The Quantum Reform of the International System of Units

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Sister institutes: National Metrology Institutes of Ukraine and the United States

National Scientific Centre "Institute of Metrology"

NIST

National Institute of Standards and Technology

Measurement is fundamental to all areas of science and technology. To measure, one must have a system of units. For us, that is the metric system or "International System of Units"

The International Union of Pure and Applied Physics was a major force in the creation of the International System of Units (Système International d'Unités –SI) in 1960, and this talk is part of IUPAP's promotion of the quantum reform of the SI.

I am honored to have been invited to join you today to explore science and technololgy in the midst of Russia's on-going and brutal war against Ukraine. To the students in the audience who continue to pursue their education, and the faculty members and researchers who continue to mentor the next generation and strive to make the world a better place through the pursuit of scientific discovery, your courage and perseverance are truly inspirational.

The United States, our allies, and our partners worldwide are united in support of Ukraine in response to Russia's unprovoked, and unjustified war. The continued bravery of the Ukrainian people in defending your sovereignty, territorial integrity, and democracy is an inspiration to us all.

The metric system came into being with the French Revolution, at the end of the 18th century.

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

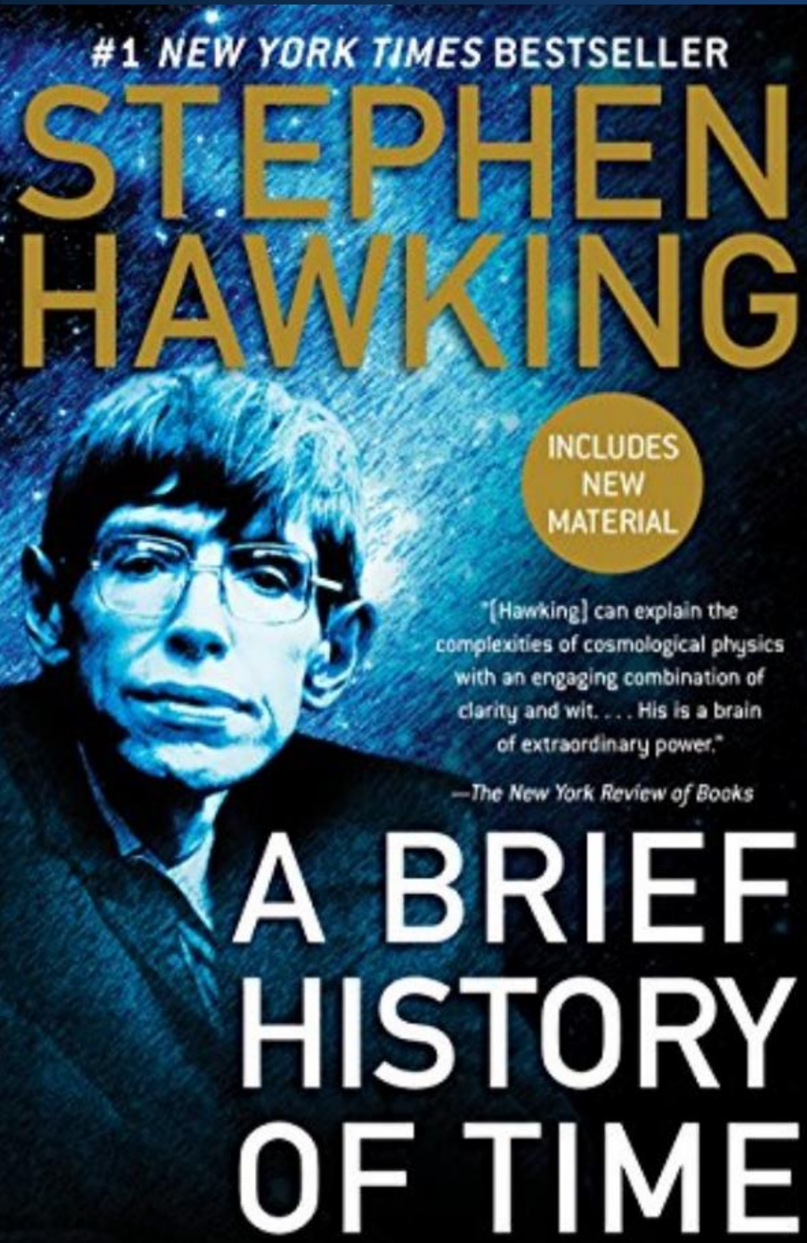
The Metric System

The International System of Units

Le Système Internationale d'Unités (SI)

expresses physical quantities in terms of seven base units.

The reform is that all of the base units of the International System of Units are now defined by fixing the values of constants of nature.



To see how this can be done, and how an earlier unit of measure (time) evolved over time and with apologies to Stephen Hawking,

I will attempt to bring you my version of "A Brief History of Time"

Conventionally, 1 second = 1day X (1/24x60x60)

= 1 day/86 400

But since about 1900, we have known that the day changes.

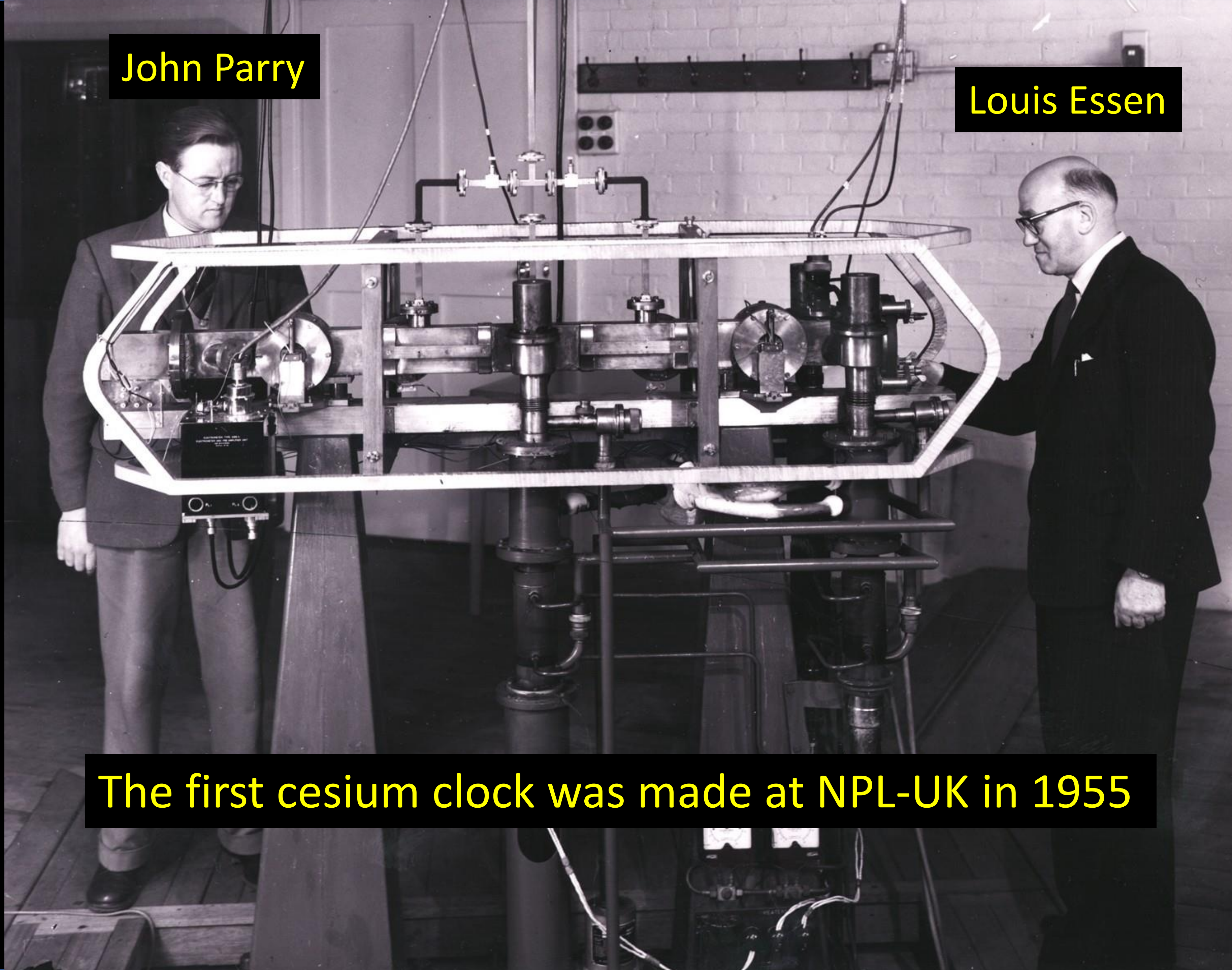
Photo: IEEE

Edward U. Condon [left], director of the National Bureau of Standards, with Harold Lyons, inventor of the ammonia absorption cell atomic clock [above].

Atomic Clocks

Better than the Earth:

The earth may change, but atoms (and molecules) do not—as far as we know. This ammonia molecule clock, built at the National Bureau of Standards (the ancestor of NIST), in 1949 was the first "atomic" clock.

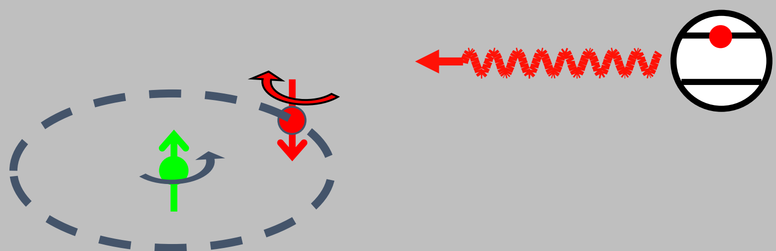


The first cesium clock was made at NPL-UK in 1955

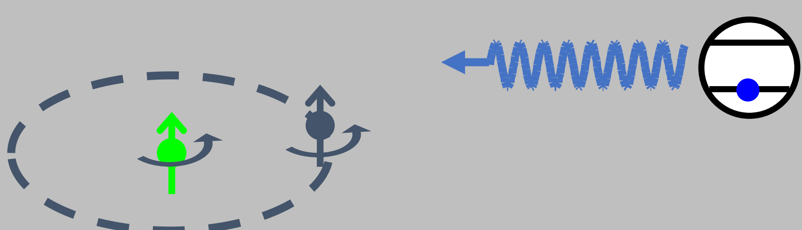
Atomic Clock Operation (over-simplified version)

(The truth is a bit (a lot) more complicated.)

Microwaves, about 9.192 631 770 GHz



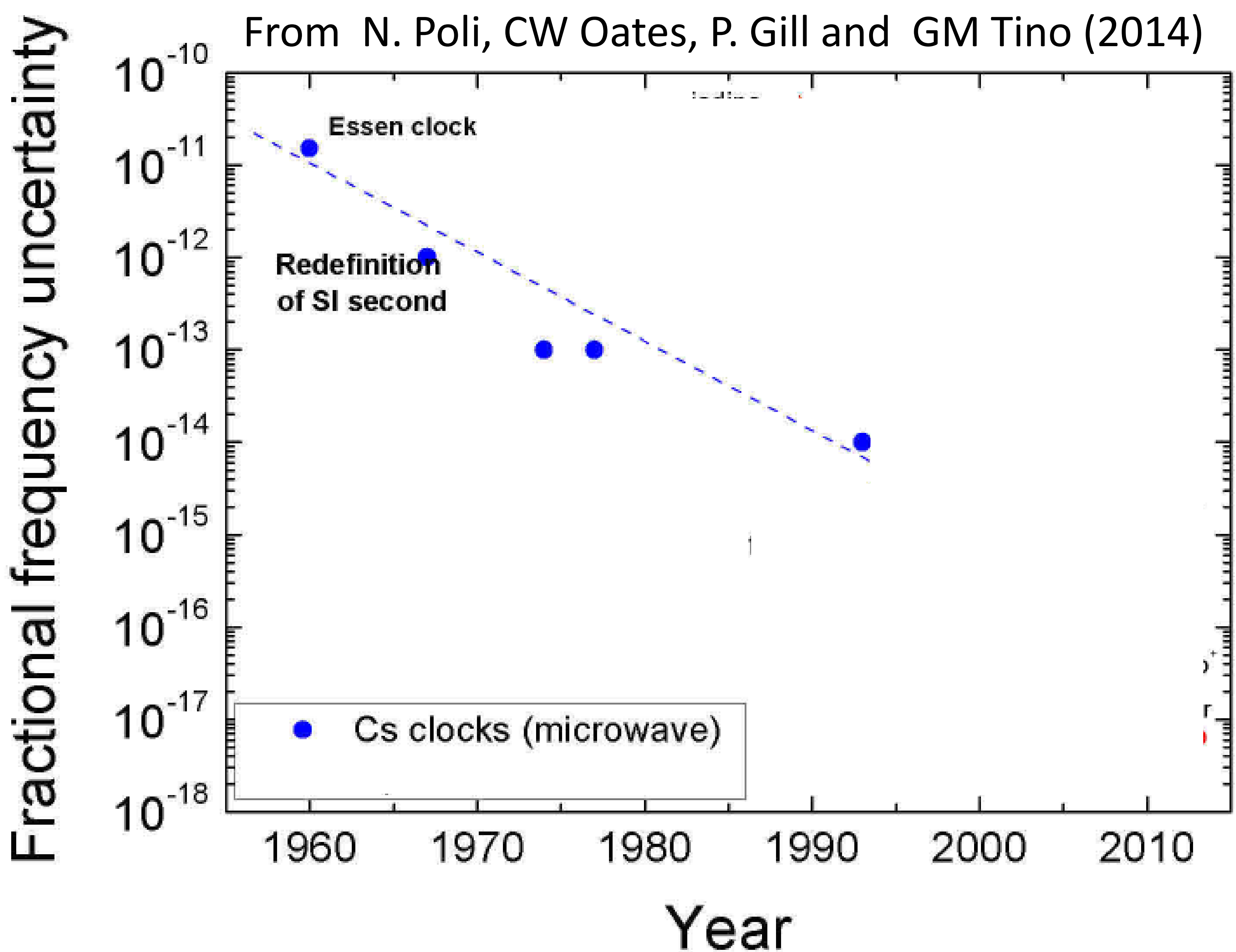
When the frequency is "just right" the atom changes state: electron flips.



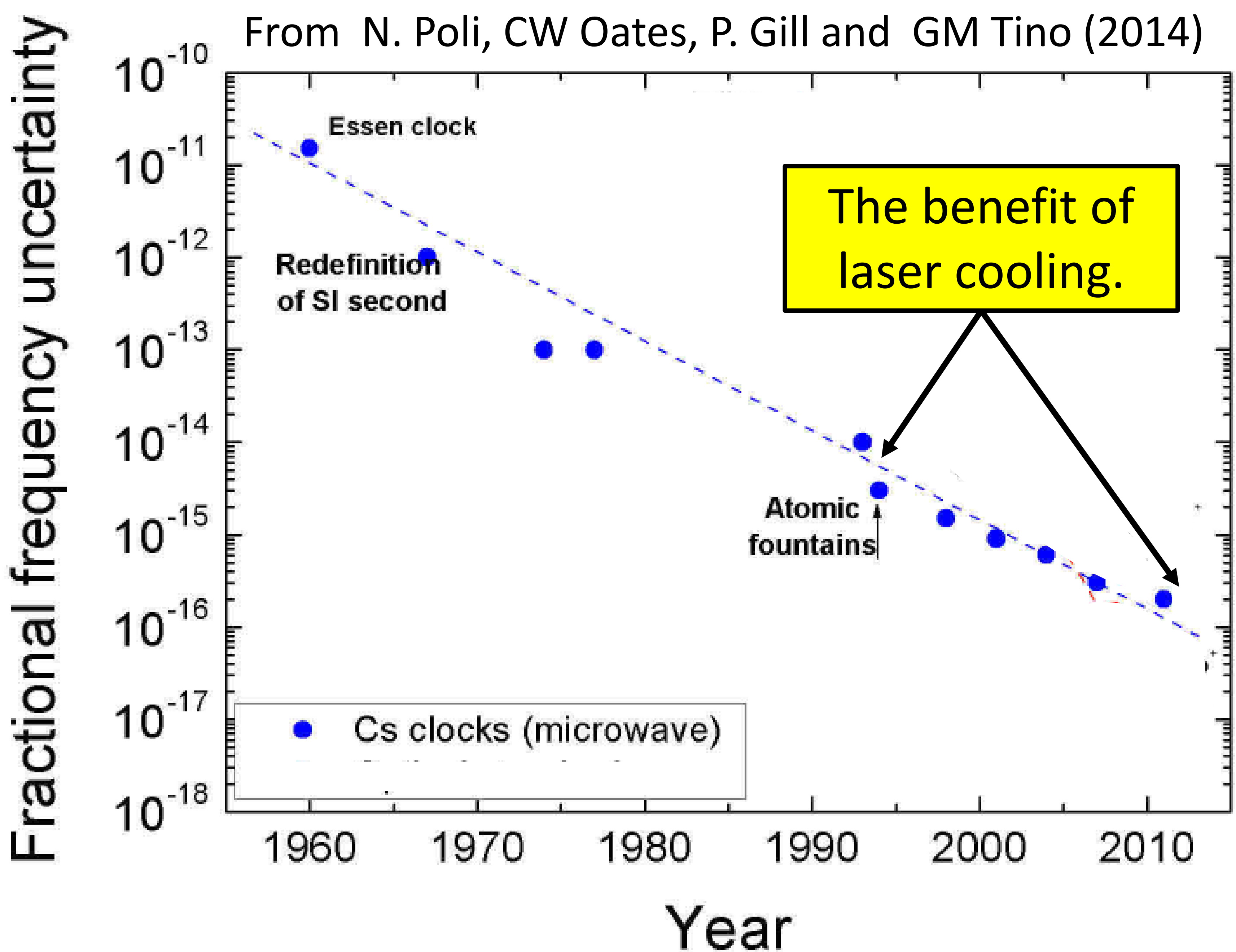
When the frequency is just a little off, the atom does not change state.

Atomic Time

The second is the duration of 9 192 631 770 periods of the radiation corresponding to the transition between the two hyperfine levels of the ground state of the caesium-133 atom (13^{th} CGPM 1967).


From N. Poli, CW Oates, P. Gill and GM Tino (2014)
Fractional frequency uncertainty
10^{-10}
10^{-11}
10^{-12}
10^{-13}
10^{-14}
10^{-15}
10^{-16}
10^{-17}
10^{-18}
Essen clock
Redefinition of SI second
Cs clocks (microwave)
1960
1970
1980
1990
2000
2010
Year

The performance of Cs clocks stalled at a bit better than 10^{-14} because the Cs atoms move so fast (over 100 m/s). Laser cooling, many of the techniques of which were developed at NIST, addressed that and improved the performance to a few parts in 10^{16}.



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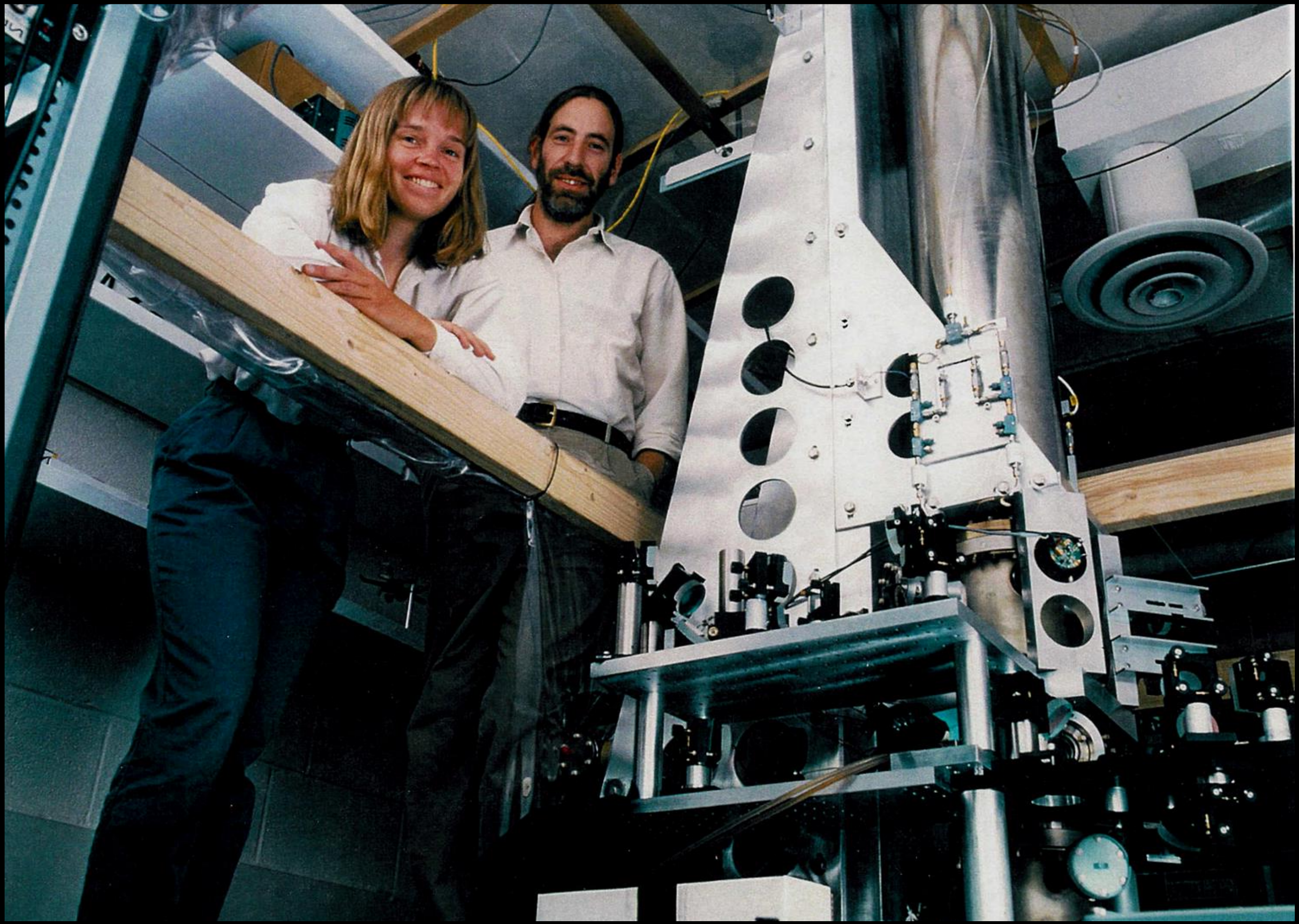
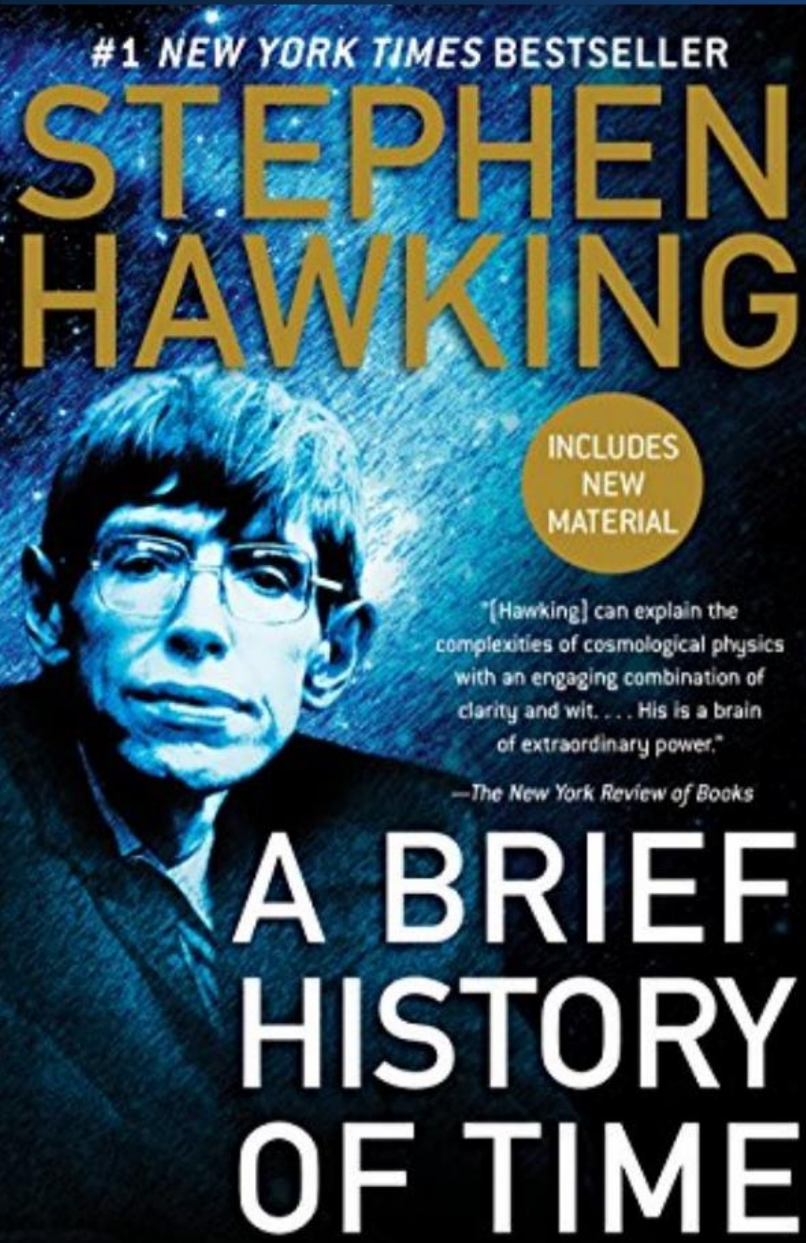


Cs fountain clocks like this, with atoms cooled below 1 μK (with techniques developed at NIST) keep time to a few parts in 10^{16}. This is the most accurately measured quantity in the SI.

The Key Concept

An arbitrary artifact, the rotating earth, whose rotation may change for any number of reasons, is replaced by a *constant of nature*—the frequency of a ***quantum*** transition in some atom.

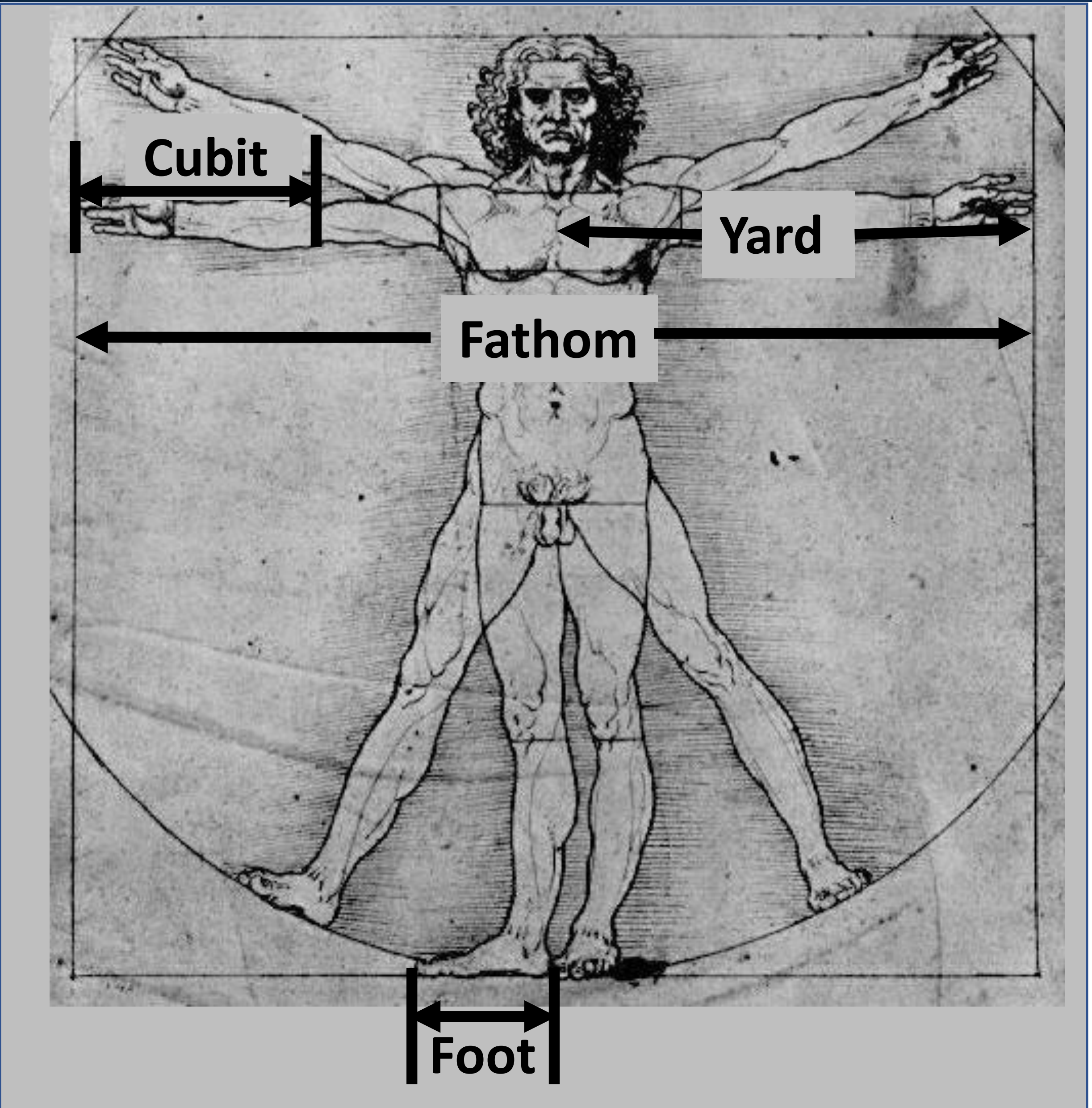


Next, even better:

"A Short History of Length"

While time was important historically, length was REALLY important, because it involved commerce and construction.

Ancient length standards



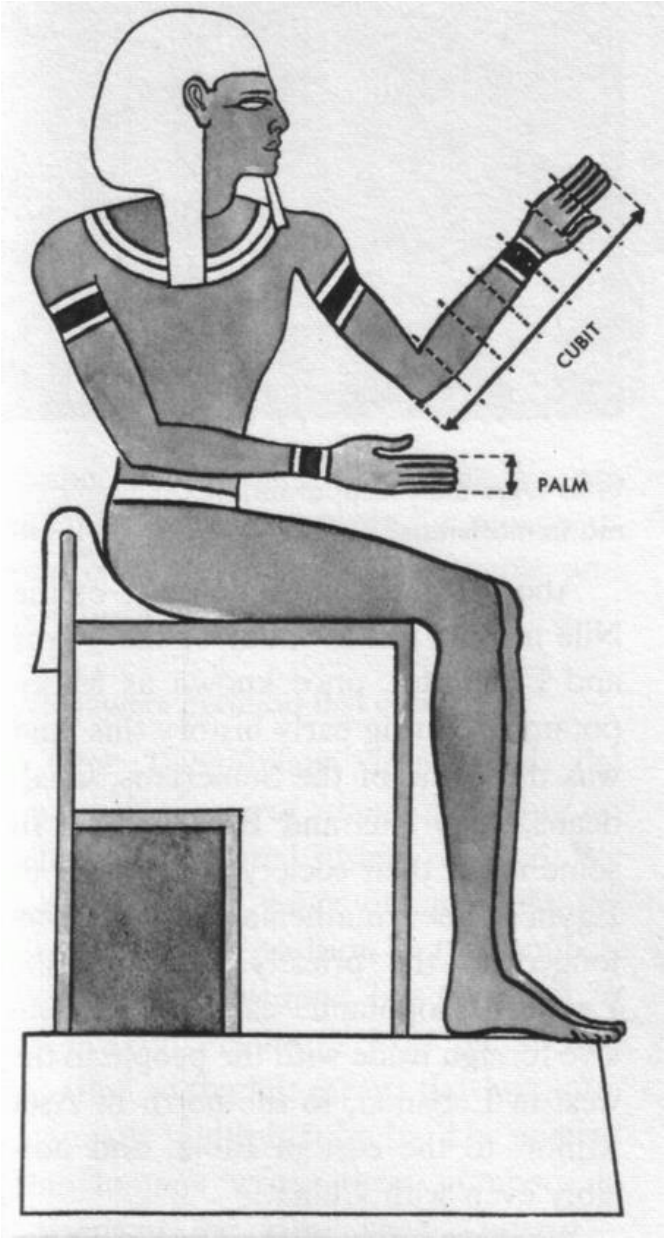
The early approach to length used the human body as the standard.

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

NIST

- 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

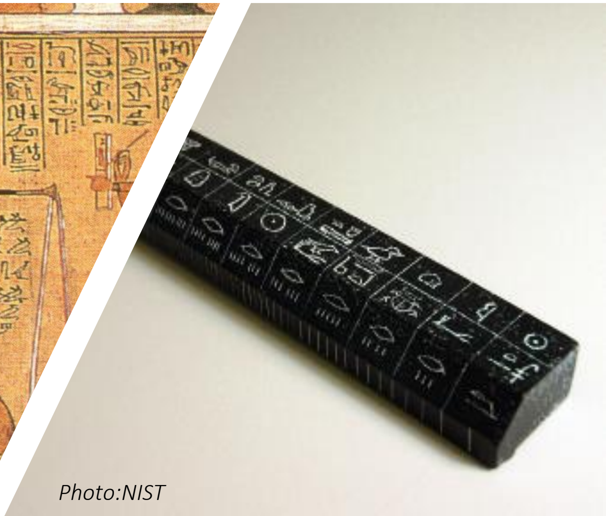


Photo:NIST

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

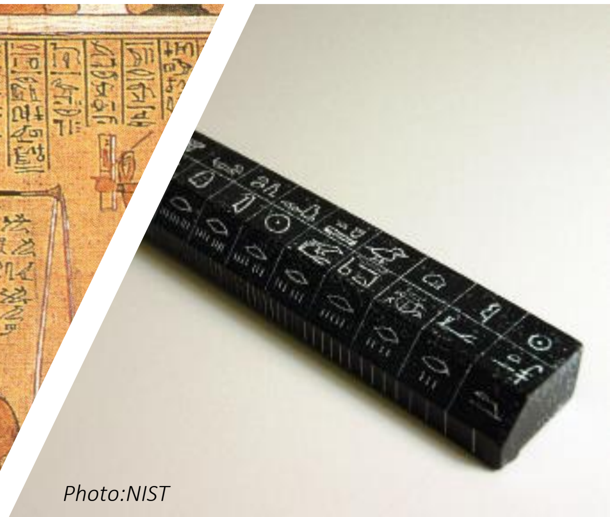


Photo:NIST

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

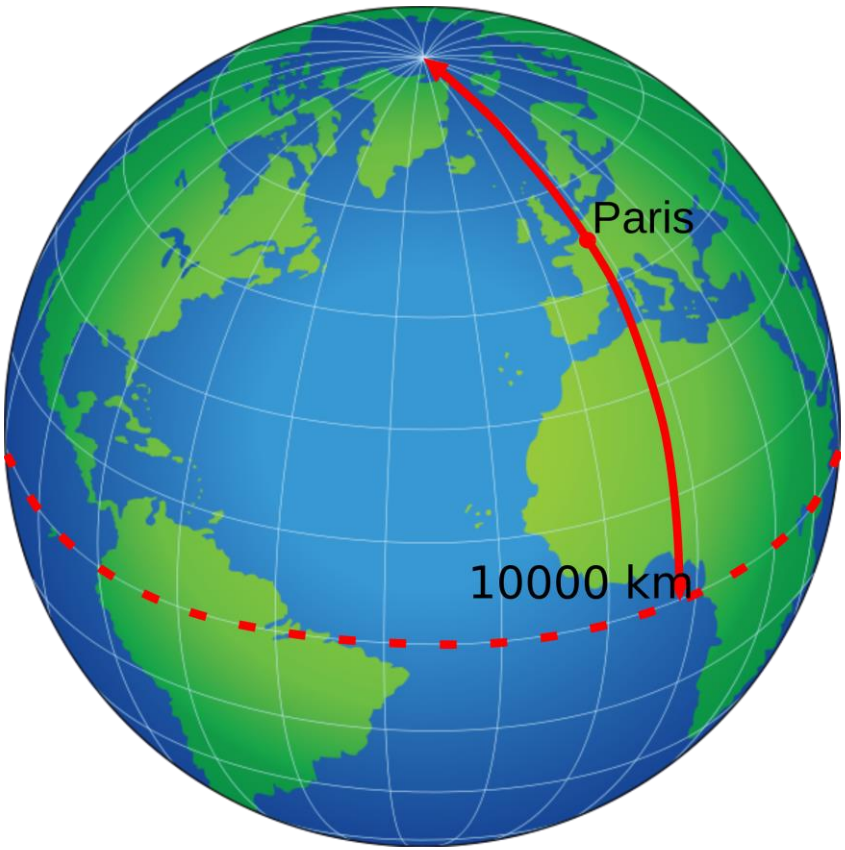


Image: U.S. Government

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.

Photo credit: http://monnaiesanciennes.free.fr/images_elsen_104/MED-000576-002dc.jpg

The Metre of the 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."

1799: Mètre des Archives (Platinum Bar)

Source: http://en.wikipedia.org/wiki/History_of_the_metre

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

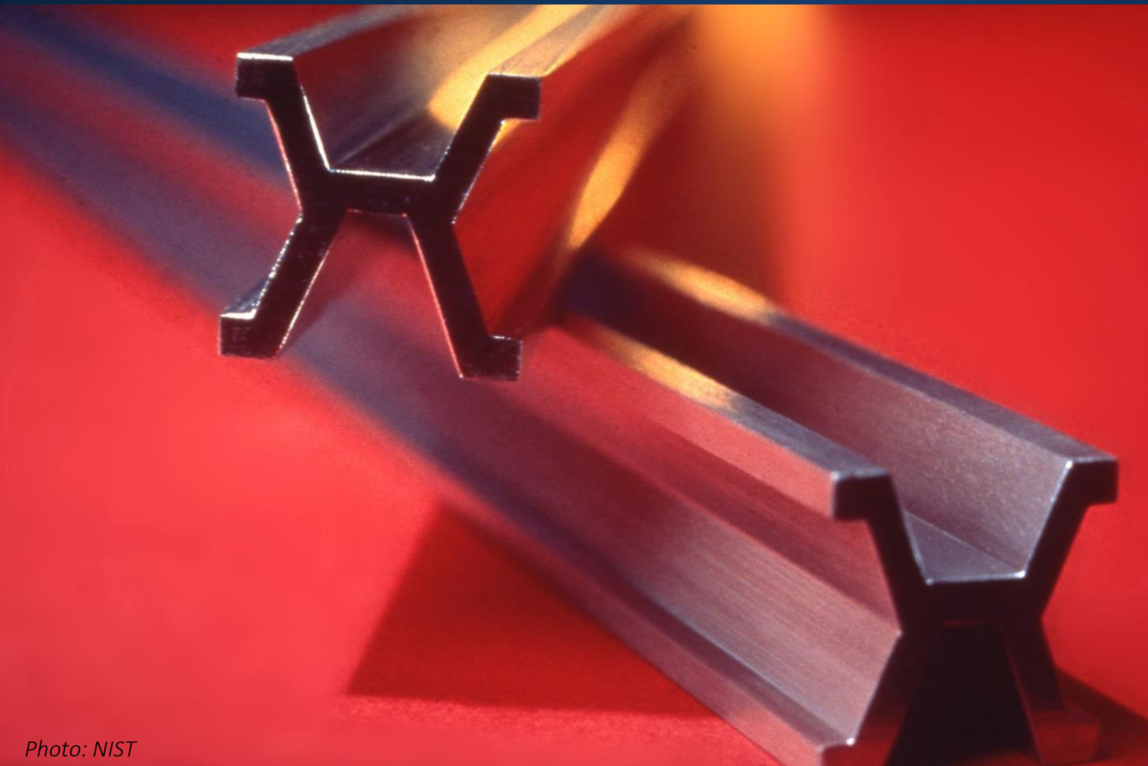
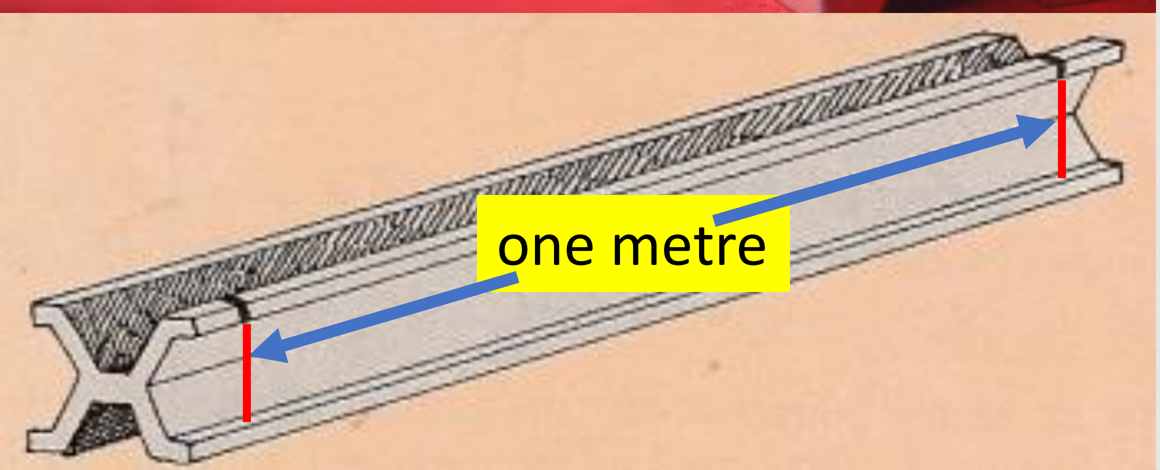


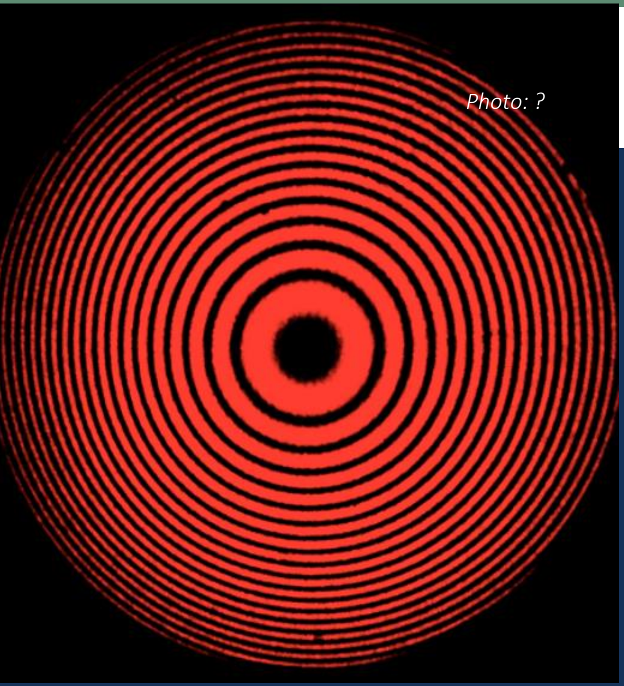
Photo: NIST

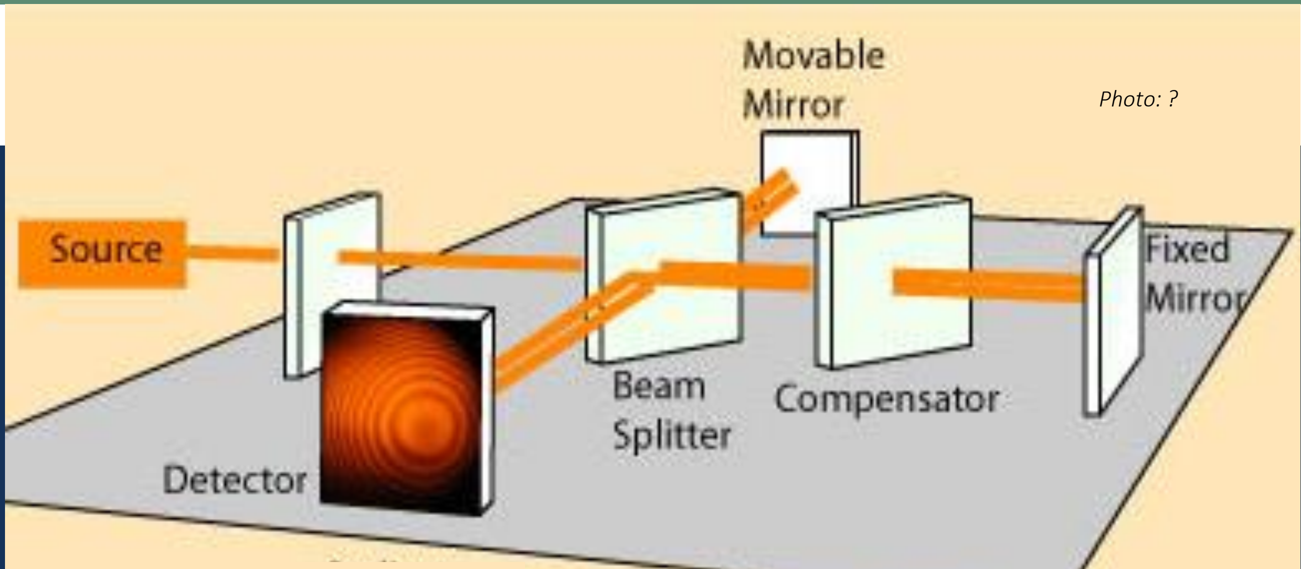


Following the famous **1875 Convention du Metre**, the metre of the archives was **replaced with a line standard**, the International Prototype of the Metre.

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

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.

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.

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:

$$\lambda f = c$$

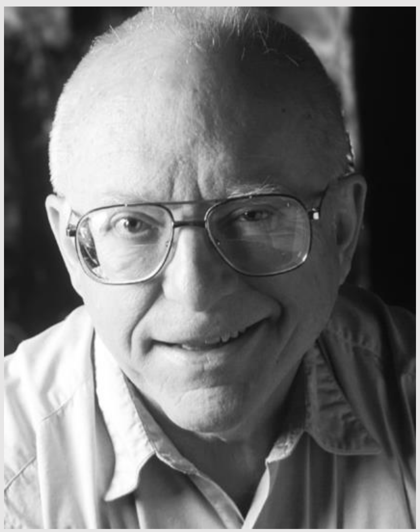
If we know the frequency f of any light, we know its wavelength λ.

This definition incorporates future improvements in lasers and frequency measurements.

The 2005 Nobel Prize In Physics

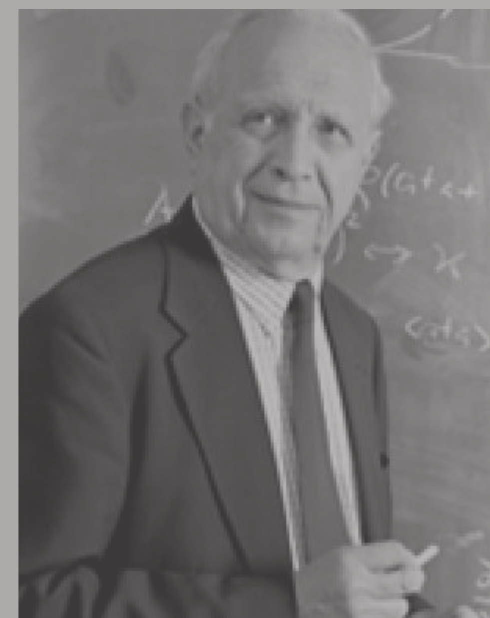
NIST

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



John "Jan" Hall
Photo: NIST

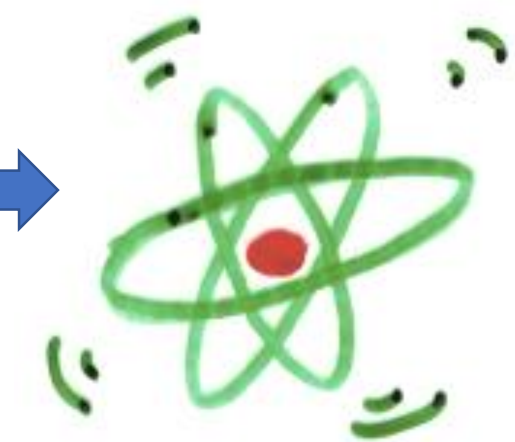
Theodor W. Hänsch
Photo: Courtesy Theodor Hänsch



Roy J. Glauber
Photo: J. Reed

The Key Concept

The meter went from an artifact to an atomic constant of nature to a *fundamental* constant of nature.



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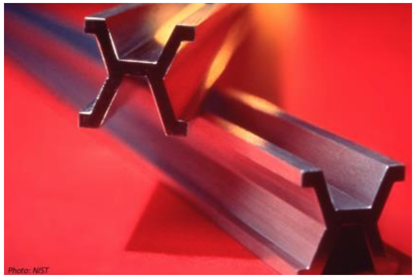
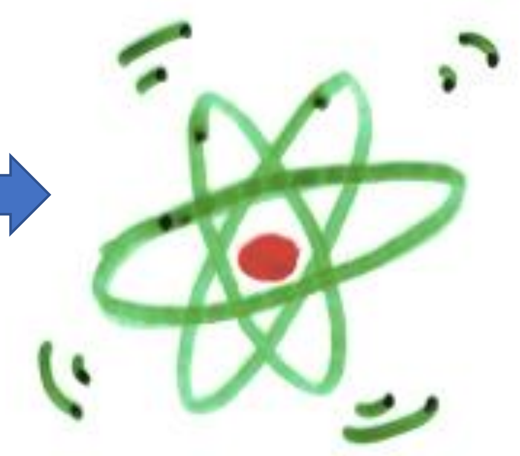
The Key Concept

The meter went from an artifact to an atomic constant of nature to a *fundamental* constant of nature.

No need ever to change again.





c

Beautiful definitions

The definition of the metre is both brilliant and beautiful—even more beautiful than the definition of the second.

On 20 May 2019, the international metrology community brought this beauty to the kilogram (and to the ampere, kelvin, and mole).

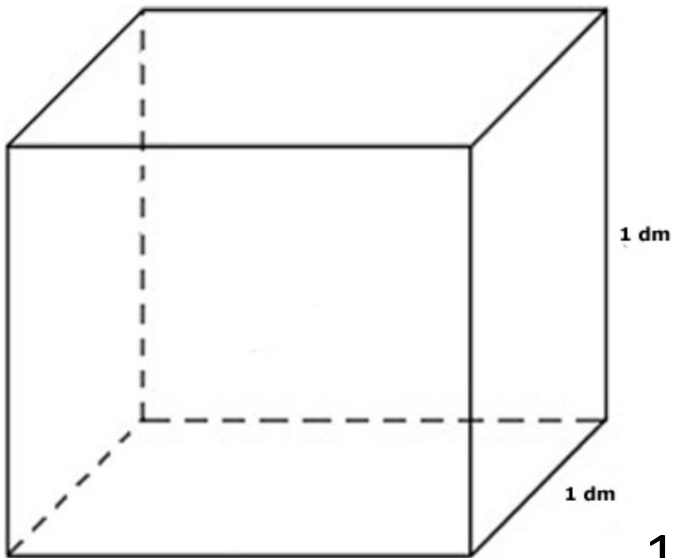
Why and How?

A Light History of Mass

Ancient mass standards

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

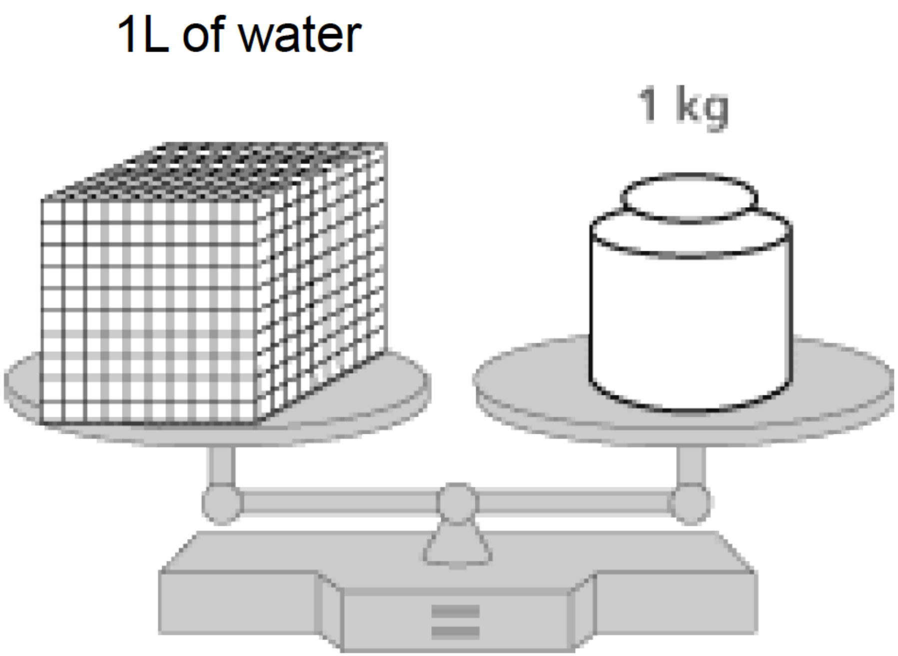
Revolutionary mass standard



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, in 1799, a platinum artifact became the kilogram of the archives—a return to the ancient practice, just as with the metre.

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 was the <u>last</u> artifact.

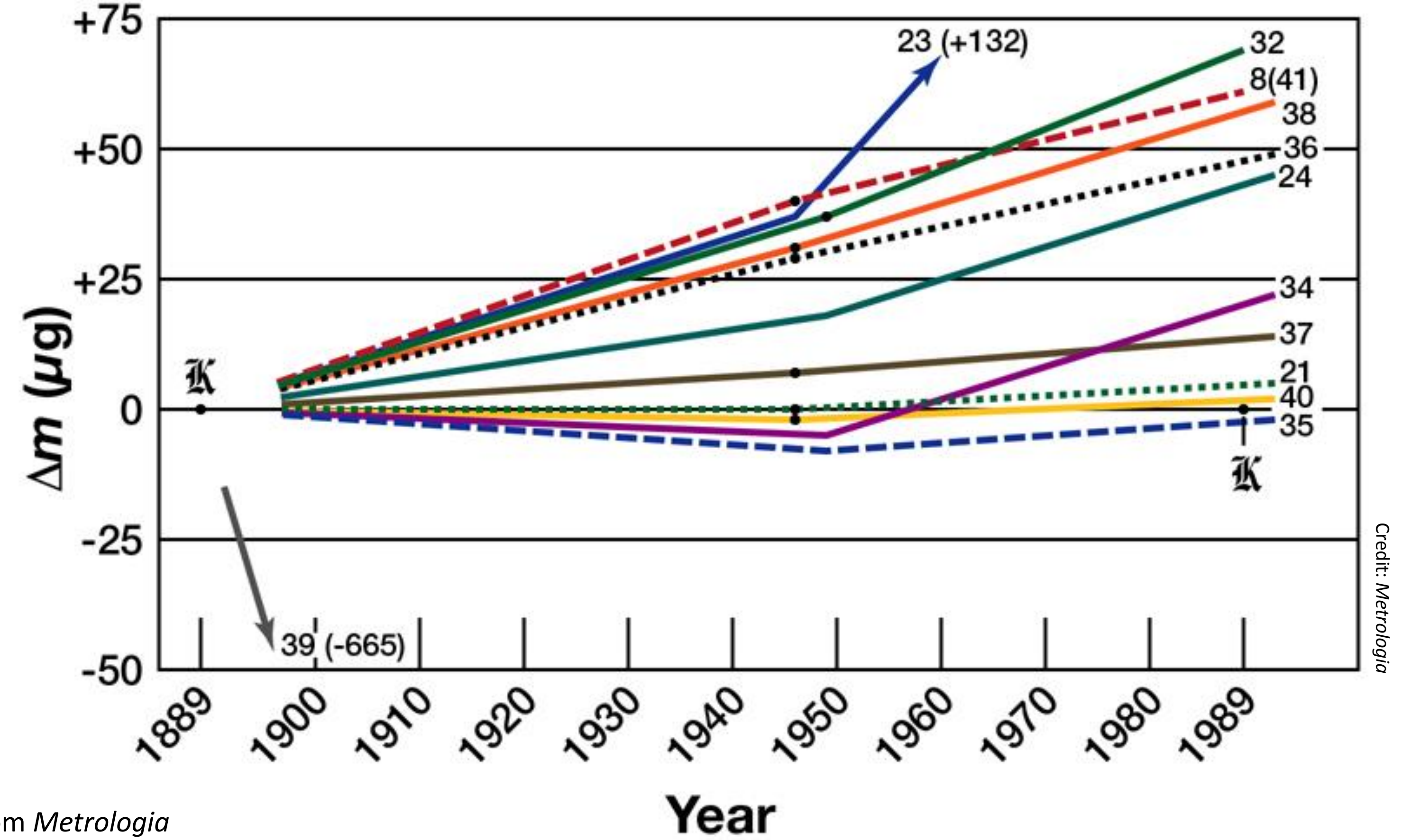
The Old Definition

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

That in the 21st century, the unit of mass was an artifact, a piece of metal made in the 19th century, based on an object made in the 18th century, is a scandal. If someone left a fingerprint on the IPK, all of us would lose weight.

Nobody has left a fingerprint on the International Prototype Kilogram, but its mass is “changing” nevertheless.

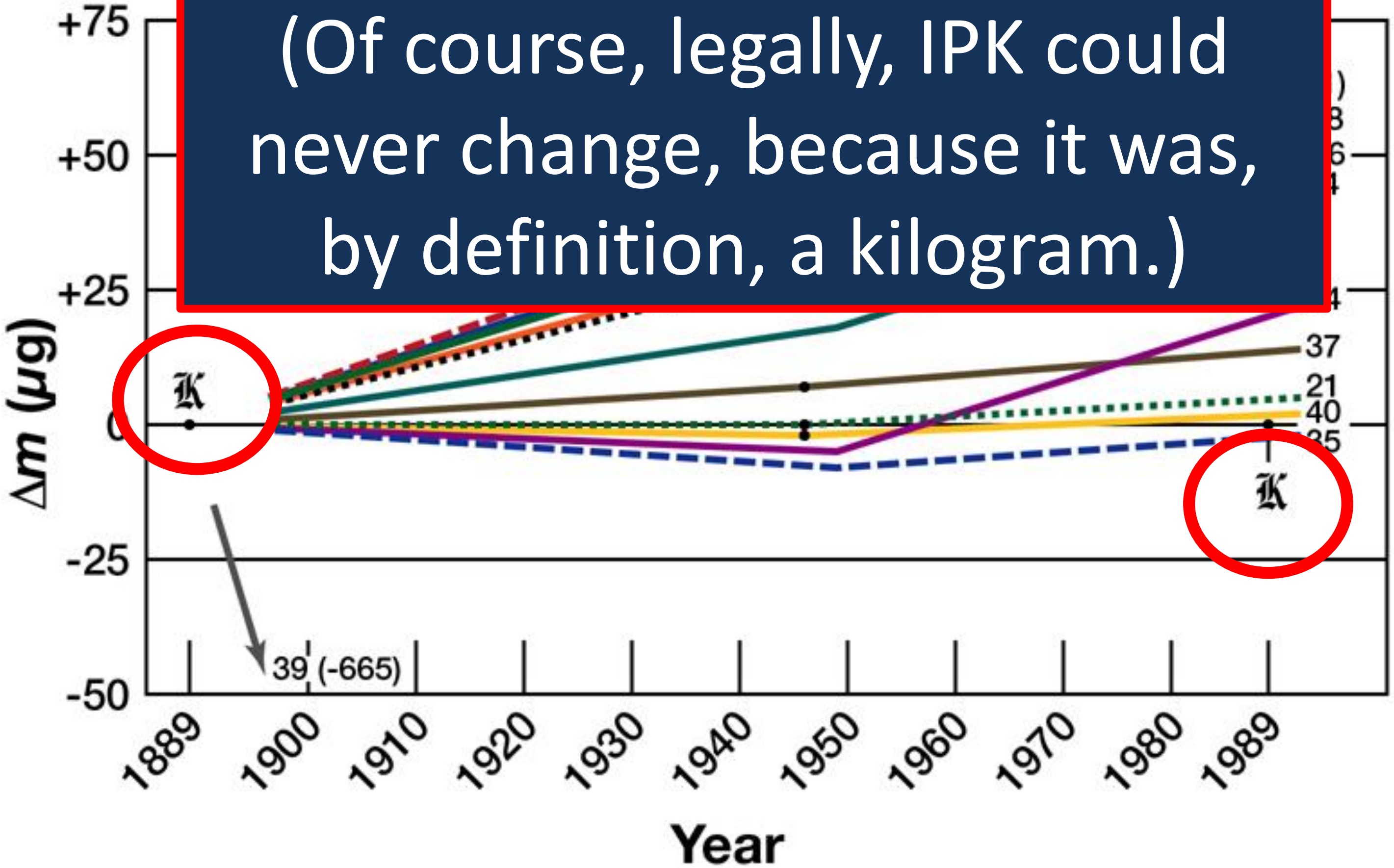
The International Prototype Kilogram appears to be changing!!



Credit: graph from *Metrologia*

The International Prototype Kilogram appears to be changing!!

(Of course, legally, IPK could never change, because it was, by definition, a kilogram.)



Credit: *Metrologia*

Fixing the Kilogram Problem

This scandalous situation had to be fixed. We wanted 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

NIST

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*.

We will not be weighing photons (we could, but not well enough). Instead, to use Planck’s constant to define the kilogram, we use a procedure where we measure the mass (in kilograms, not atomic mass units) of a single atom, then multiply that to get to a full kilo.

Credit: NPL

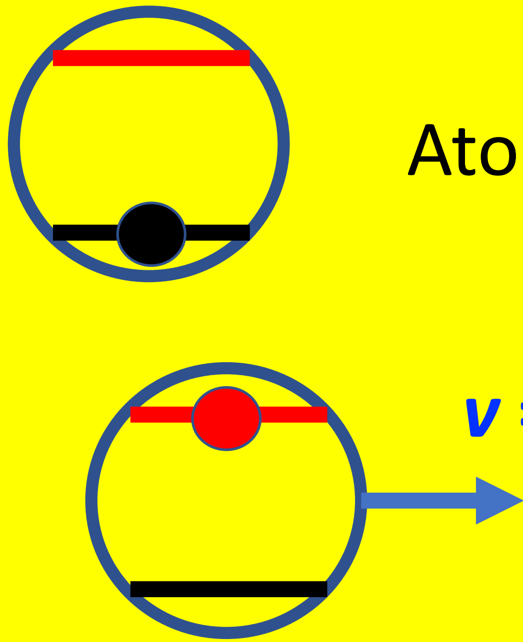
Mass from *h* : a single atom

NIST

one photon

$E = hf$

$p = h/\lambda$



Atom at rest in ground state

$\boldsymbol{v = h/m\lambda}$

Atom moving at $v = h/m\lambda$
in excited state

Atom interferometry measures the recoil velocity; λ is "easy", so fixing *h* gives the atomic mass *<u>in kilograms</u>*.

From an atom to a kilogram

NIST

Near-perfect silicon spheres at PTB and elsewhere allows “counting” the Si atoms, and so converts atomic mass to macroscopic mass.

Credit: ©Physikalisch-Technische Bundesanstalt (PTB)

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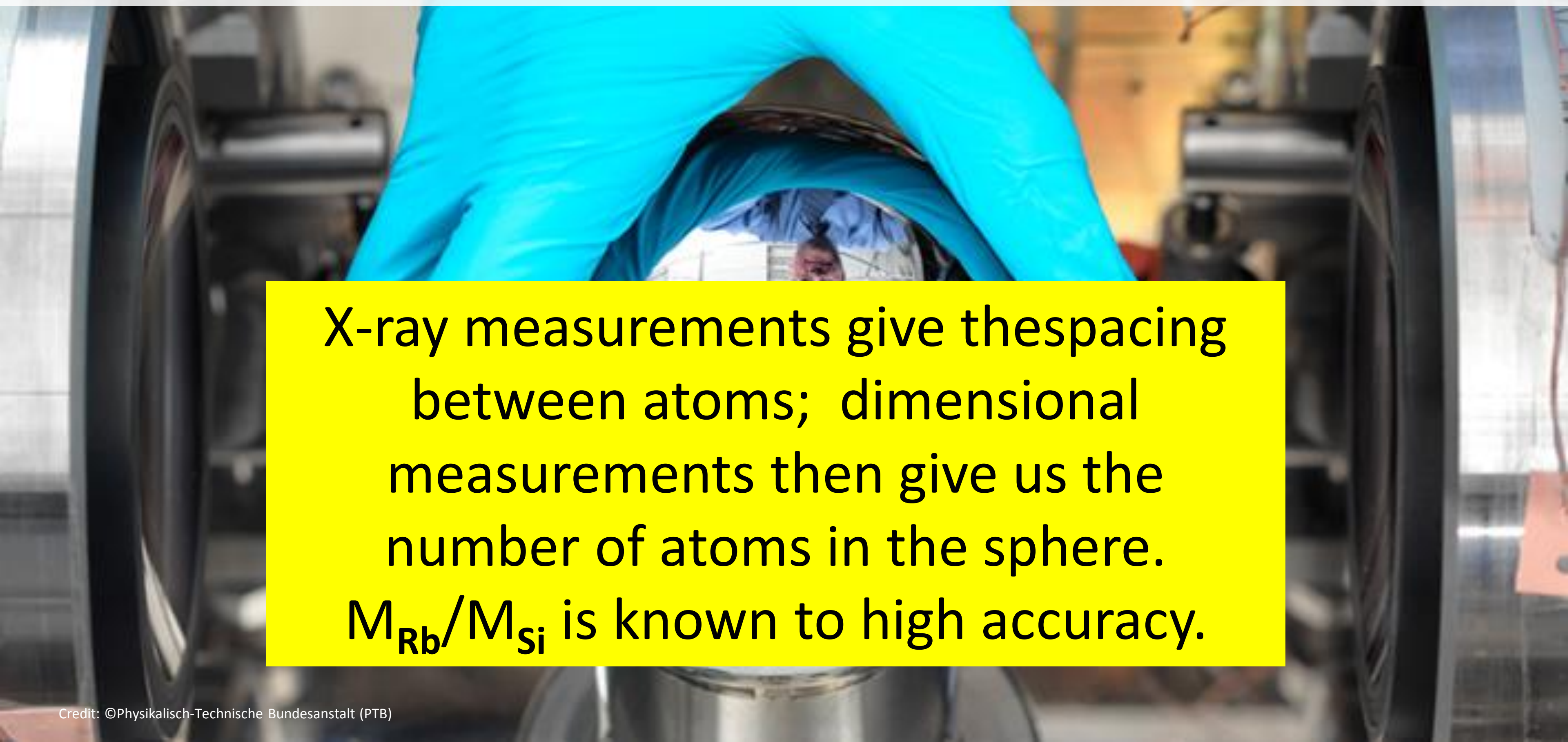
Near-perfect silicon spheres at PTB and elsewhere allows "counting" the Si atoms, and so converts atomic mass to macroscopic mass.



X-ray measurements give thespacing between atoms; dimensional measurements then give us the number of atoms in the sphere. M_{Rb}/M_{Si} is known to high accuracy.

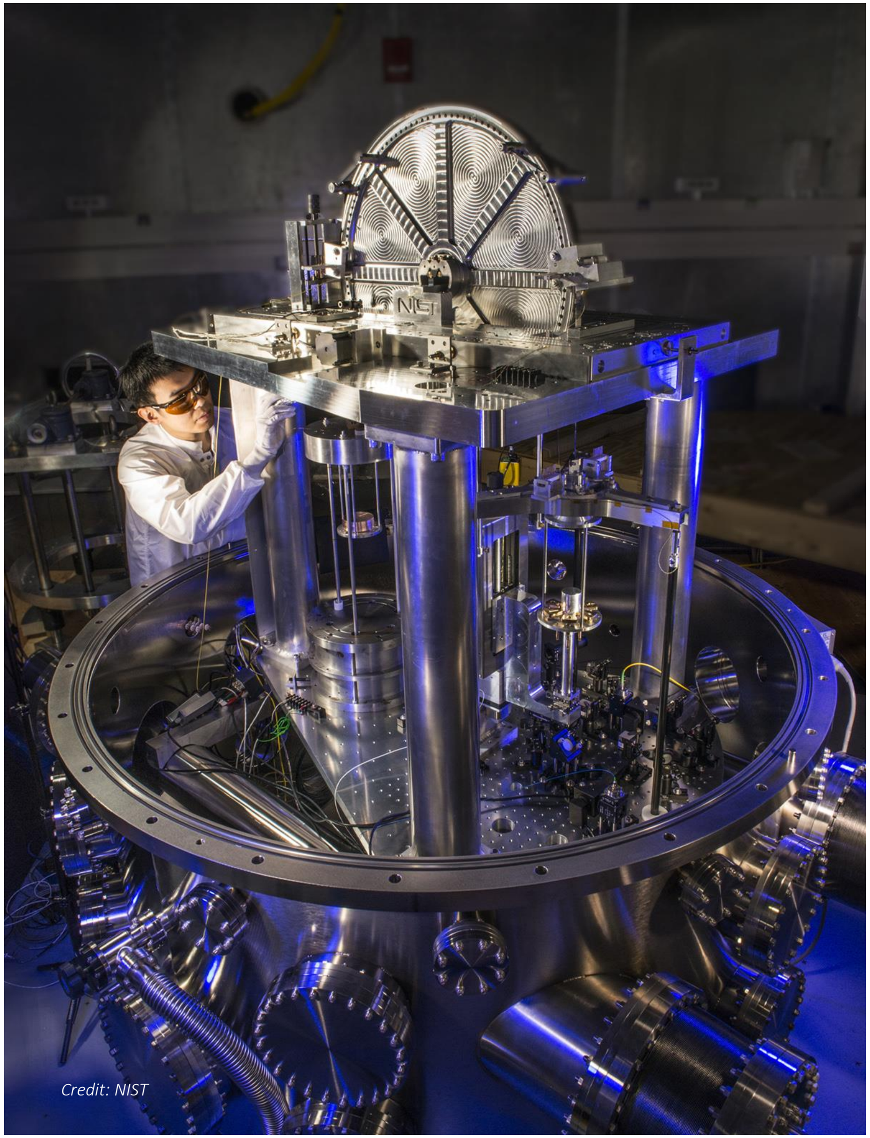
Credit: ©Physikalisch-Technische Bundesanstalt (PTB)

Another way to get mass from *h*:

Bryan Kibble 1938-2016

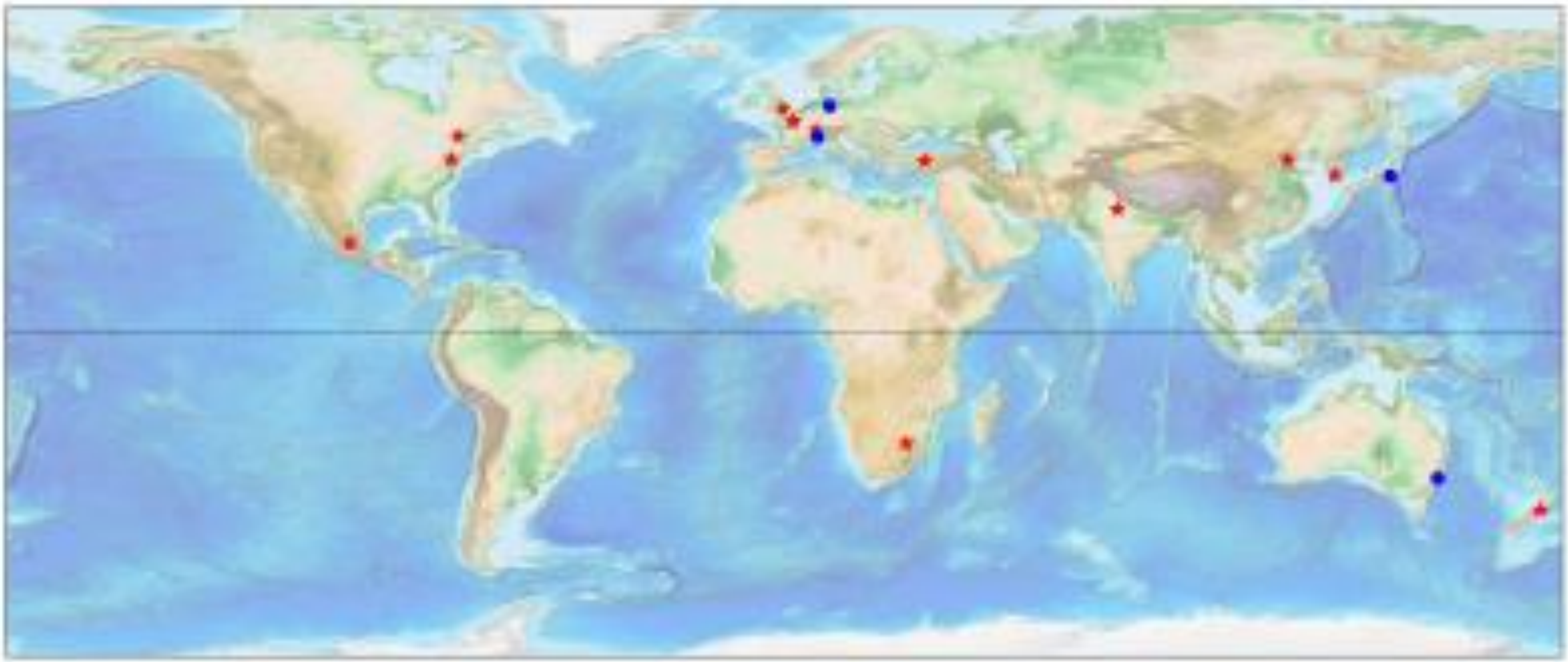
One of the beautiful features of defining mass via *h* is that the definition does not specify the method to be used. Here we turn to an electro-mechanical device known as a Kibble Balance or Watt Balance.

NIST Kibble Balance



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

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

26th General Conference of Weights and Measures

Redefinition of SI Adopted
Versailles, France 2018

The unanimous agreement about the changes to the International System of Units by some 60 countries across the world, in spite of differing perspectives and intense negotiations, is a good example of how things ought to be handled in relationships between nations.

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Unprovoked assault on a neighbor is not.

Another part of the story: the ampere

Before: "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."

Now: Define the electron charge $e = 1.602\ 176\ 634 \times 10^{-19}$ C , 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.

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: the Avogadro constant:

$$N_A = 6.022\ 140\ 76 \times 10^{23}\ \mathrm{mol}^{-1}.$$

The Kelvin: formerly 1/273.16 of the triple point of water. Now, we specify the thermal energy per kelvin of the atomic constituents, i.e., we define the Boltzmann constant $k_B = 1.380\ 649 \times 10^{-23}$ J/K

The New SI

NIST

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 had the biggest revolution in measurement units since the French Revolution.

The New Système Internationale

NIST

All of the base units of the International System of Units are now defined by fixing the values of constants of nature.

Realizing the dream

À tous les temps,
à tous les peuples.

For all times, for all peoples.

Photo credit: http://monnaiesanciennes.free.fr/images_elsen_104/MED-000576-002dc.jpg

Except, it seems, for time itself, which is still tied to a *specific* atom (Cs) rather than to a *fundamental* constant.

As for the future
of time....
only time will tell.

The End