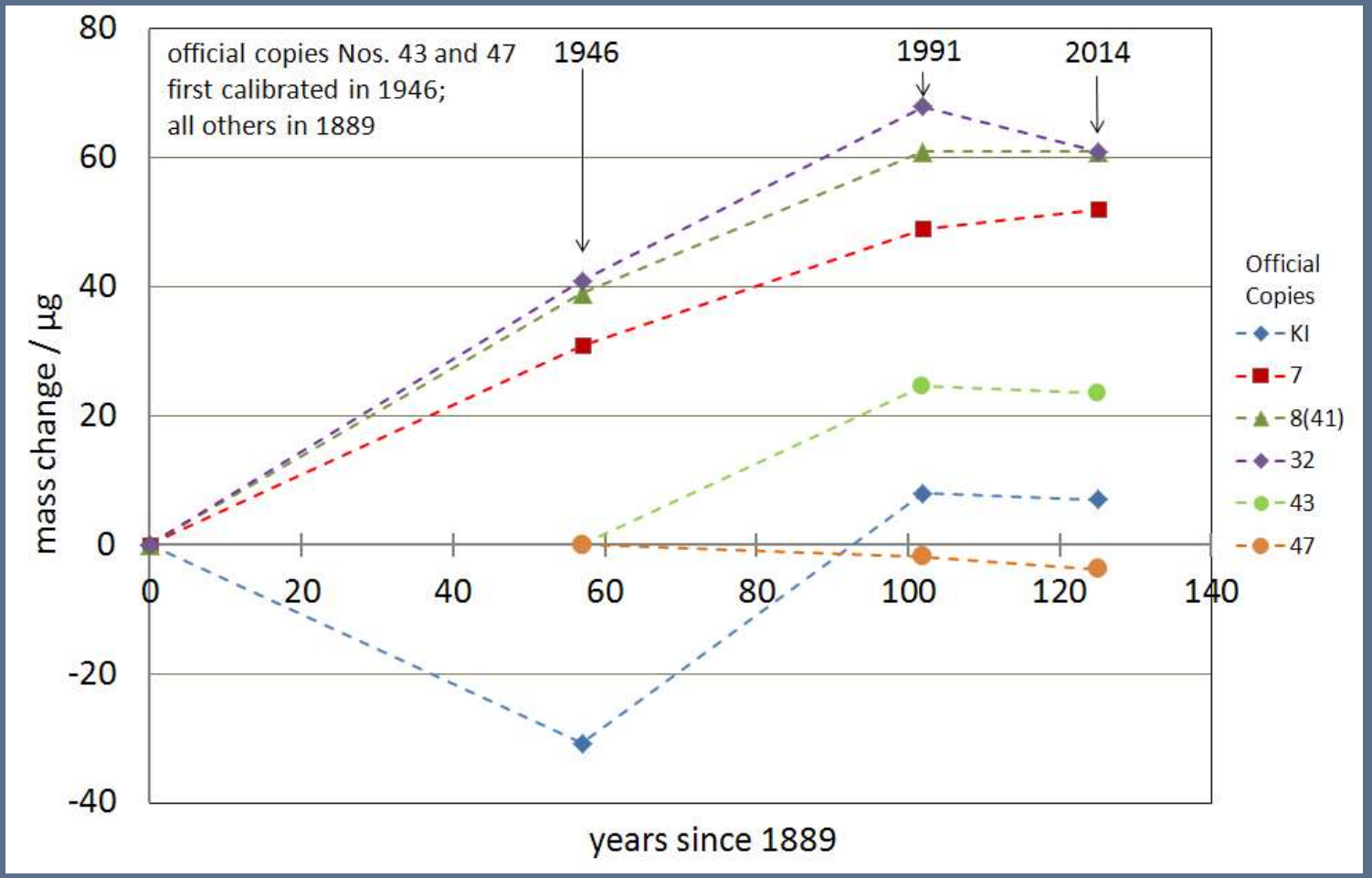
- After the 1875 *Convention du Mètre* a new artifact kilogram (the International Prototype Kilogram–IPK) was made of Pt-Ir.
- This was the *last* artifact.

IPK and its Witnesses Appeared to be Changing

(Of course until the redefinition IPK could not legally change, because it was by definition “the kilogram”.)



IPK and its Witnesses Appeared to be Changing



NIST and Mass Metrology

From the very beginning NIST had two prototype kilograms: K4 and K20 our official copy

In 1996 NIST purchase K79

In 2008, NIST purchased K92 but when NIST received it, its calibration certificate *bothered us.*

In 2010 we recalibrated K20 and the following year K4. As a result NIST shifted its mass scale by +0.045 mg/kg

After the *Extraordinary Calibration* of the IPK in 2014, the BIPM announced its mass scale was too high by 0.035 mg/kg

NIST was one of the only NMI's in the world to recognize the BIPM had a problem – within our k=2 uncertainty.

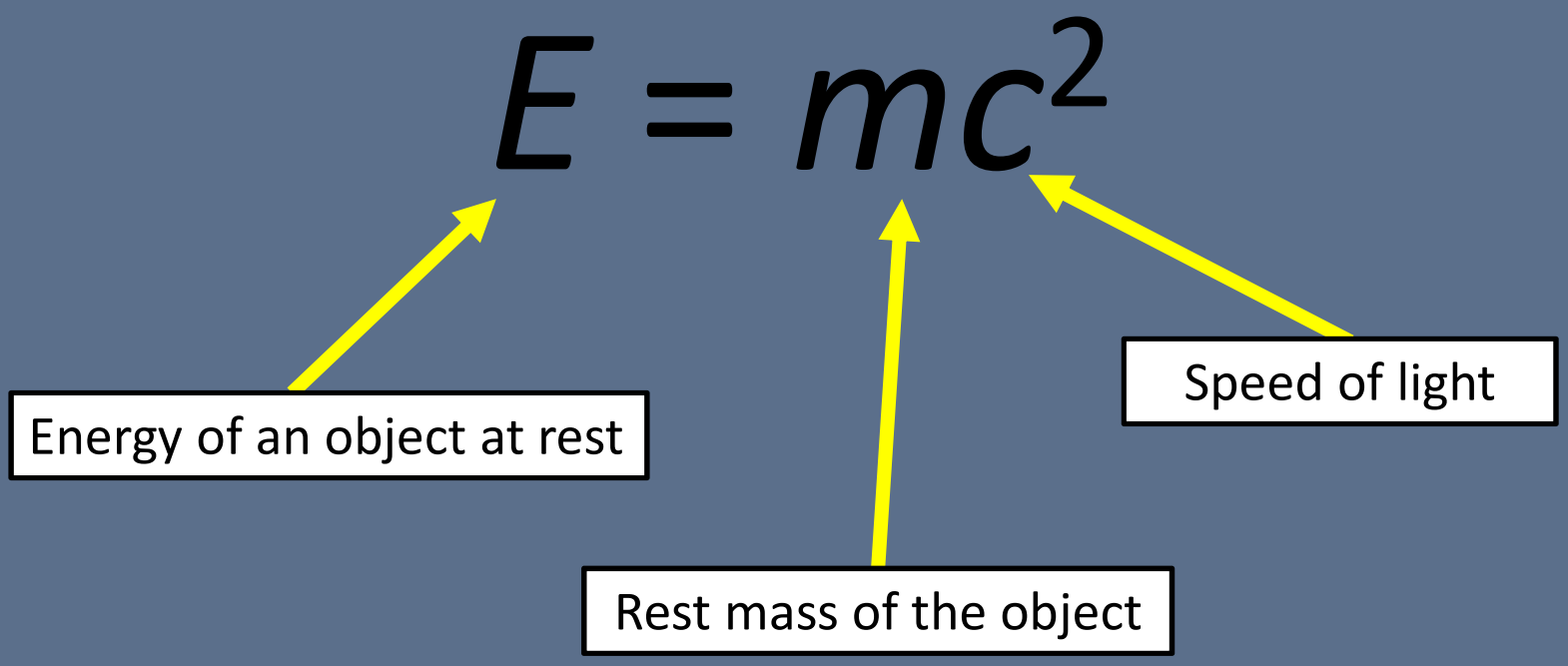
Fixing the Kilogram Problem

This situation had to be fixed. The International Community *wished* to realize the original aims of the *Treaty of the Metre* and use a *beautiful* approach as was done for the metre.

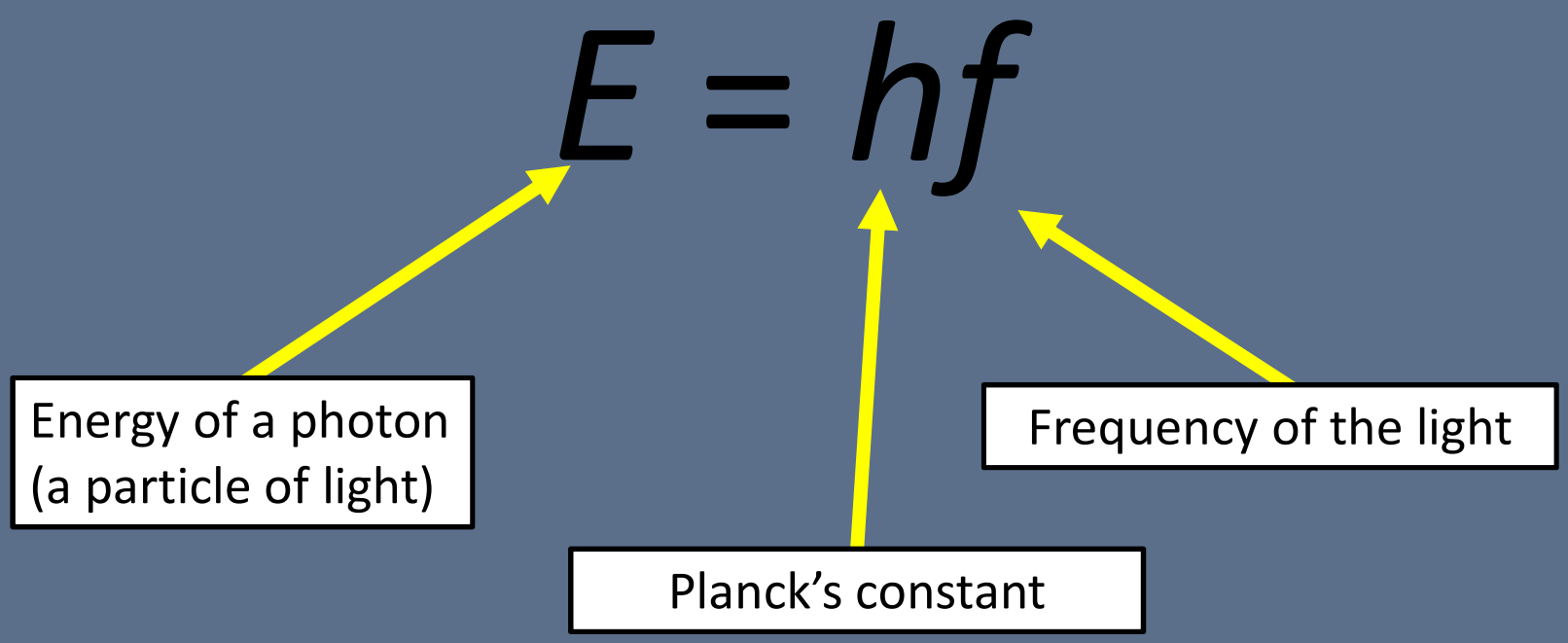
To define the metre, we defined the speed of light *c*.

What constant do we use for kg?

The most famous Equation in History



A slightly less famous Equation

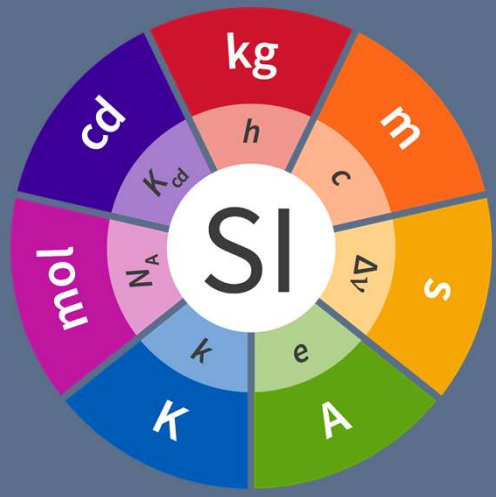


From Planck's Constant to Mass

$$E = mc^2 = hf$$

$$m = hf/c^2$$

The change in mass of a particle when it emits a photon of frequency *f*.



Defining Planck's constant *h* allows us to define mass.

Planck's Constant and the Kibble Balance

We will not be weighing photons (we could, but not well enough). Instead, to use Planck's constant to define the kilogram, we turn to the electro-mechanical device known as a Kibble Balance or Watt Balance.

Bryan Kibble 1938-2016

Operating Principles of the NIST-4 Watt Balance

NIST Physical Measurement Laboratory

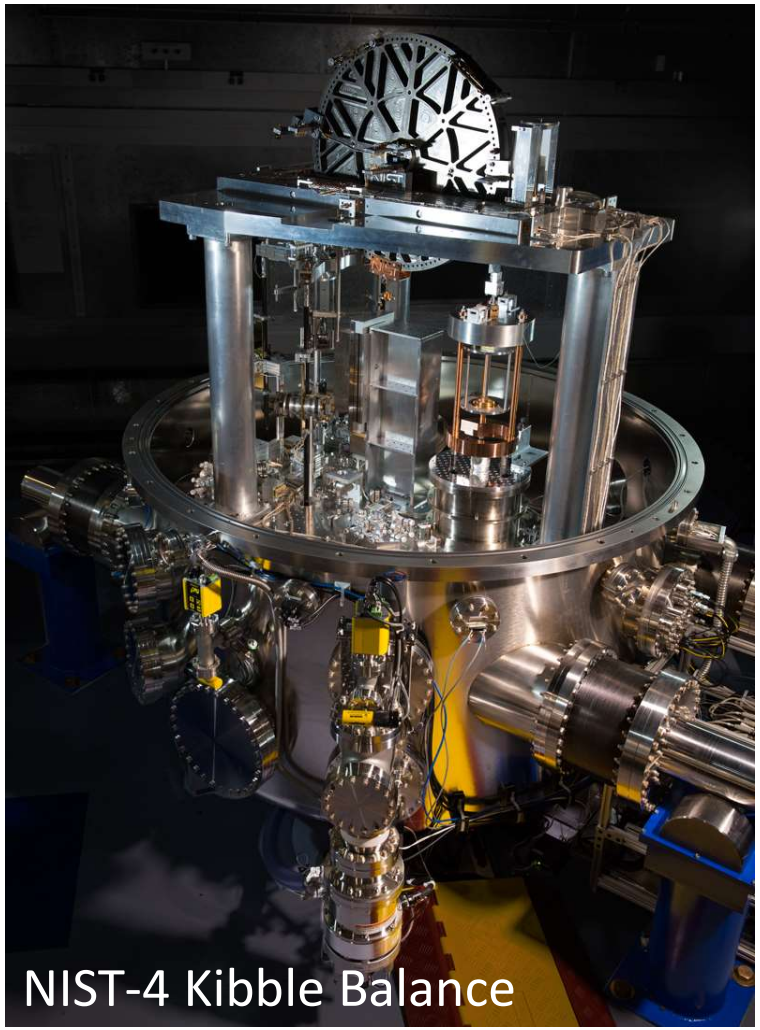
Kibble Balance Basics

- **Weighing or Force mode:** An unknown weight *mg* is balanced by an electromagnetic force on a horizontal coil of wire-length *L* in a radial magnetic field of flux density *B* when a current *I* flows through the coil $mg = BLI$

- **Calibration or Velocity mode:** The magnet's strength *BL* is measured by moving the coil at a velocity *v* while recording the voltage *V* across the coil terminals $BL = \frac{V}{v}$

- The two modes can compare mechanical and electrical power, hence the name, watt balance

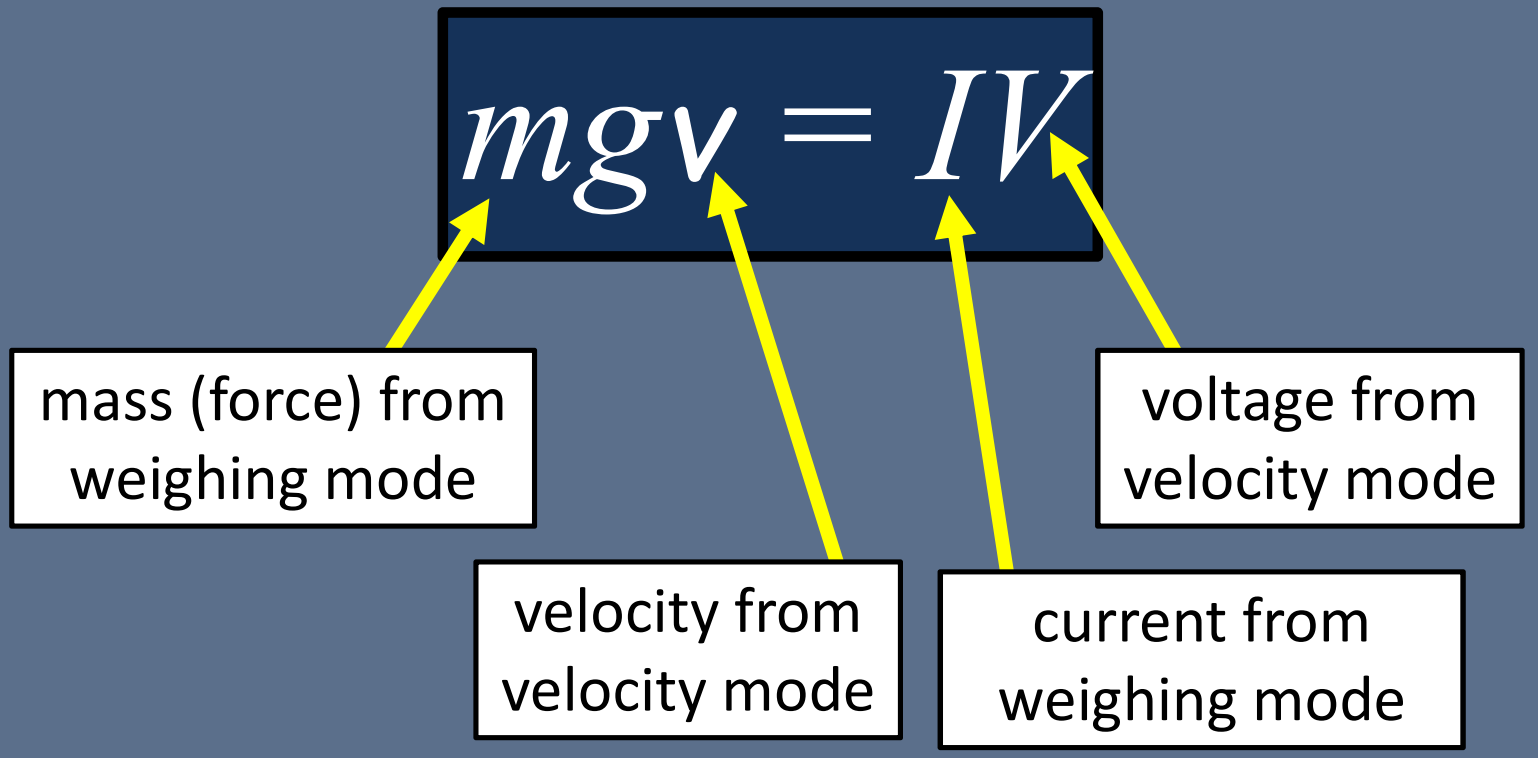
$$mgv = VI$$


NIST-4 Kibble Balance

Kibble (Watt) Balance Principal

Mechanical Power = Electrical Power

$$mgv = IV$$



From Watt to Planck

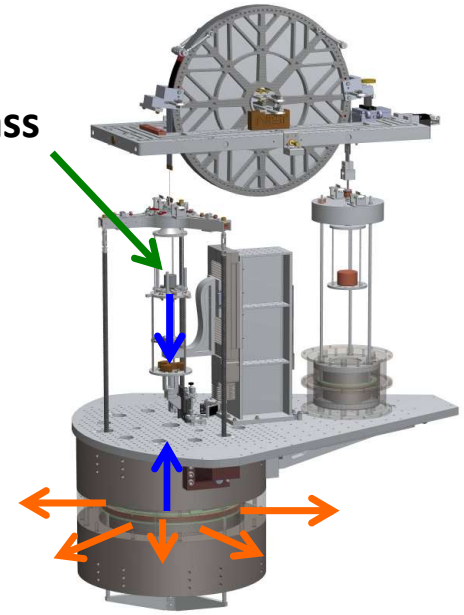
$$m = IV/gv$$

But—how does this relate to Planck's constant?

Answer—the quantum way of doing electrical measurements: the quantum Hall effect (von Klitzing) and the Josephson effect.

Kibble Balance Principles

Force mode



$$mg = BLI \qquad V = vBL$$

$$BL = \frac{mg}{I} \qquad BL = \frac{V}{v}$$

$$\frac{mg}{I} = \frac{V}{v}$$

$$mgv = VI$$

$$mgv = \frac{V_1 V_2}{R}$$

$$mgv = \frac{n_1 f_1 \frac{h}{2e} n_2 f_2 \frac{h}{2e}}{c_i \frac{h}{e^2}} = \frac{n_1 n_2}{4 c_i} f_1 f_2 h$$

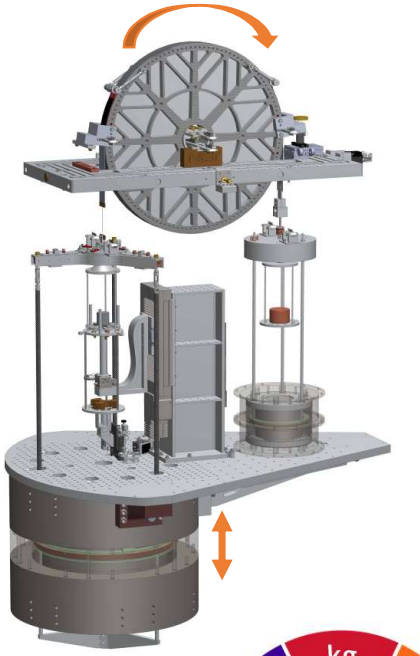
$$h = \frac{4c_i}{n_1 n_2} \frac{gv}{f_1 f_2} m$$

before redefinition

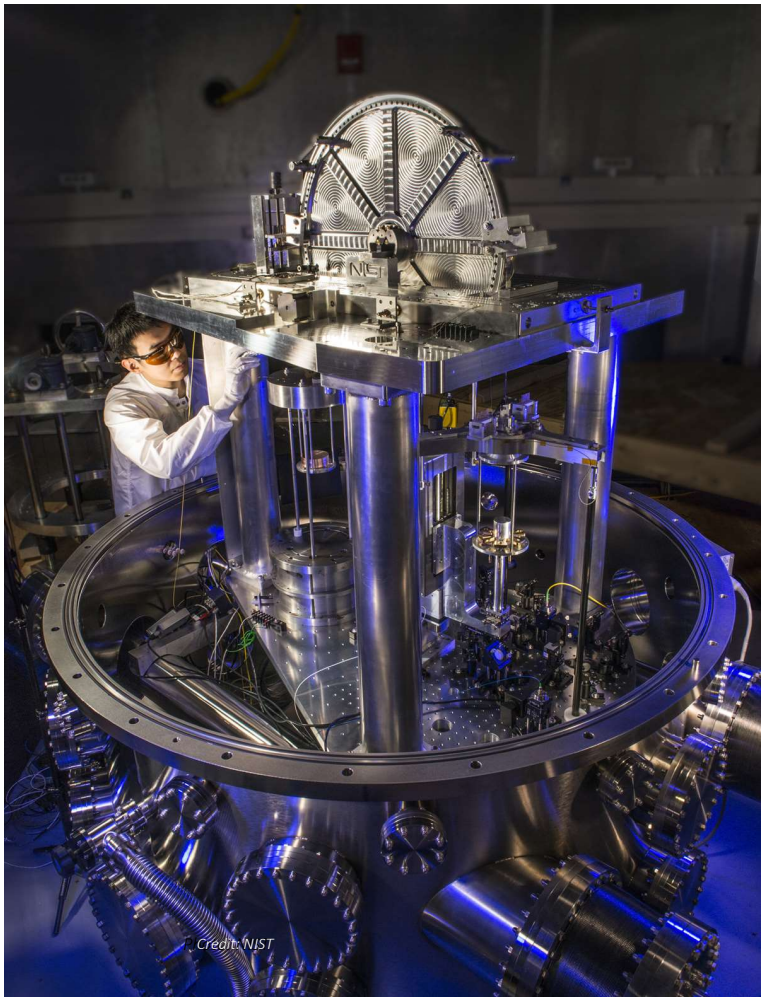
after redefinition

$$m = \frac{n_1 n_2}{4c_i} \frac{f_1 f_2}{gv} h$$

Velocity mode



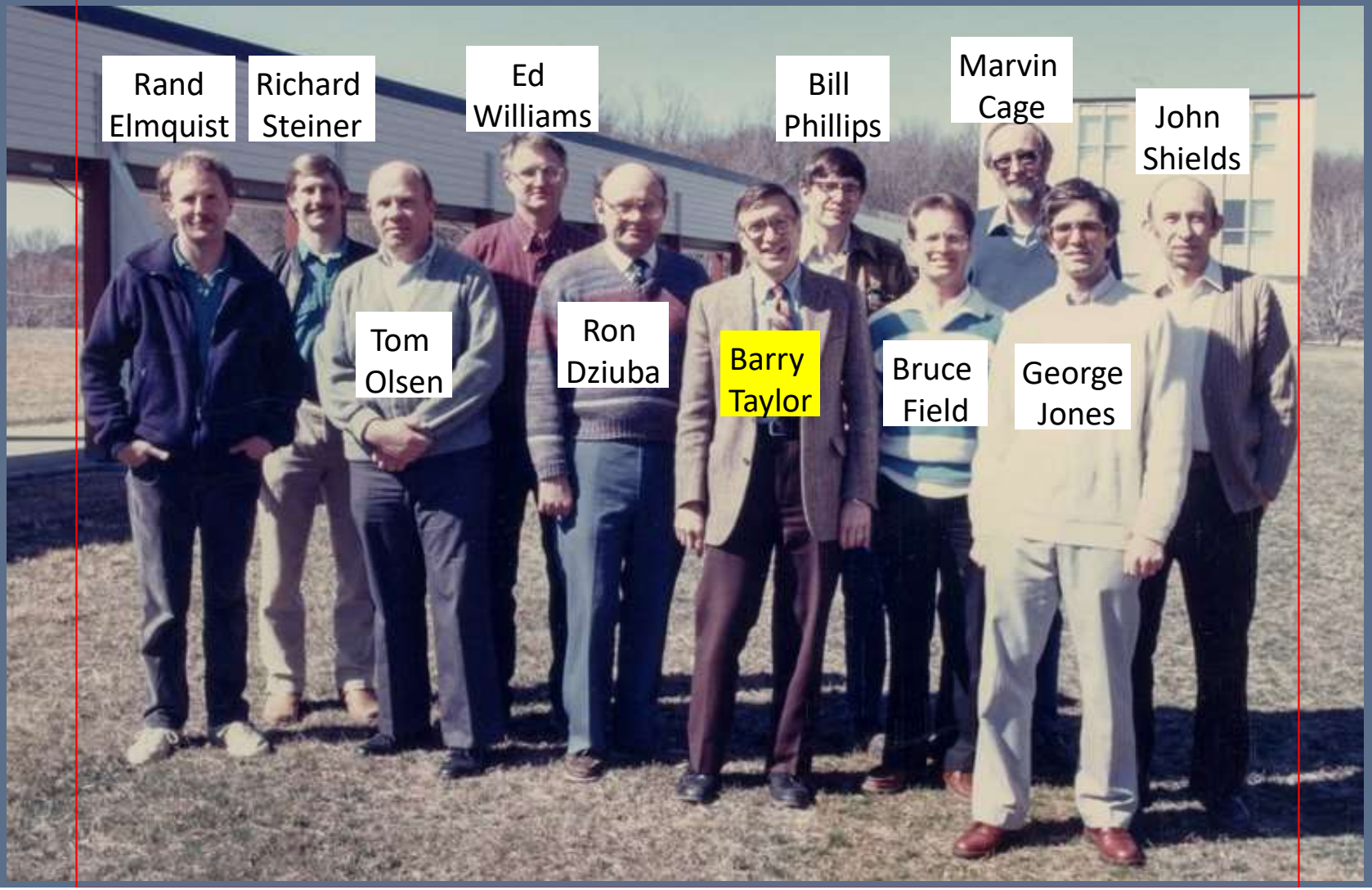
NIST Kibble Balance



Such Kibble balances will realize the kilogram to about 10^{-8}, which is better than the changes due to "dirt".

Who made it happen at NIST?

NIST Original Team – 1988



NIST Kibble Team 2013 -

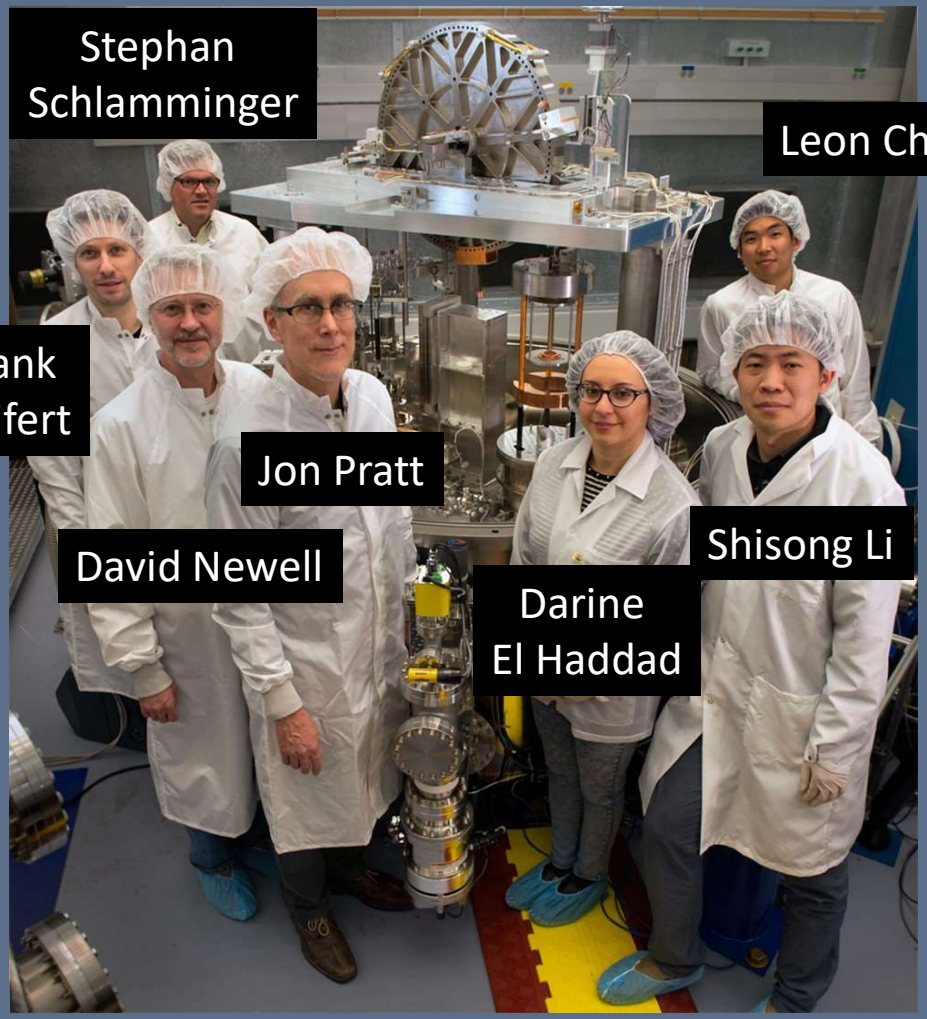
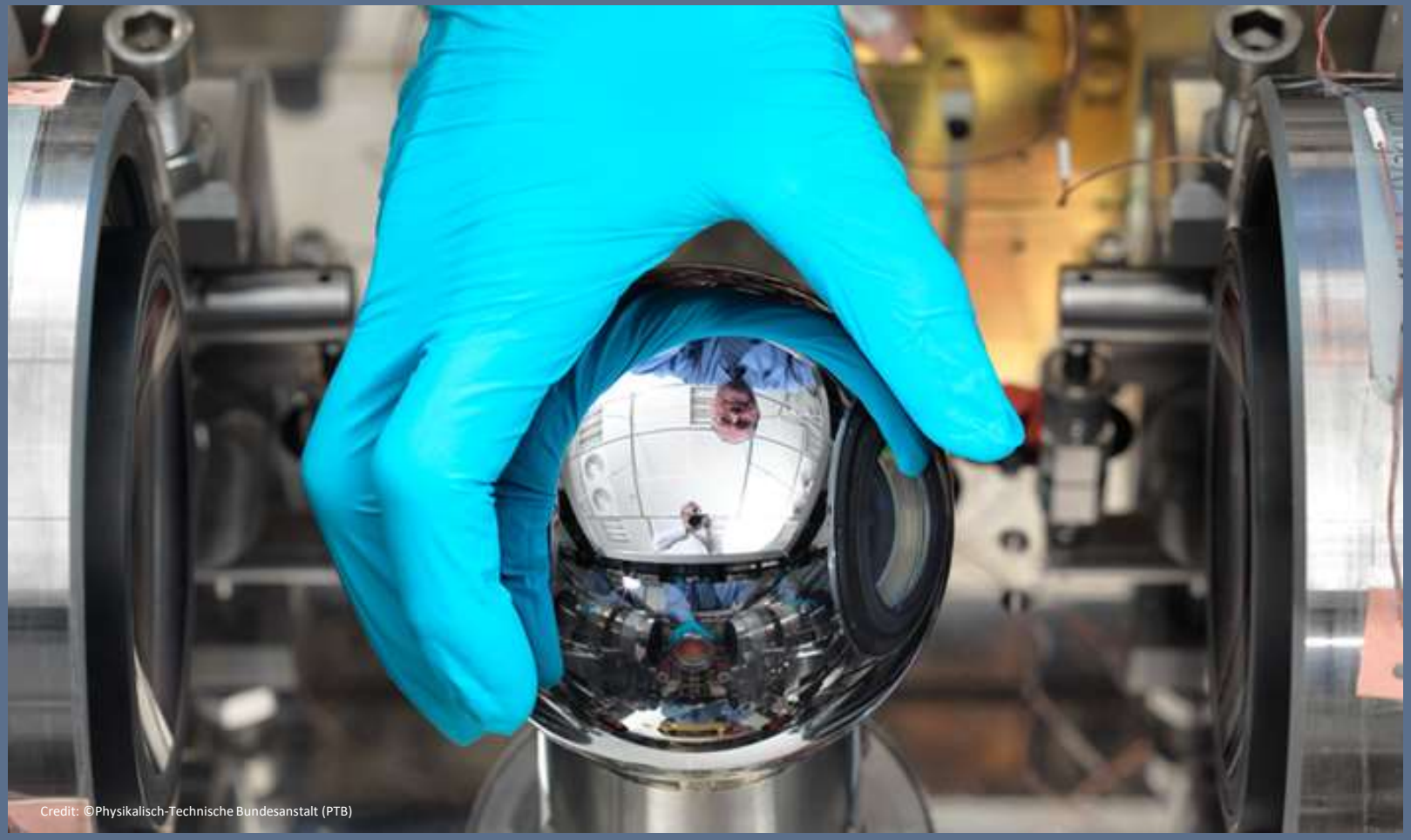


Photo: Jason Stoughton/NIST

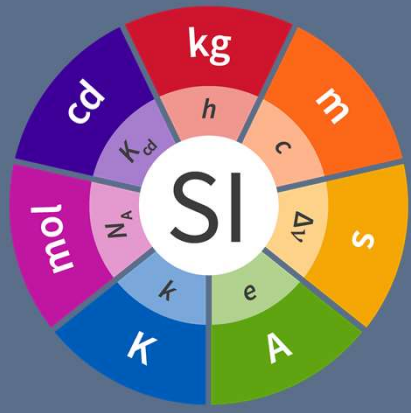
In 2018 (left to right): Patrick Abbott, Edward Mulhern, Zeina Kubarych, Alireza Panna, Dean Jarrett, Peter Mohr, Randolph Elmquist, Stephan Schlamminger, Ruimin Liu, Richard Steiner, Bryan Waltrip, Barry Taylor, Marvin Cage, Edwin Williams, Darine Haddad, David Newell, Frank Seifert, Jon Pratt, Michael Berilla, Leon Chao and Shamith Payagala.

Another Realization of the Kilogram



Defining *h* allows other methods of realizing the kilogram:

Silicon sphere at PTB.



The Last Artifact: Trailer

Some Final Parts of the Story: The Ampere

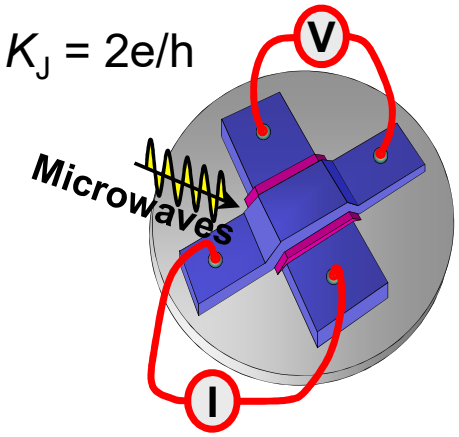
Last Year: "The ampere is that current … which … in two straight, … infinite [wires] … one metre apart in vacuum would produce … a force of 2×10^{-7} newtons per metre."

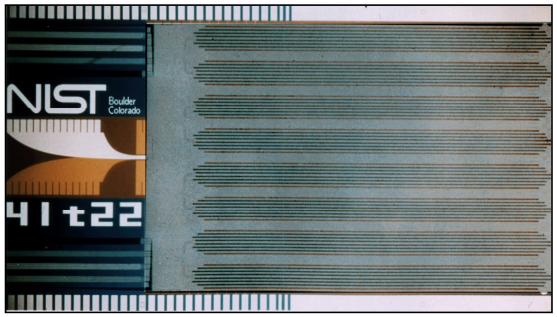
Today: Define the electron charge *e*, so the ampere is a certain number of electrons per second.

With both *e* and *h* defined, $2e/h$ and h/e^2 are exact, and allow us to use the Josephson and Quantum Hall effects to measure all electrical quantities.

Standards for Electrical Units Since 1990

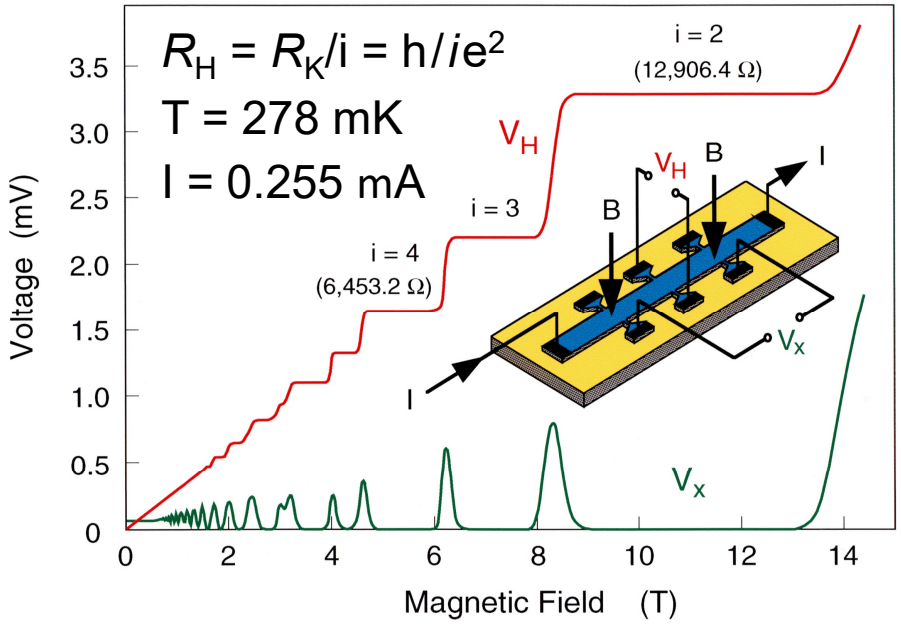
Josephson Voltage Standard





The "volt" realized by Josephson Junction devices, with K_{J-90} = 483,597.9 GHz/V

GaAs Quantum Hall Resistance

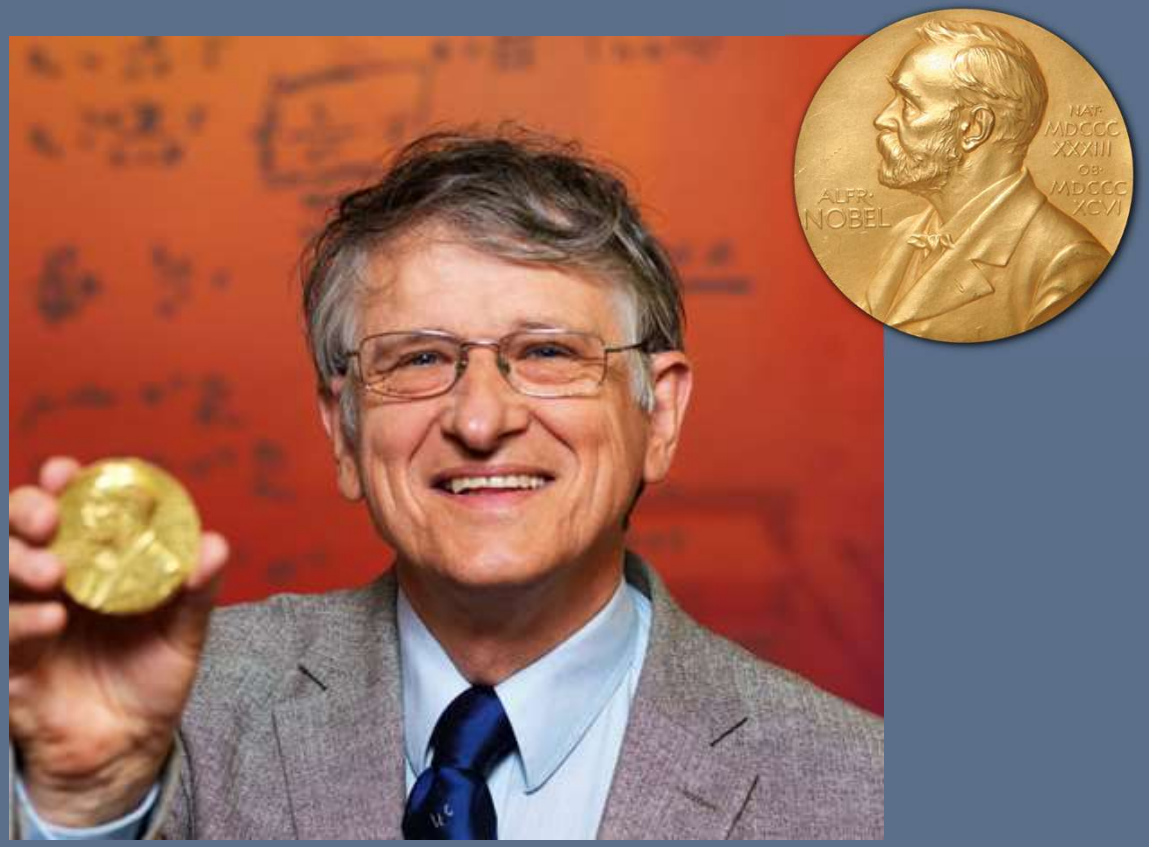


The "ohm" realized by Quantum Hall Effect devices, with R_{K-90} = 25,812.807 Ω
(Graphene QHR underway)

These **quantum standards**, the Josephson effect (1962, Nobel Prize 1973) and the quantum Hall effect (von Klitzing 1980, Nobel Prize 1985) are so robust that in 1987 the CGPM (Resolution 6) established *conventional electrical units!*

Josephson and von Klitzing

Brian Josephson
Josephson Effect – Volt
(1962, Nobel Prize 1973)

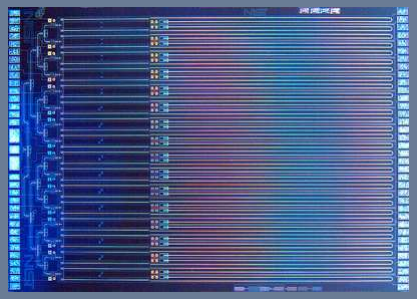


Klaus von Klitzing
Quantum Hall Effect – Ohm
(1980, Nobel Prize 1985)

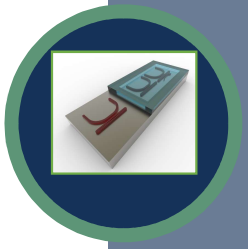
From 1990 Values to the Final Values

- The 1990 values of K_J and R_K, based on the 1990 CODATA value of e and h were abrogated.
- The new values of h and e can now be used to determine $K_J=2e/h$ and $R_K=h/e^2$ to the accuracy needed.
- Small shifts occurred but electrical quantities are forever back in the SI.
- And the future has new possibilities …

Sam Benz holding a 10 V PJVS probe

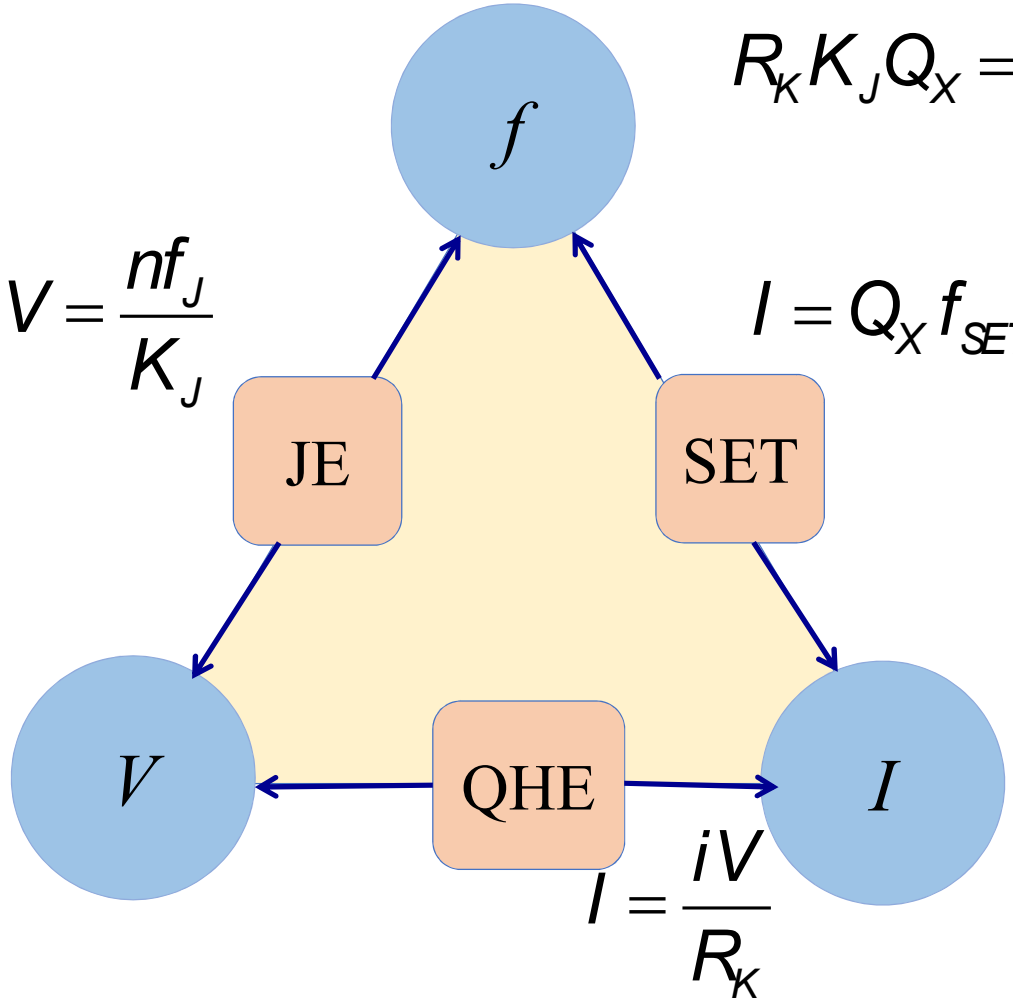


NIST 10 V PJVS chip



NIST Graphene Quantum Hall Device

Quantum Metrological Triangle: The Future?

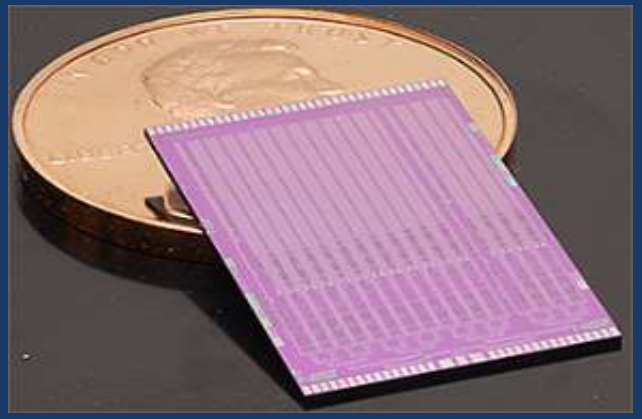


$$R_K K_J Q_X = n \frac{i}{G} \frac{f_J}{f_{SET}}$$ or $$V = R_H G I_{SET}$$

Where *G* is the gain from a Cryogenic Current Comparator (CCC)

- Single Electron Transistors:
  - Many efforts in GaAs, also Al, more recently Si
  - NIST demonstrated an Al SET at 1 pA at an uncertainty of 1.5 x 10^{-8} in 1996 (*Applied Physics Letter*, **69**, 1804 (1996))
  - PTB, as part of the Qu Ampere project, has demonstrated a GaAs SET at 100 pA at an uncertainty of 2 x 10^{-8} in 2016
  - Australians using Si SETs out of there Q. Computing project have new results (unpublished)
- QMT – which is an application of Ohm's Law (V=IR) has been realized
  - NIST demonstrated this at an uncertainty of 1 x 10^{-6} in 1999 (*Science* **285**, 1706 (1999))
  - Underway again in Qu. Ampere

Quantum-Based Voltage Standards



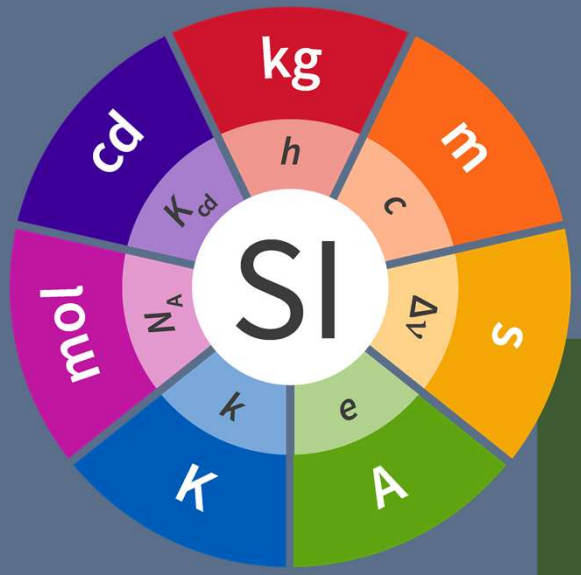
DC Volt

- Programmable Josephson Volt Standard
- Quantized voltages: ±10 V

AC Volt

- Programmable Josephson Arbitrary Waveform Synthesizer
- Quantum accuracy up to 1 MHz

Two More units



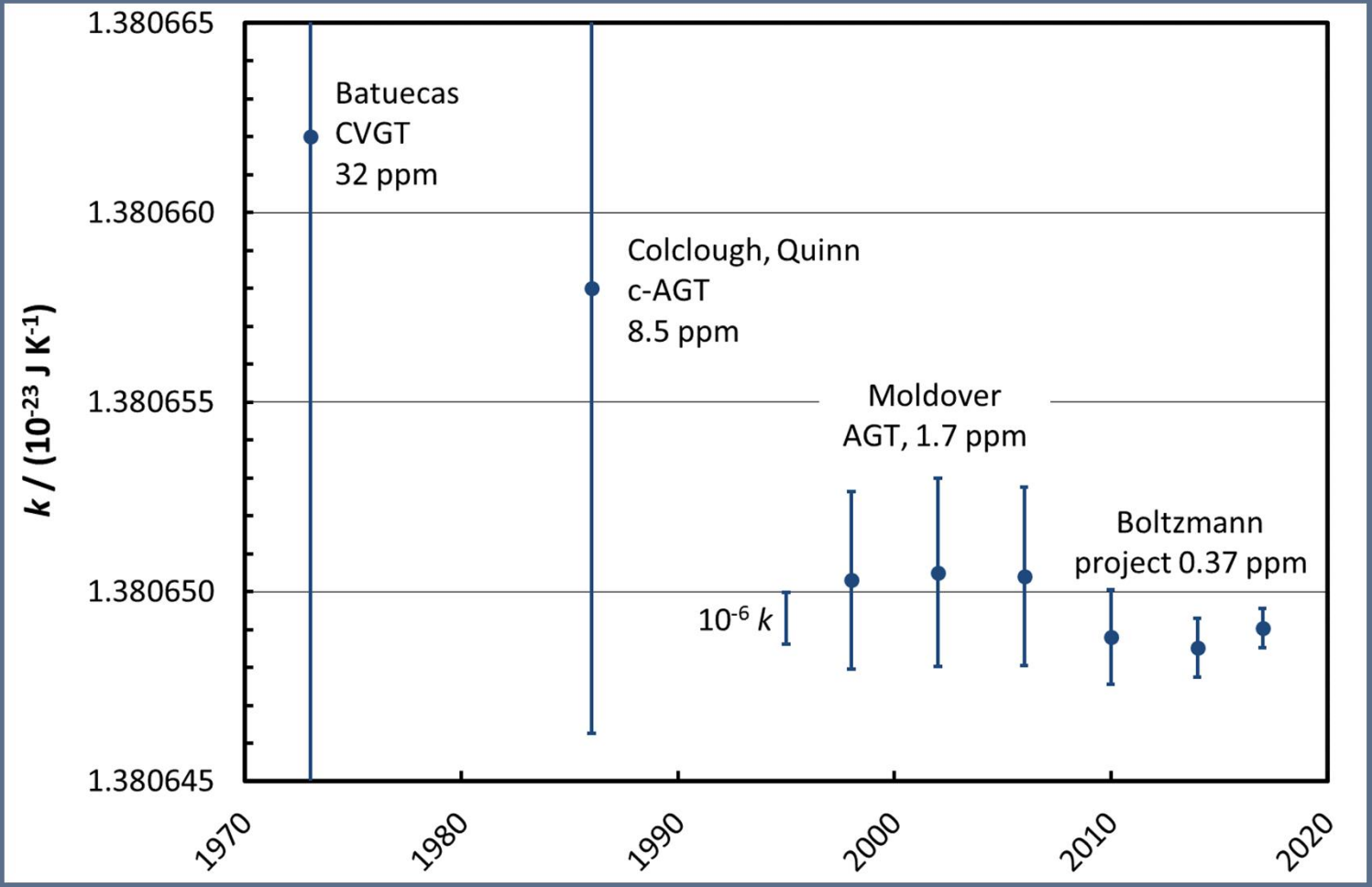
The Mole: Formerly, the amount of substance with a number of entities equal to the number of ^{12}C atoms in a 12 grams of ^{12}C. Now, simply a number (we define the Avogadro constant).

The Kelvin: formerly 1/273.16 of the triple point of water. Now, we specify the thermal energy per kelvin of the atomic constituents (we define the Boltzmann constant k_B).

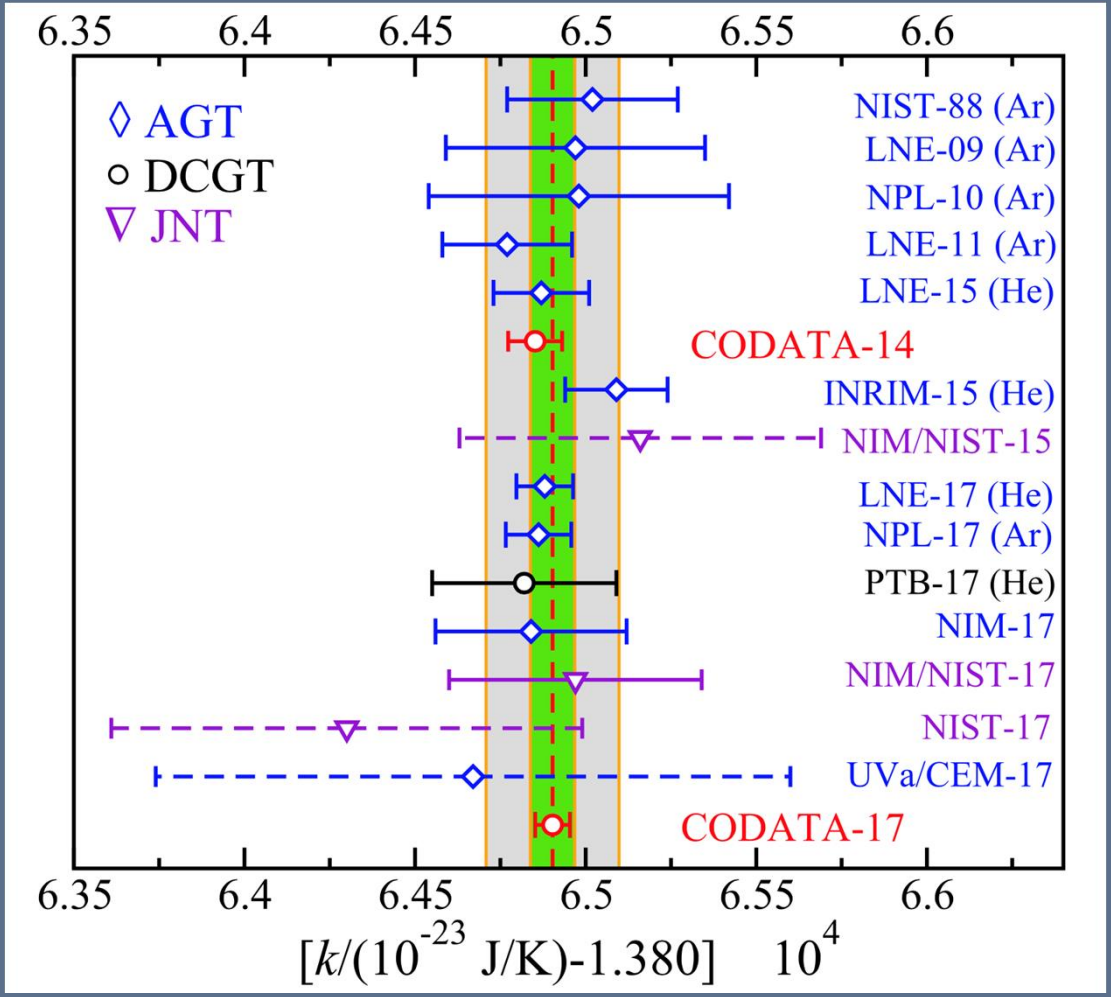
Historical Values of Boltzmann Constant

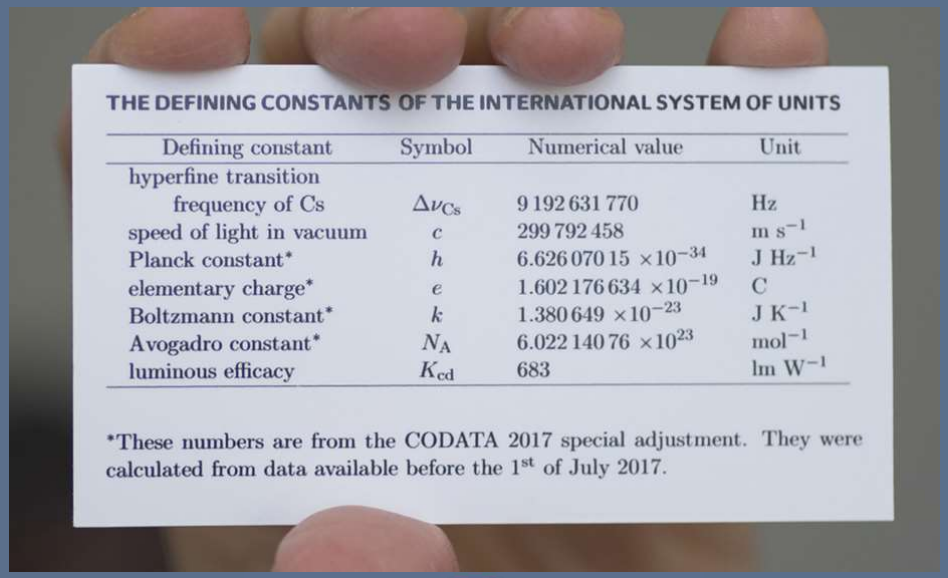
Figure 1. History of the adjusted values of the Boltzmann constant taken from the periodic reviews of the CODATA TGFC with relative uncertainties indicated. The time axis are the dates of the CODATA adjustments. The error bars indicate standard uncertainties.

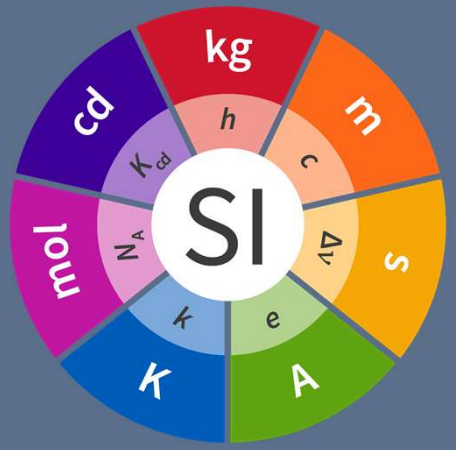
From: "The Boltzman project," J. Fischer *et al.*, Metrologia **55**, R1 (2018).



Boltzmann Constant Final Data

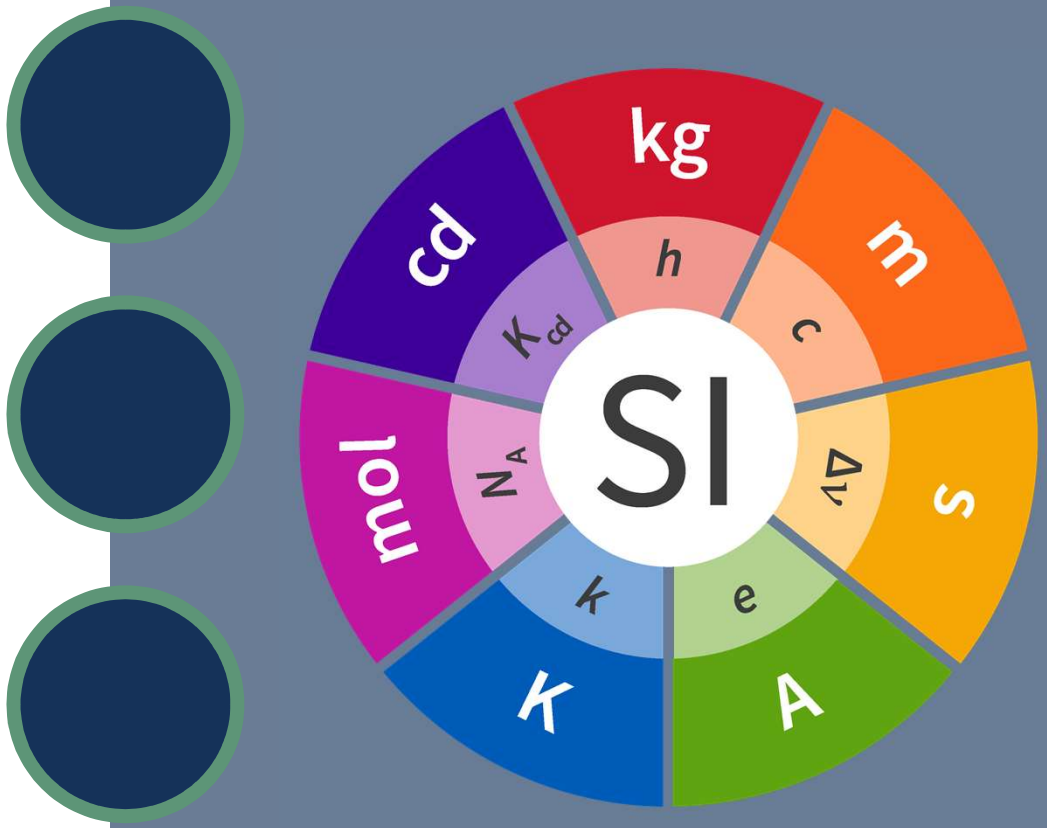






Why is the SI now Beautiful

- According to the *original wishes* of the founders of the metric system it is *now based* on nature.
- It provided a path to get away from scaling.
- It pulled electromagnetic units back into the SI.
- It is internally self-consistent.
- It makes testing the Standard Model of Physics much easier.
- It is build for the 21st Century and perhaps beyond.




Liberty leading the people means we are finally **free of artifact standards of measurement.**

Realizing the Dream

À tous les temps, à tous les peuples.

For all times, for all peoples.

Direction Générale des Entreprises : Photo

Key Concepts

- The SI (Metric System) was always intended to be based on nature and the concept used was not entirely new.
- While Metrology has evolved the BIPM and the *Treaty of the Metre* remain relevant today and into the future.
- Provided length as an example of the benefit of using a fundamental constant – c: the speed of light.
- Discussed mass, the need for a change, and the choice of Planck's constant
- Reviewed the impact on electrical quantities and their being brought back into the SI
- A quick look at the mole and Boltzmann constant.
- Conclusion: We have achieved the goals of the founders of the Metric System or SI.

QUESTIONS?