Measuring with Fundamental Constants: how the revised SI will work

OR

How can we define a system of units by defining the values of some of the fundamental constants of Nature?

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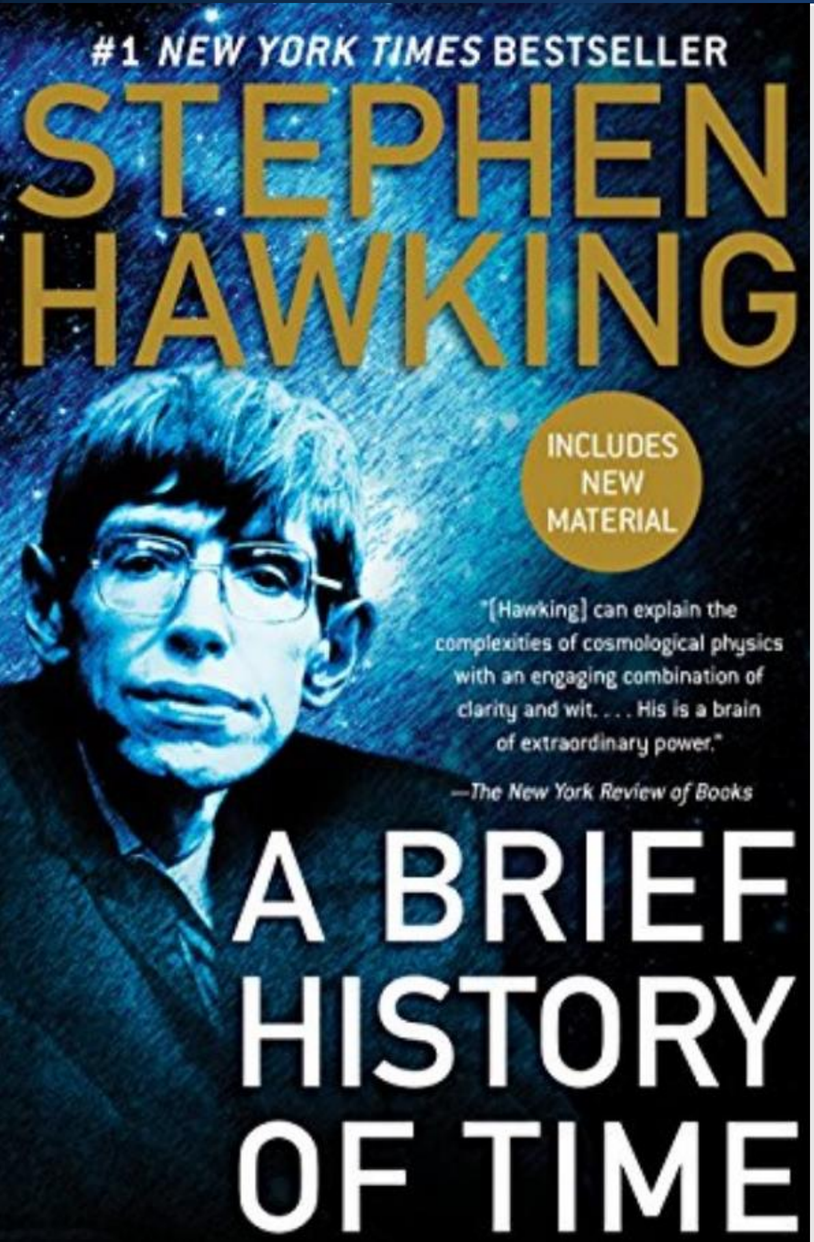
NIST National Institute of Standards and Technology U.S. Department of Commerce

26e CGPM
Versailles
13-16 novembre 2018

20 May 2019 (World Metrology Day) will experience the greatest revolution in measurement since the French revolution.

That revolution will be a change to
The International System of Units
Le Système Internationale d'Unités (SI)

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



To understand how this is possible, and with apologies to Stephen Hawking,

I will attempt to bring you a "Short History of Length"

(because length is already defined by a constant of nature)

Ancient length standards

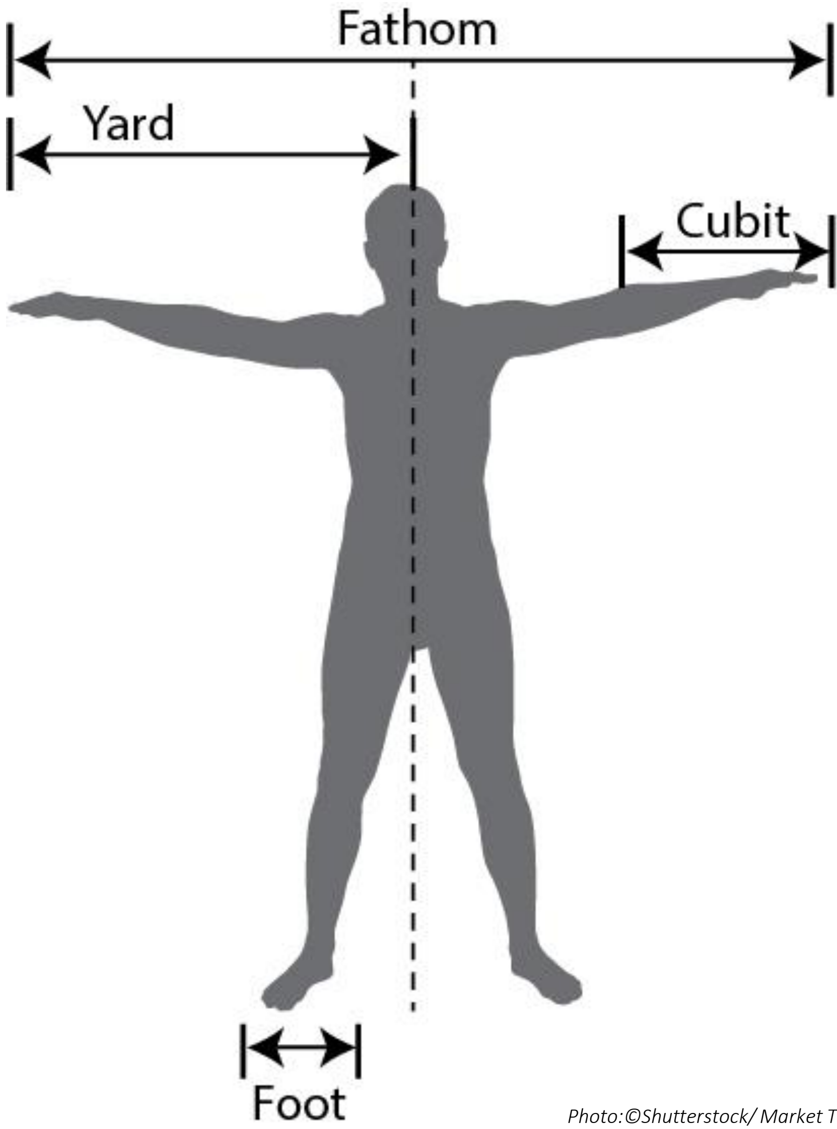


Photo:©Shutterstock/ Market Trawczynski

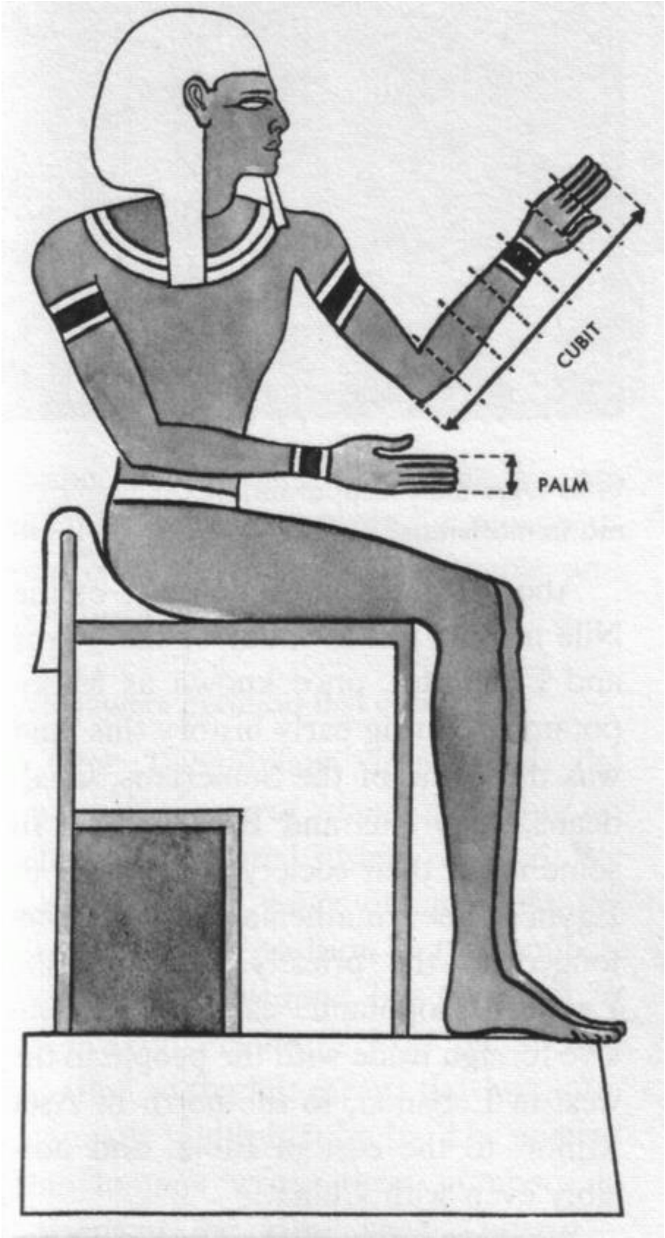
The early approach to length used the human body as the standard.

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

Photo:©Shutterstock

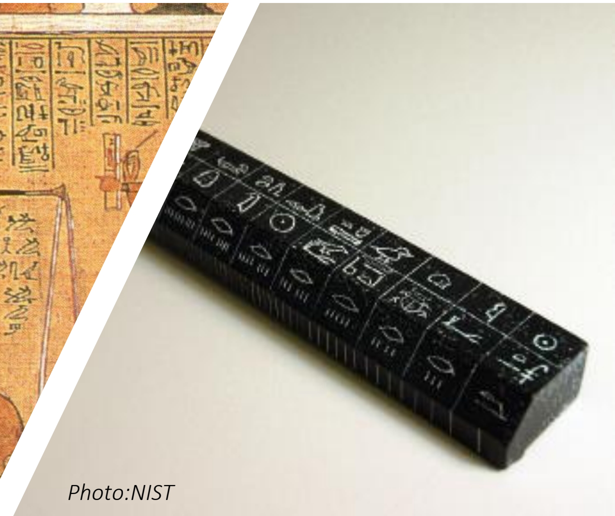


Photo:NIST

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

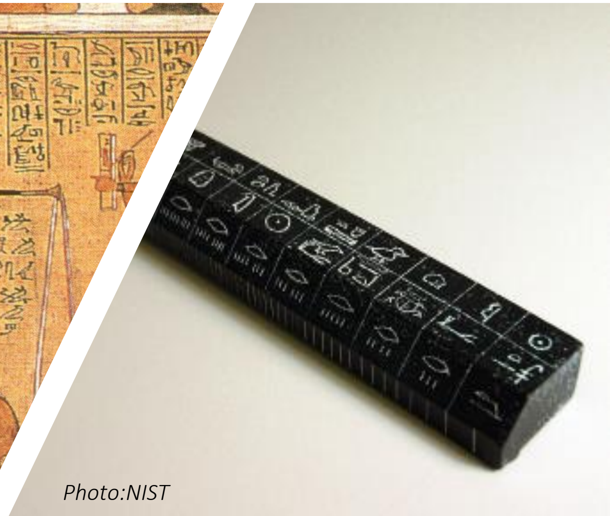


Photo:NIST

Antique length standards

Similar artifacts, sometimes varying from town to town, were common standards for length measurement in Europe.

Antique 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

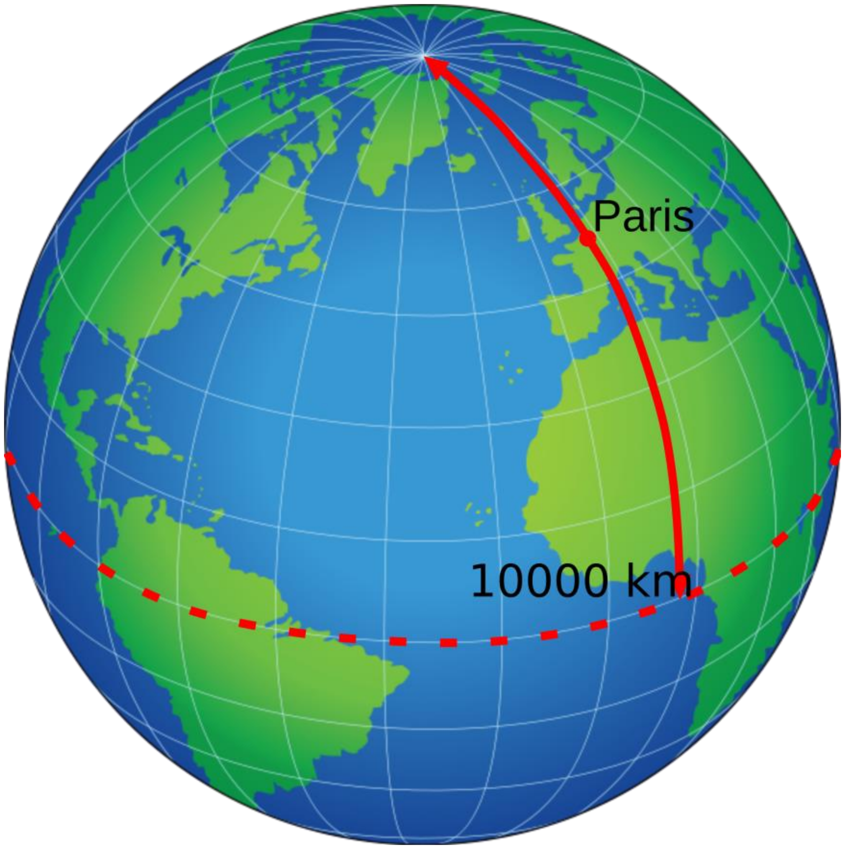


Photo: U.S. Government

During the French Revolution (ca. 1791) the metric system came into being, based on the metre, and with a particular 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 Revolutionary Dream

À tous les temps,
à tous les peuples.

For all times, for all peoples.

Direction Générale des Entreprises : Photo

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

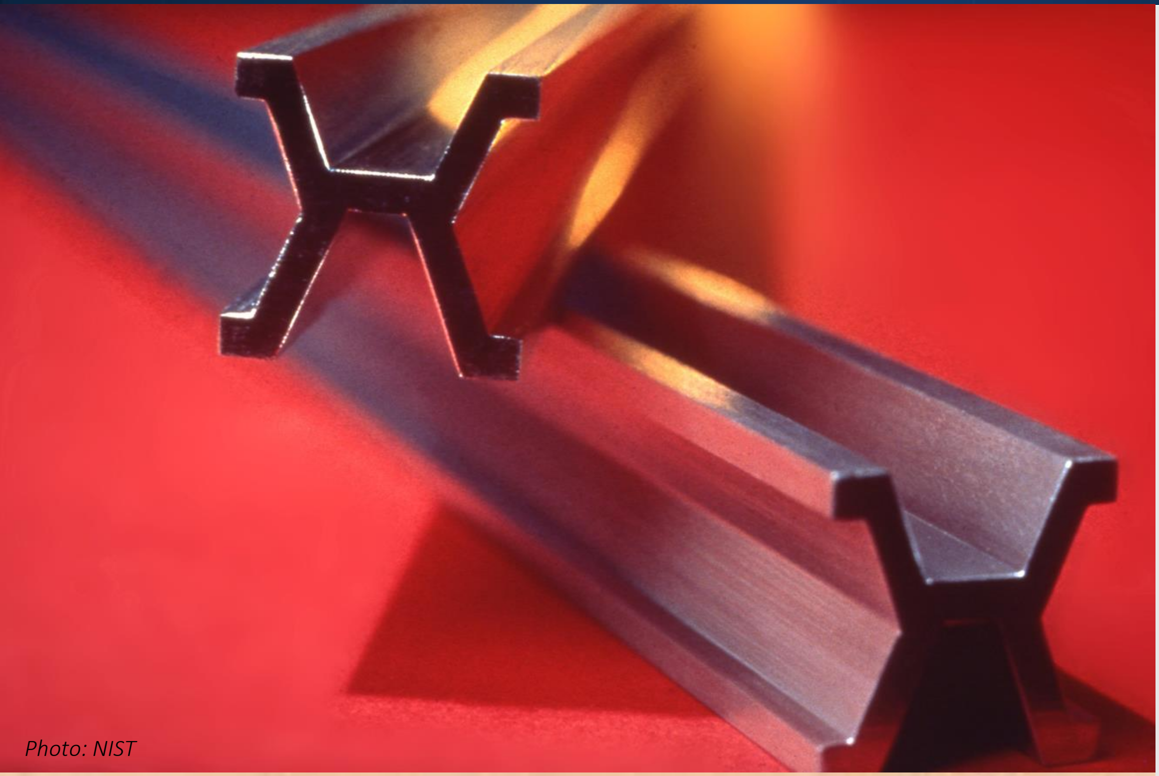
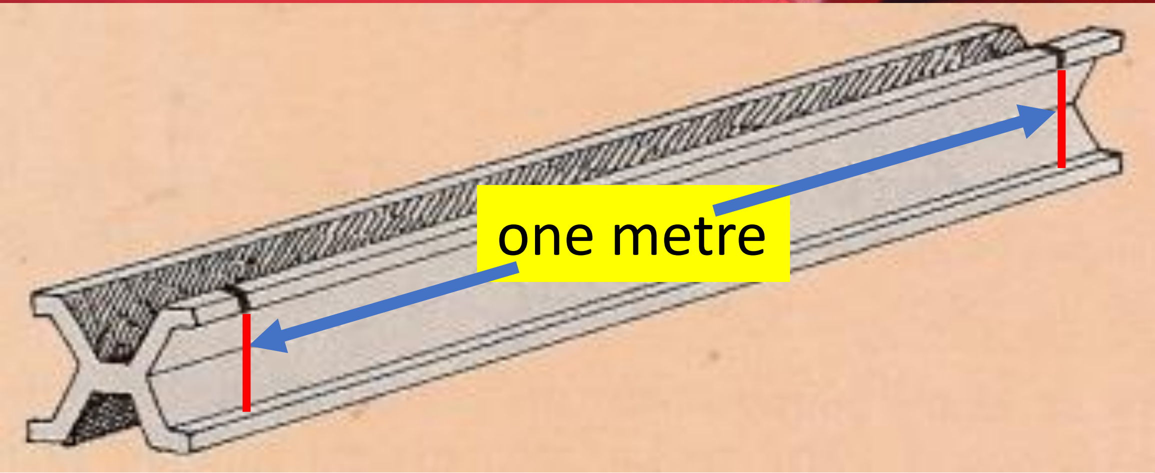


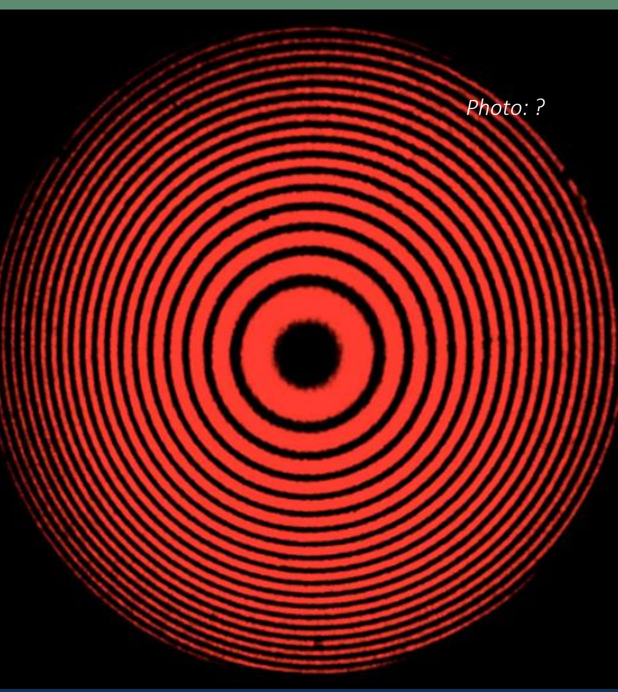
Photo: NIST

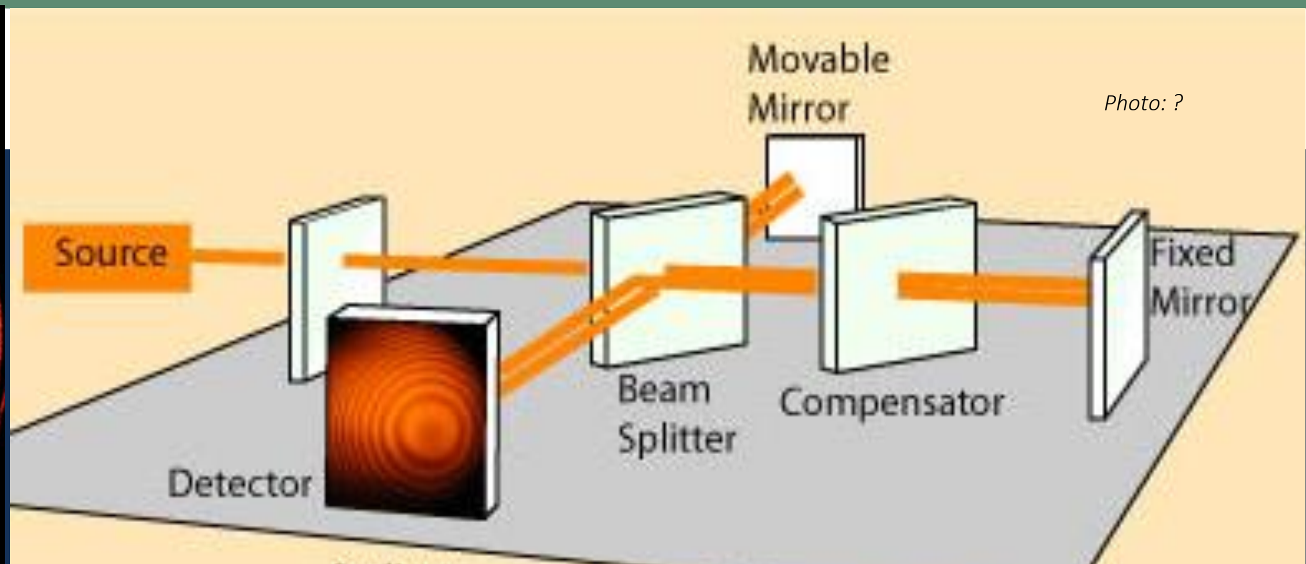


Following the famous **1875 Convention du Metre**, the metre of the archives was **replaced with a line standard**, the International Prototype of the Metre.

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.





Interference Fringes

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

NIST

Photo courtesy of Samuel M. Goldwasser, Sam's Laser FAQ

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.

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

The brilliant choice:

Define the speed of light.

The Brilliant, BEAUTIFUL definition of the metre (17th CGPM, 1983)

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:

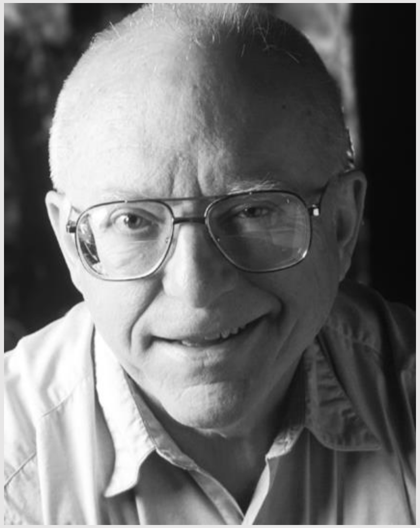
$$\lambda f = c$$

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

This definition incorporates improvements in lasers and frequency measurements.

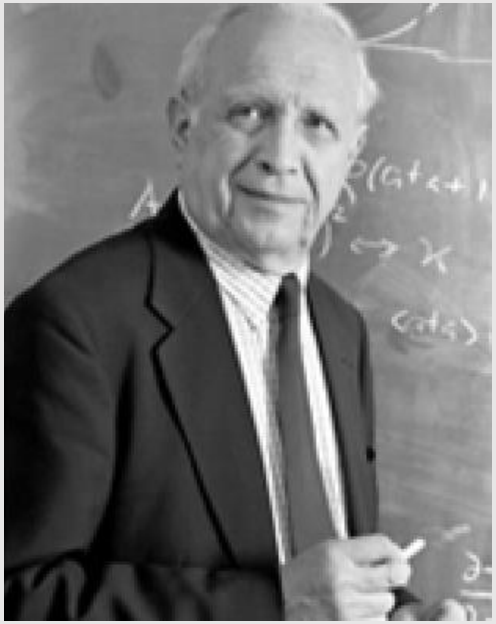
The 2005 Nobel Prize In Physics

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.

Today, the CGPM is about to bring this same beauty to the kilogram.

Why and How?

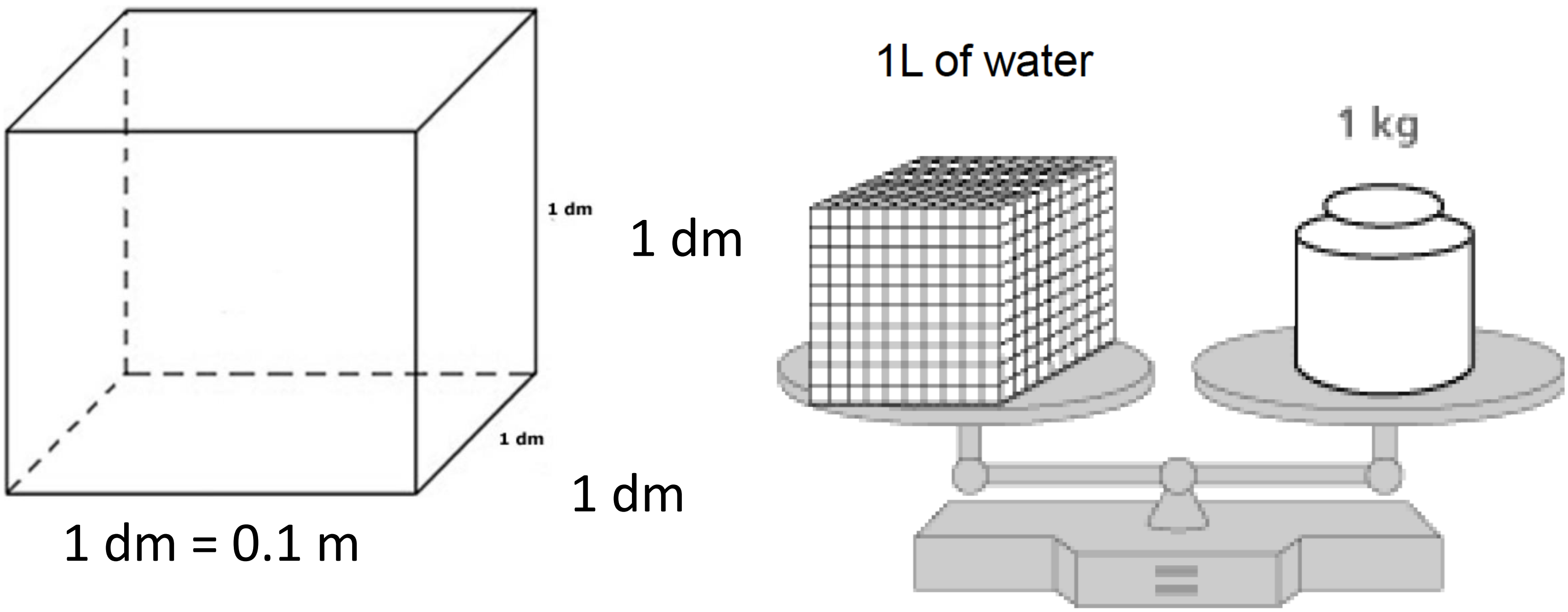
A Light History of Mass

Ancient mass standards


“Mesopotamian weights made from haematite” by geni is licensed under GFDL CC-BY-SA

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

Revolutionary mass standard



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

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

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.

IPK

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

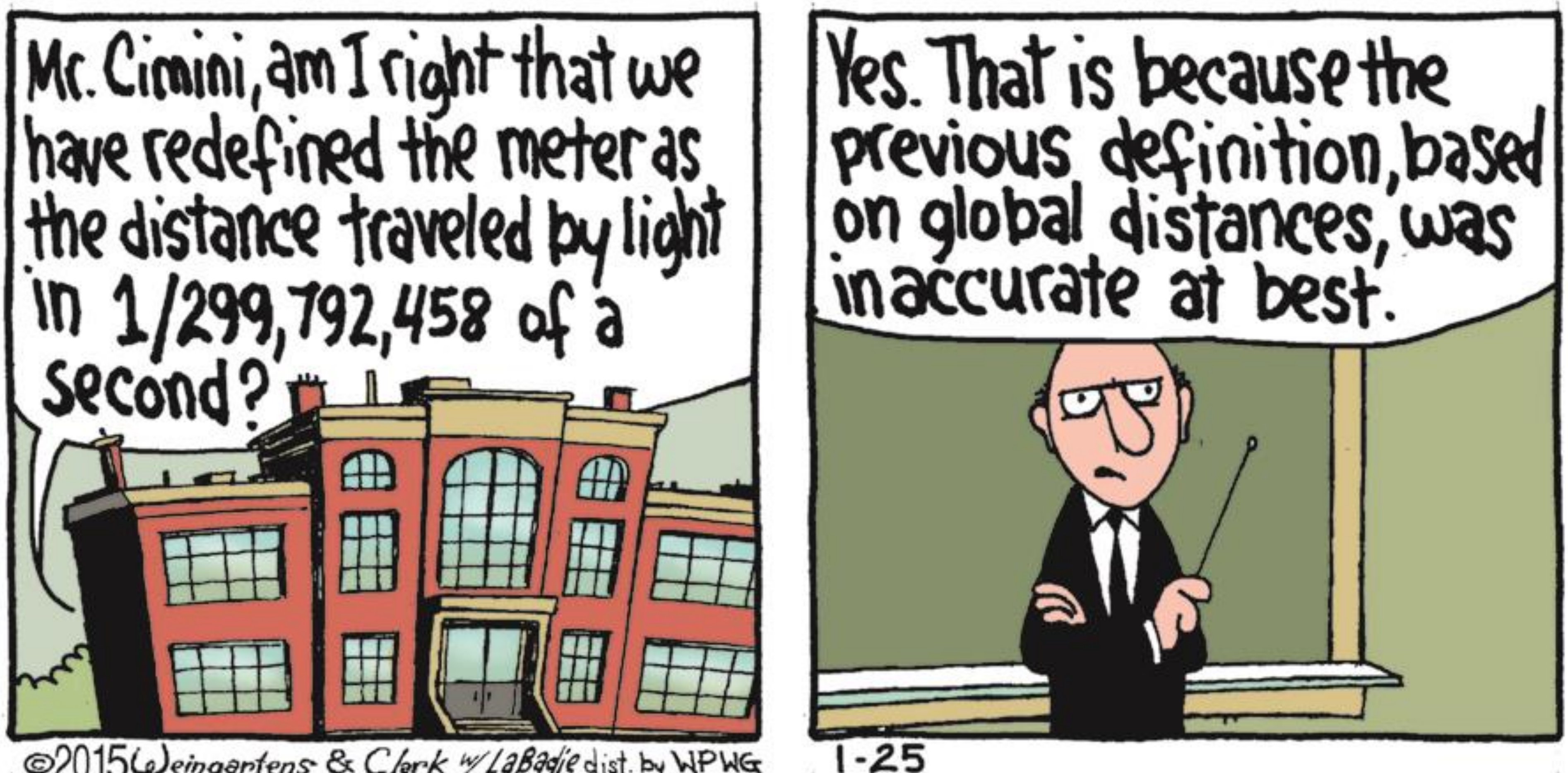
This is the <u>last</u> artifact.

The Current Definition

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

Today, in the 21st century, the unit of mass is an artifact, a piece of metal made in the 19th century, based on an object made in the 18th century. This is such a scandal that American newspaper comic strips make fun of it.

Barney & Clyde



Barney and Clyde used with permission of David Clark, Dan Weingarten, Gene Weingarten and the Washington Post Writers Group.

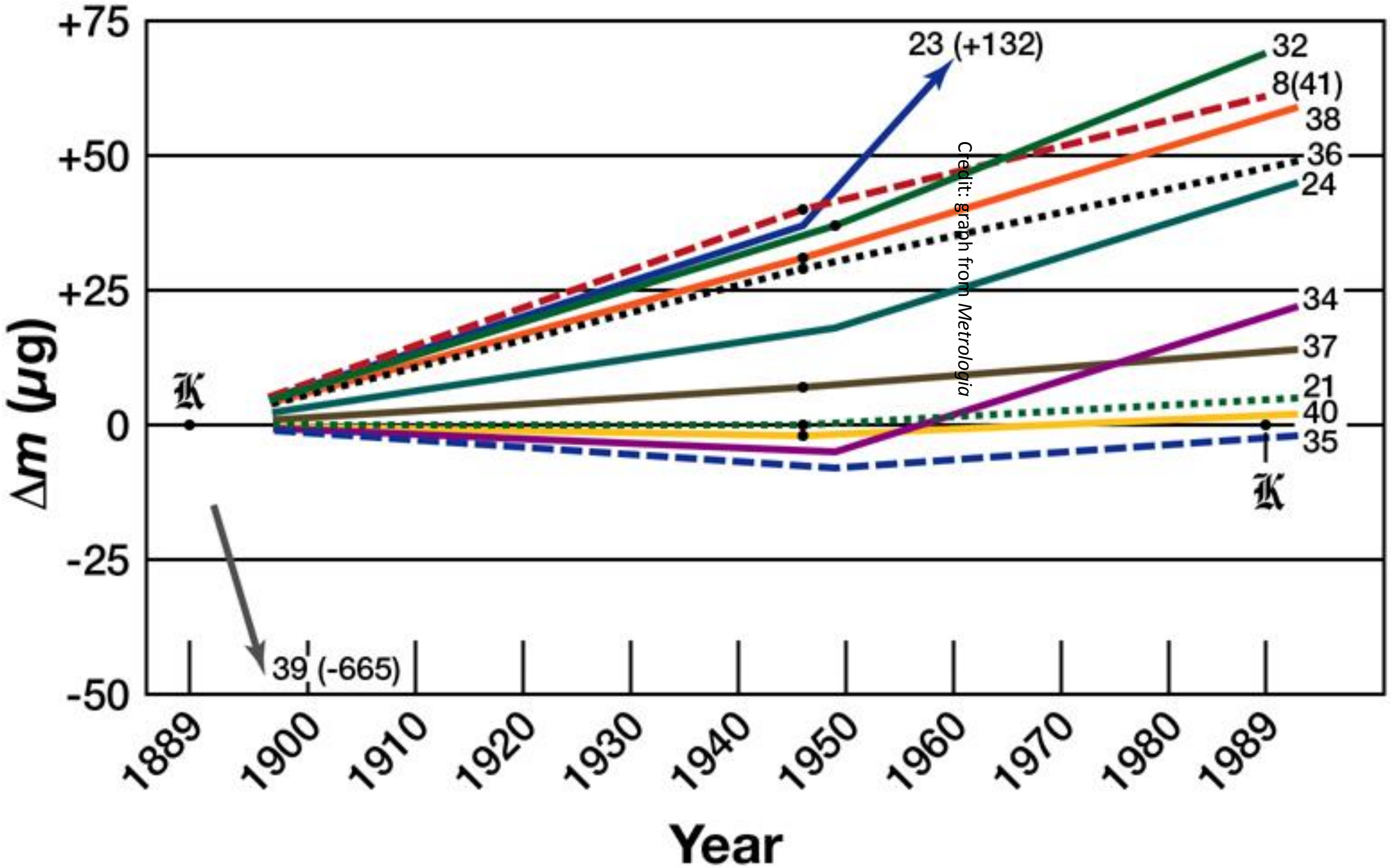
Barney & Clyde

Barney & Clyde

Barney & Clyde

Nobody has sneaked in and shaved off a piece of the IPK, but its mass is "changing" nevertheless.

The International Prototype Kilogram appears to be changing!!



Credit: *Metrologia*

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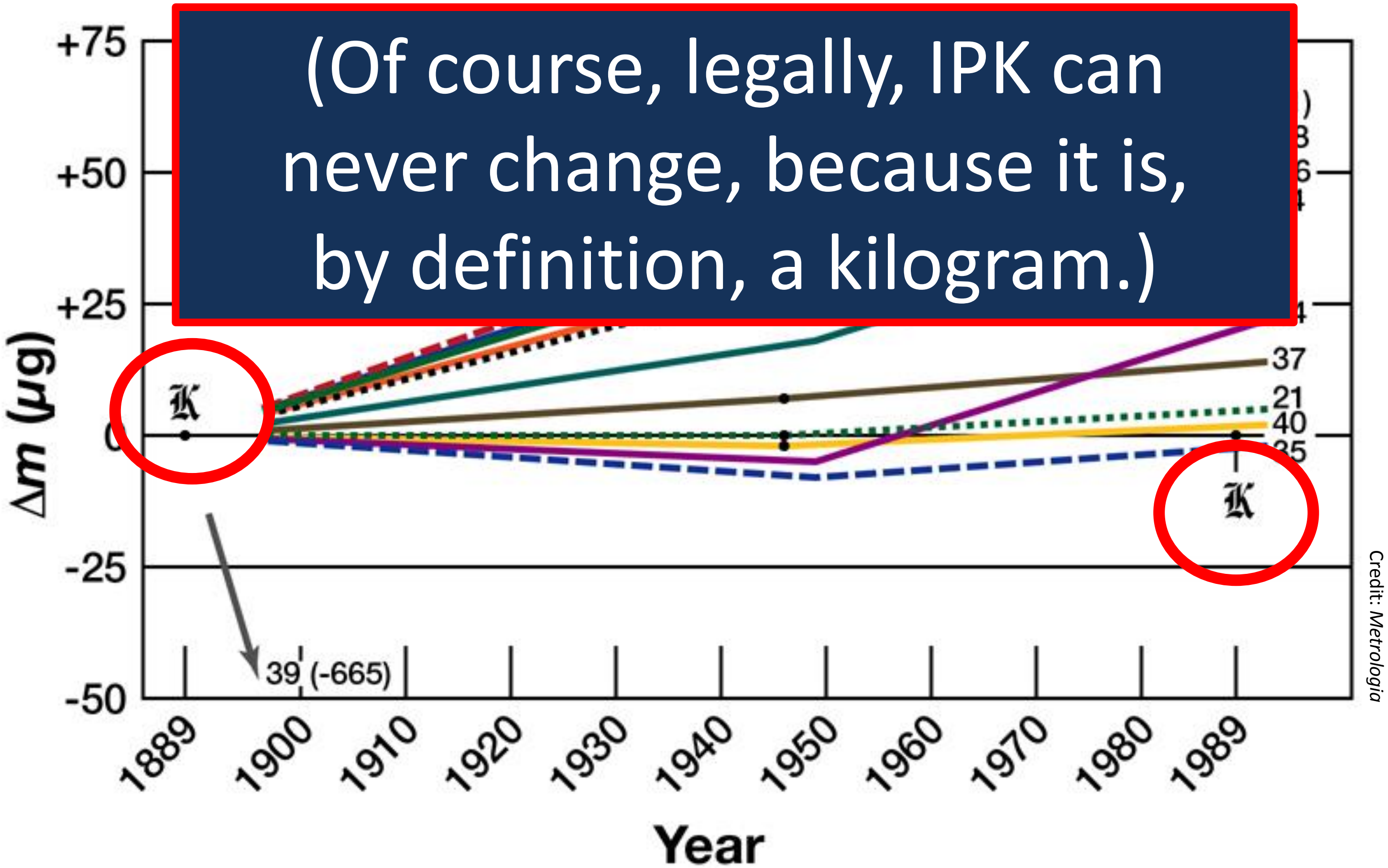

Fixing the Kilogram Problem

This scandalous situation must be fixed. We want to use the beautiful approach used for the metre.

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

What constant will we use for kg?

The most famous equation in history:

$$E = mc^2$$

Energy of an object at rest

Rest mass of the object

Speed of light

A slightly less famous equation:

$$E = hf$$

Energy of a photon
(a particle of light)

Planck's constant

Frequency of the light

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

$$E = mc^2 = hf = E$$

$$m = hf/c^2$$

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

Bryan Kibble 1938-2016

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.

Operating Principles of the NIST-4 Watt Balance

NIST Physical Measurement Laboratory

Watt Balance

$$mgv = IV$$

mass (force) from weighing mode

velocity from velocity mode

current from weighing mode

voltage from velocity mode

Watt Balance

Mechanical Power = Electrical Power

$$mgv = IV$$

mass (force) from weighing mode

velocity from velocity mode

current from weighing mode

voltage from velocity mode

Watt Balance

$$\boxed{m = IV/gv}$$

From Watt to Planck

NIST

$$\boxed{m = IV/gv}$$

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

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

From Watt to Planck

$$m = IV/gv$$

Voltage is proportional to $h/2e$
(because of Josephson)

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From Watt to Planck

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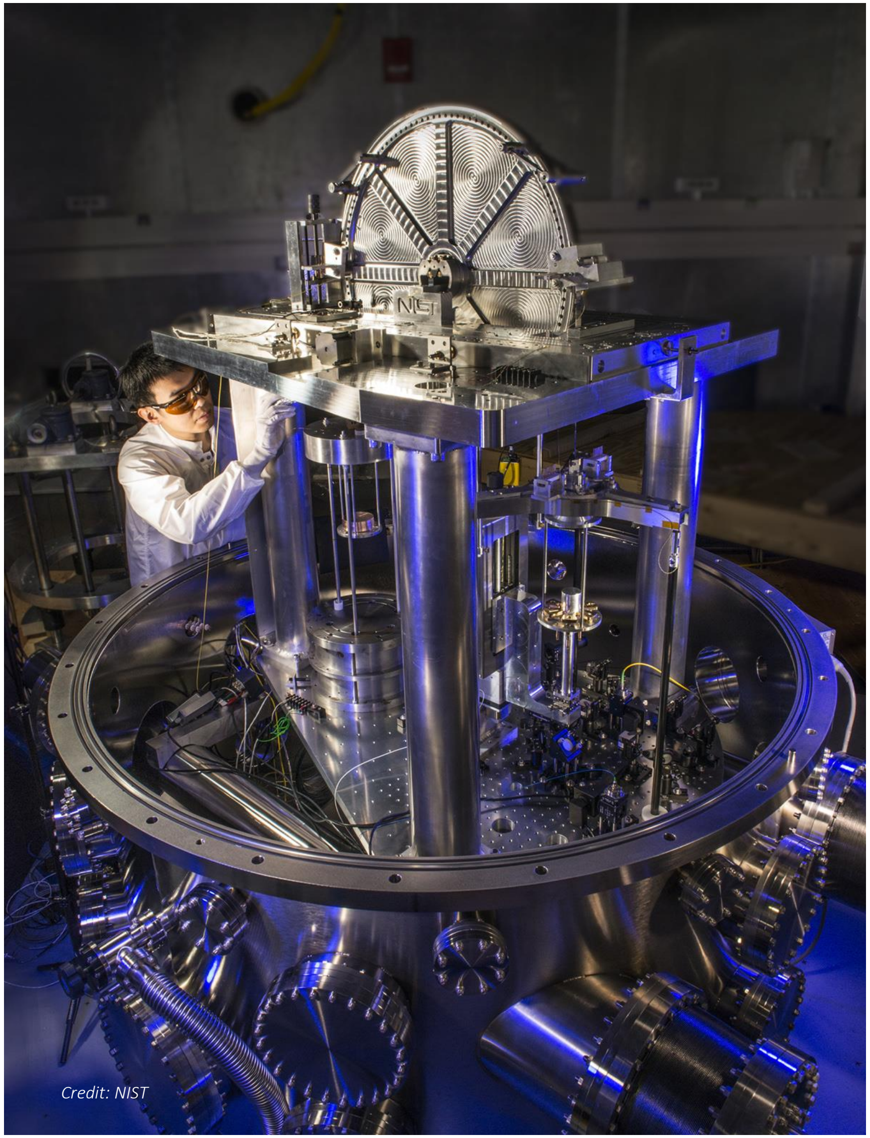
(we will define the electron charge, using the QHE, so the ampere is electrons/second)

Voltage is proportional to *h*/2*e* (because of Josephson)

$$m \sim h$$

NIST Kibble Balance



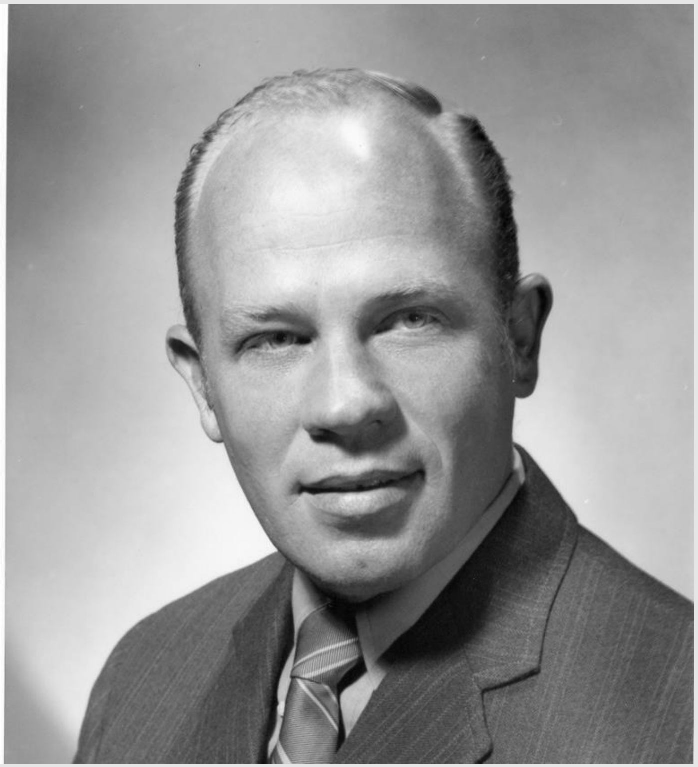
Such Kibble balances will realize the kilogram to about 10^{-8}, which is better than the changes due to “dirt”.

Who made it happen at NIST?

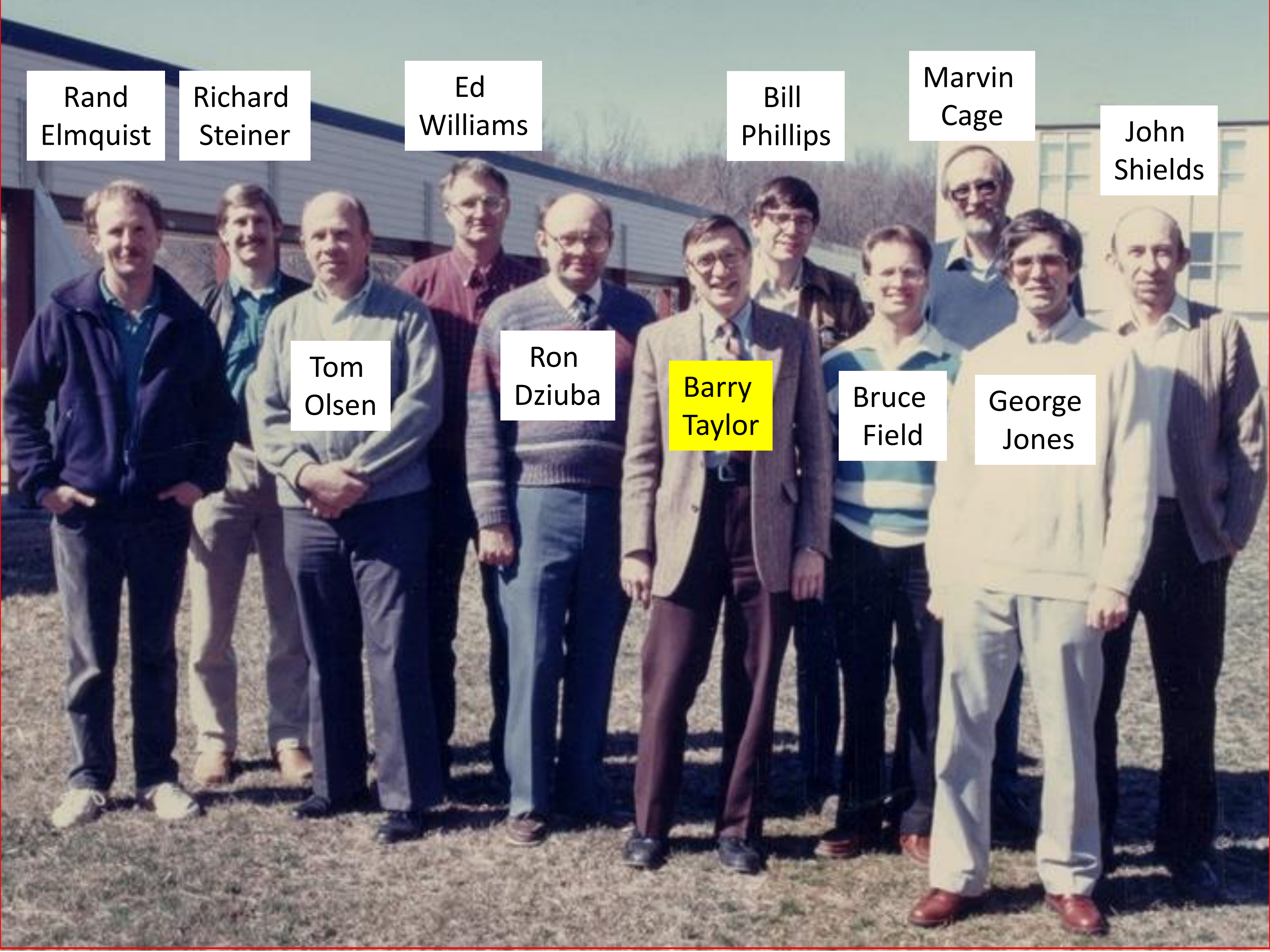
The early heroes at NIST

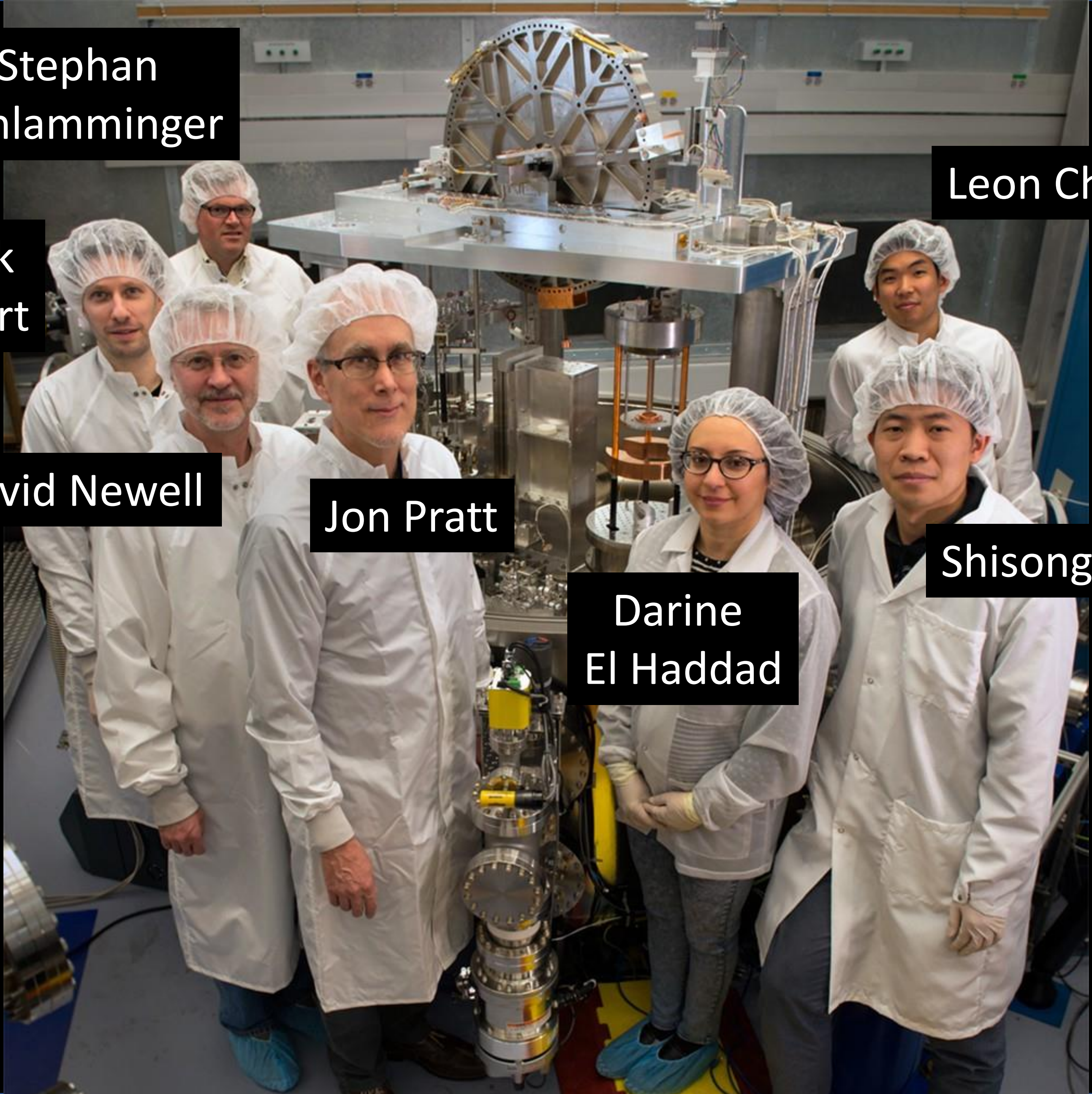
Ed Williams and Tom Olson were already designing NIST’s first Kibble balance when I (WDP) arrived in 1978.

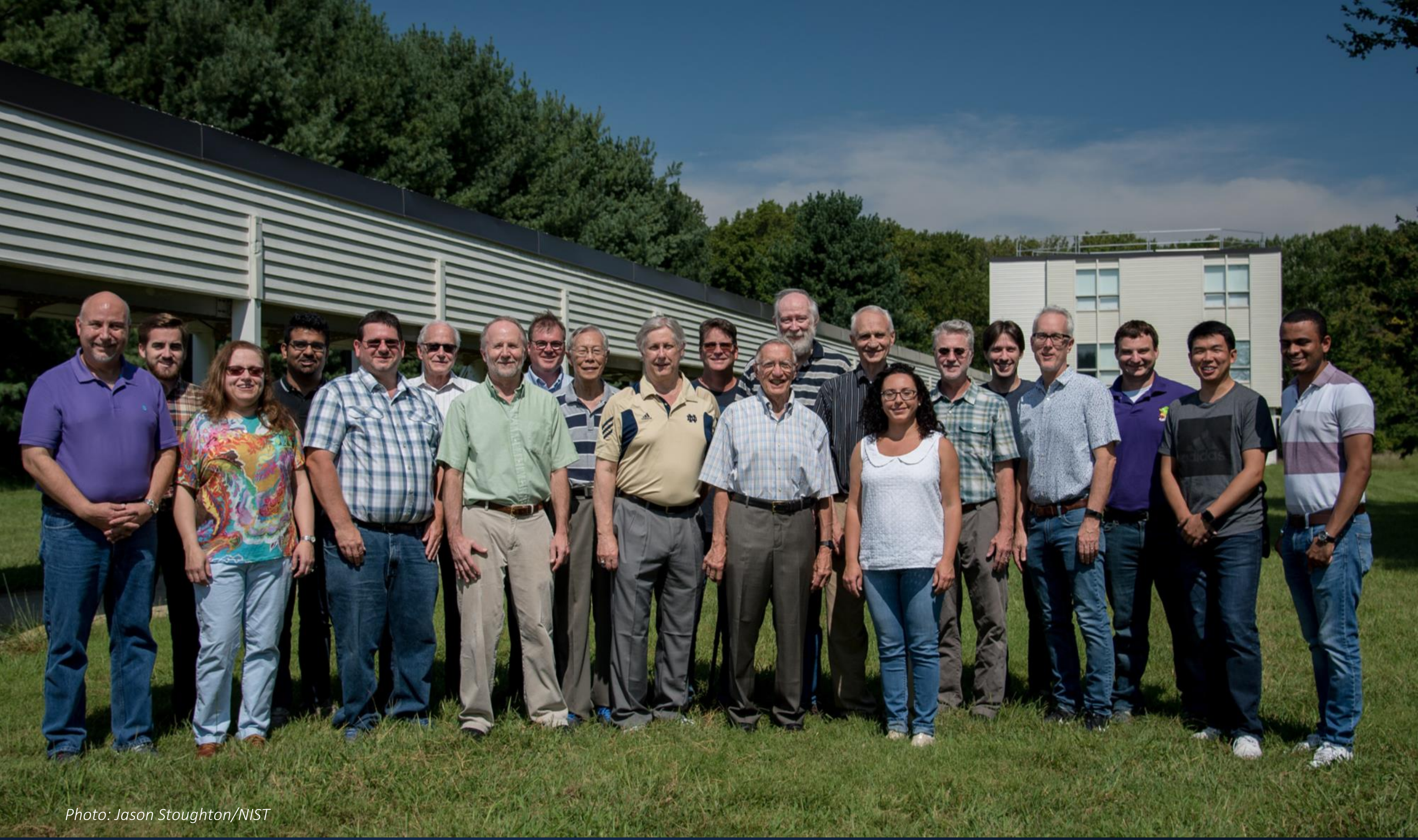
Ed Williams
Photo: NIST



Tom Olsen
Photo: NIST


Rand Elmquist
Richard Steiner
Ed Williams
Bill Phillips
Marvin Cage
John Shields
Tom Olsen
Ron Dziuba
Barry Taylor
Bruce Field
George Jones


Stephan Schlamminger
Leon Chao
Frank Seifert
David Newell
Jon Pratt
Shisong Li
Darine El Haddad



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.

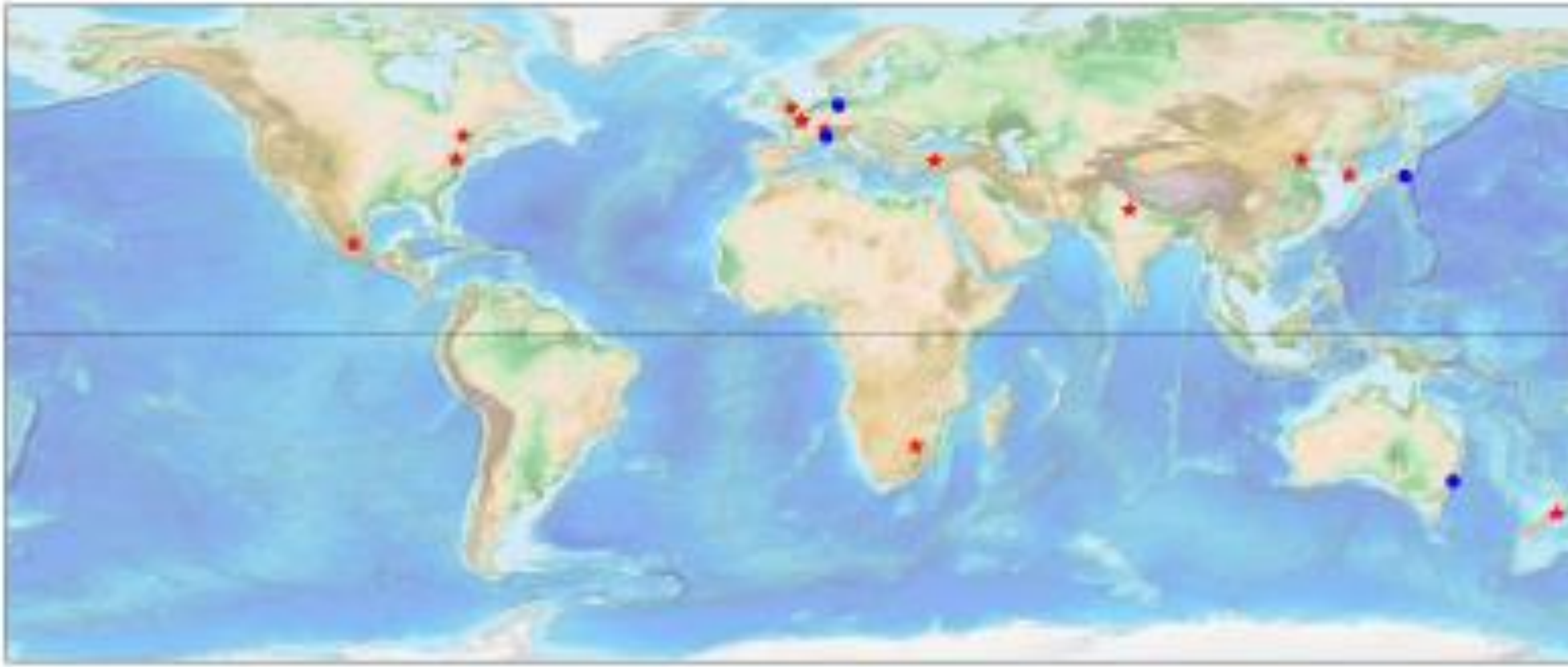

A TOUS LES TEMPS A TOUS LES PEUPLES

Another realization of the kilogram

Defining *h* allows other methods of realizing the kilogram: Silicon sphere at PTB.

Credit: ©Physikalisch-Technische Bundesanstalt (PTB)

Other Kibble balance work: NPL (UK), Metas (Switzerland), LNE (France), NIM (China), BIPM (the World), NRC (Canada), UME (Turkey), NMISA (South Africa), and others



Silicon work: (PTB (Germany); INRIM (Italy); NMI (Australia); NMIJ (Japan); NIST (US), BIPM, NPL (UK) and others

A final part of the story: the ampere

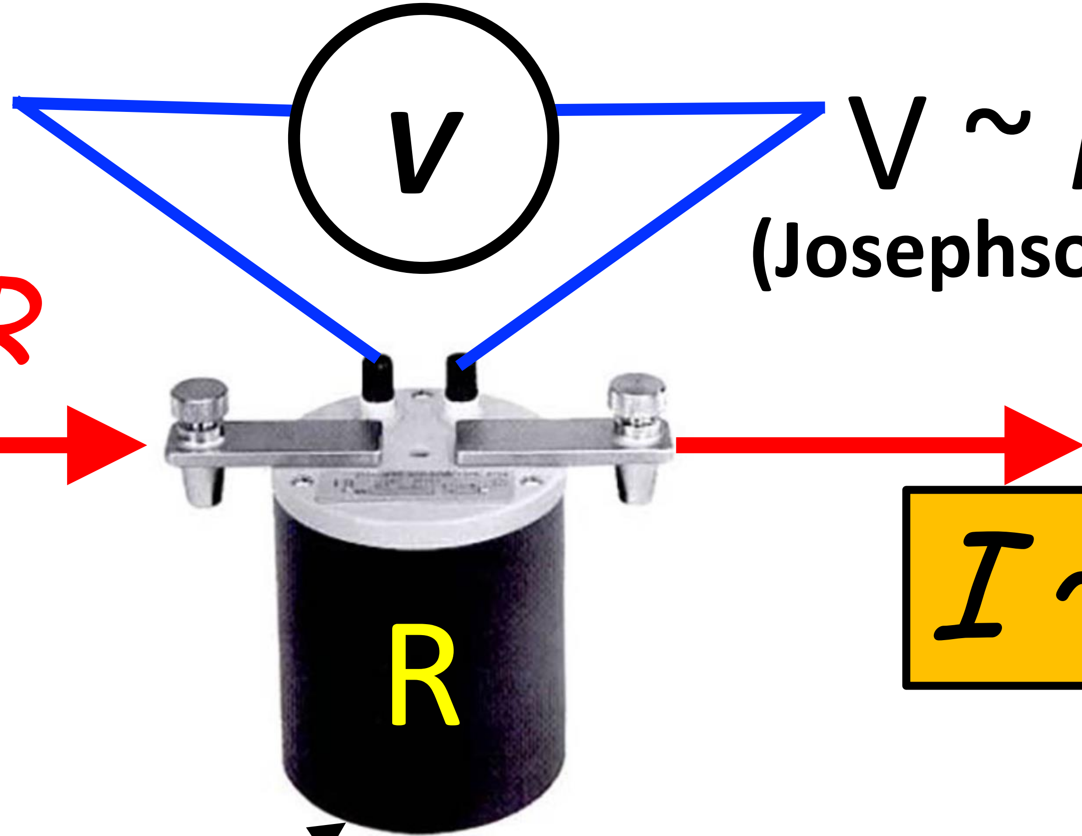
NIST

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

The Future: 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.

Unified Electrical Standards



$V \sim h/2e$

(Josephson Effect)

$I = V/R$

$I \sim e$

$R \sim h/e^2$

(Quantum Hall Effect)

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).

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.

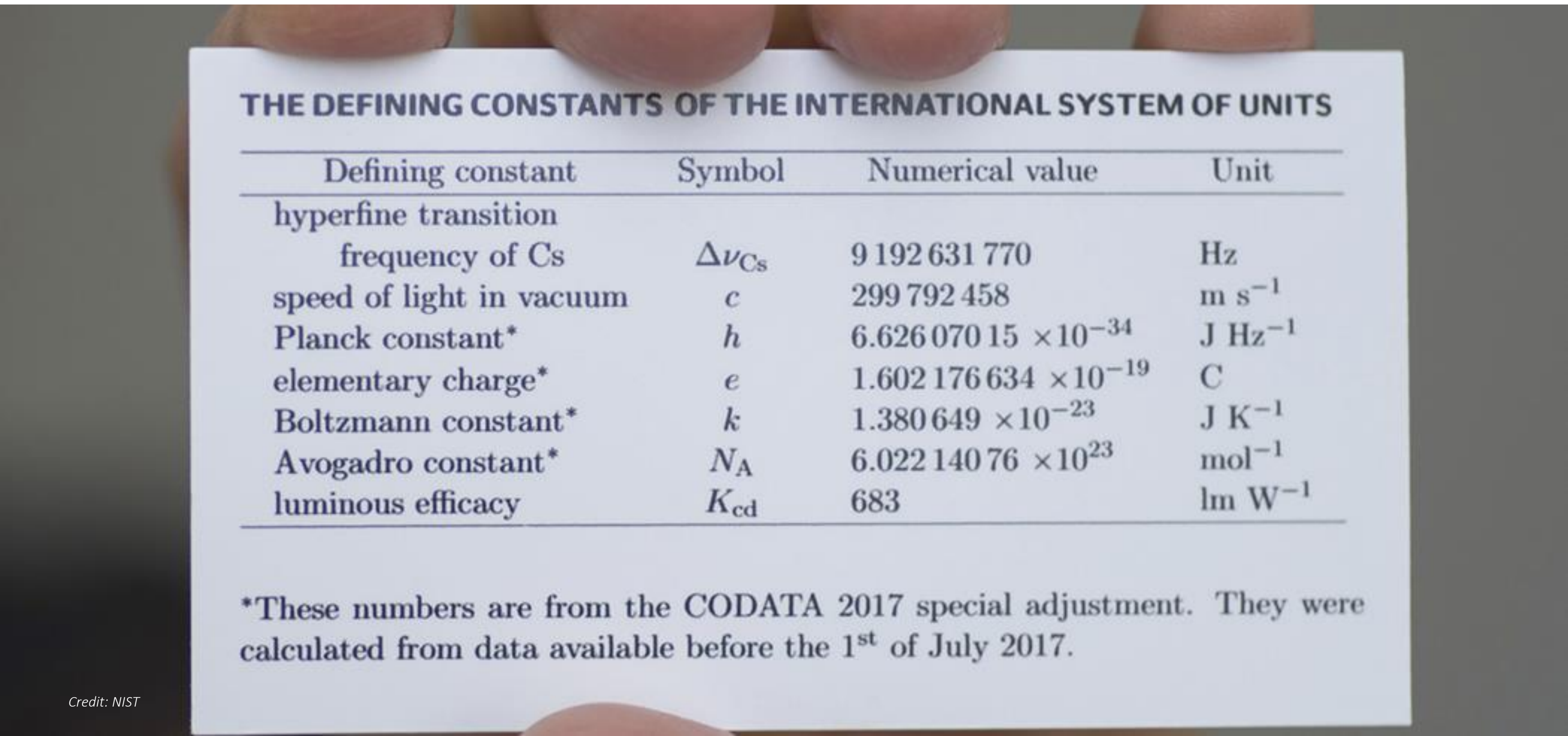
On 20 May 2019 (the anniversary of the signing of the 1875 Convention du Metre), we will have the biggest revolution in measurement units since the French Revolution.

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

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.

Now you can keep the SI in your wallet.



THE DEFINING CONSTANTS OF THE INTERNATIONAL SYSTEM OF UNITS

Defining constant	Symbol	Numerical value	Unit
hyperfine transition frequency of Cs	$\Delta\nu_{\mathrm{Cs}}$	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

Realizing the dream

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à tous les peuples.

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