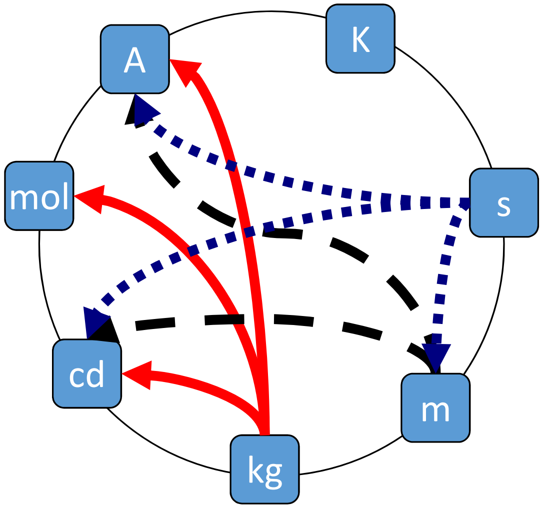
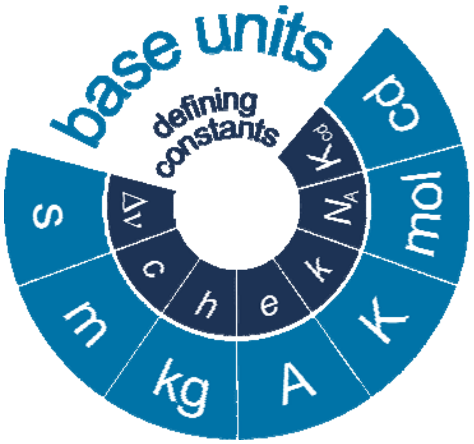
“for all time, for all people”[1]

- In 2018, the CGPM is expected to vote on a proposal to revise the International System of Units (SI).

Current SI spanned by 7 base units.



Revised SI spanned by 7 defining constants.



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[1]: attributed to Charles-Marie de La Condamine

A long time in the making

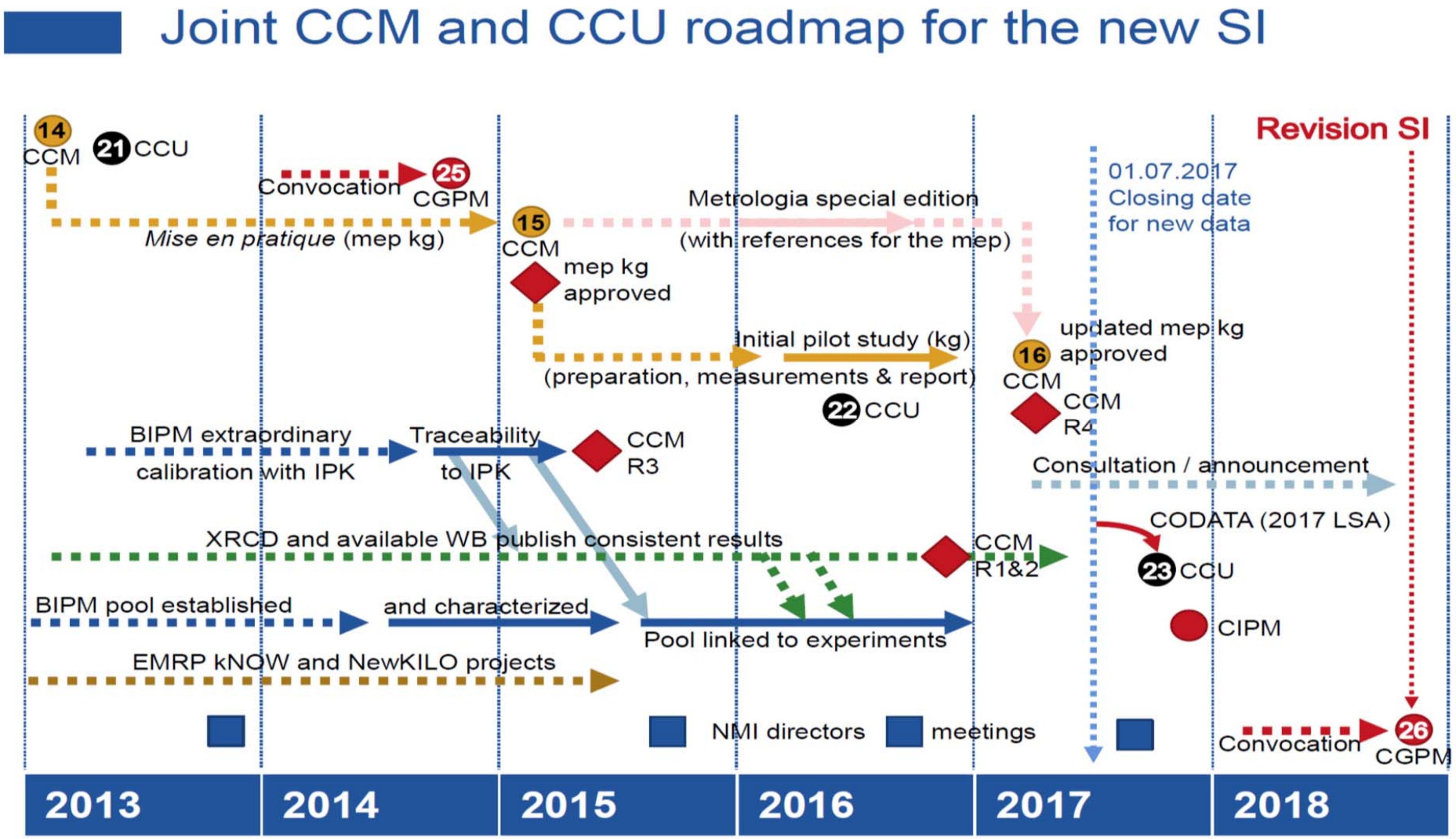
1990
Some of the electrical units (V, Ω) split off from the SI due to advances in quantum metrology that are incompatible with an SI that has its roots in 19th century mechanics. Starting in 1990 electrical measurements are reported in conventional units.

1991
B.N. Taylor recognizes that the watt balance can be used to realize the kilogram from fundamental constants.

2005
Group of five (Mills, Mohr, Quinn, Taylor, Williams) publishes
Redefinition of the kilogram: a decision whose time has come

2005
The Consultative Committee for Mass and Related Quantities(CCM) formulates conditions for a redefinition of the kilogram

2013
The Consultative Committee for Units (CCU) and CCM produce a roadmap.



What will change?

- No significant change for s, m, cd.
- The revised SI affects the kg, A, K, mol.
- These SI units will remain contiguous through the revision.
- The electrical measurements will again be reported within the SI. This will cause a small shift (relatively of 10^{-7}) in the electrical units.
- The realization of the units can be accessed anywhere (Before, e.g., the kilogram was only accessible at BIPM) through multiple paths.

The kilogram

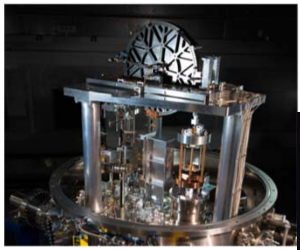
From

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

- Artefact based
- Only accessible at one location
- Only accessible at certain times (3 x in 100 years)
- Only at one nominal value.

To

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 6.626 070 040 $\times 10^{-34}$ 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 $\Delta\nu_{Cs}$.



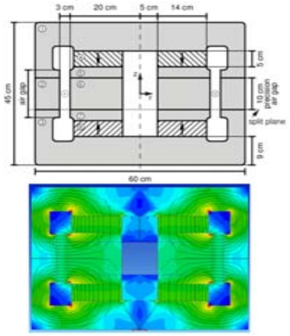
Kibble (watt) balance

X-ray Crystal Density Method

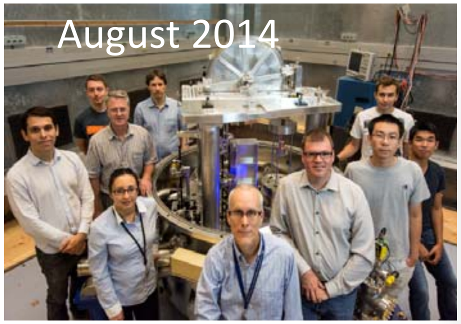
- Definition is based on fixed *h*
- Scalable
- Realization can be performed at any time

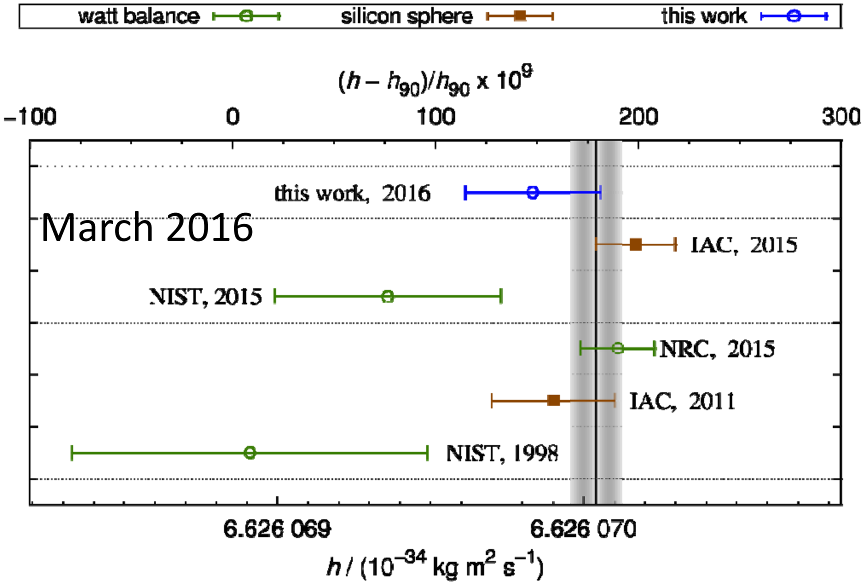
NIST’s new value for the Planck constant -- from design to first result in 5 years.

May 2011




December 2013

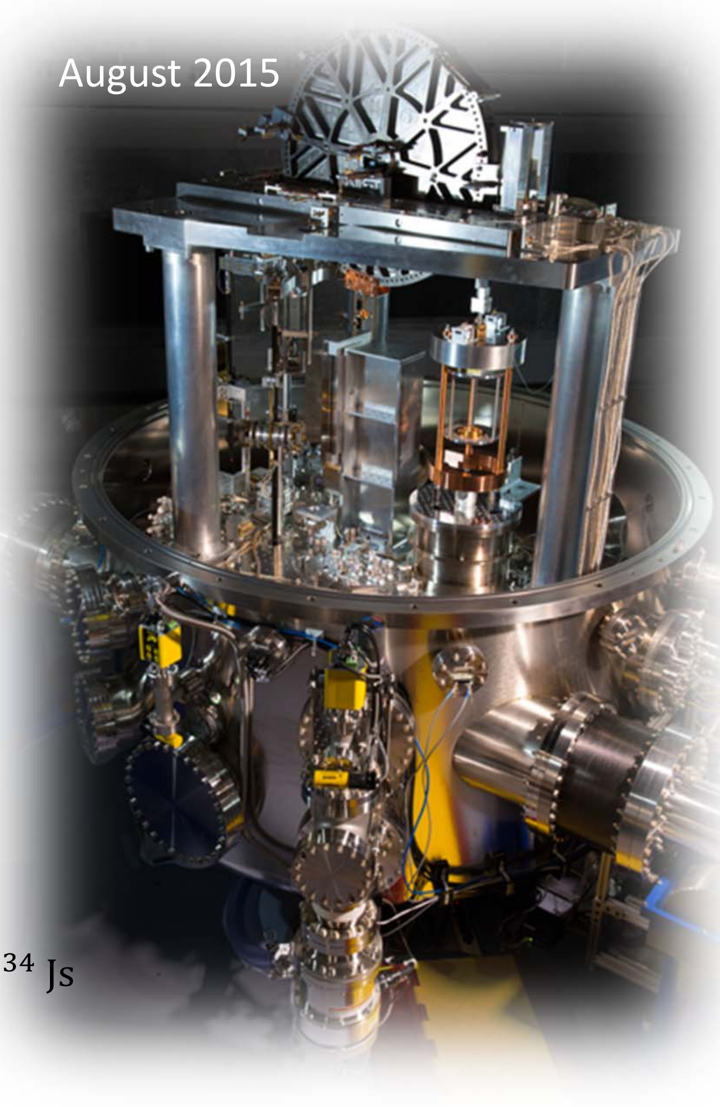

August 2014


March 2016

Source	**Uncertainty (10^{-9})**
Statistical	24.9
Magnetic field	15.4
Electrical	10.9
Alignment	6.5
Mass metrology	6.3
Mathematical	5.0
Balance mechanics	5.0
Local acceleration, g	4.4
Velocity	1.7
Total relative uncertainty	**33.6**

$$h = 6.626\,069\,83(22)\ \times 10^{-34}\ \mathrm{Js}$$

- current relative uncertainty (1-sigma): 34 x 10^{-9}
- projected rel. uncertainty by June 2017: 20 x 10^{-9}


August 2015

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

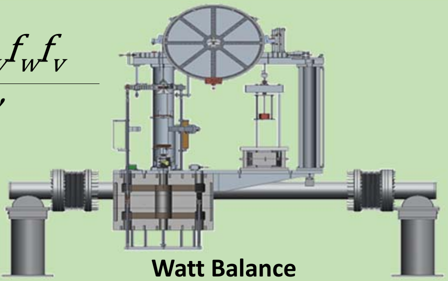
MISE EN PRATIQUE

For the Realization and Dissemination of the Redefined Kilogram

Patrick J. Abbott, Edward Mulhern, Eric Benck, Zeina Kubarych

Realization

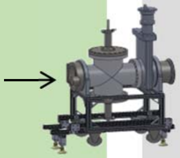
$$m = \frac{4 n_w n_v f_w f_v}{\alpha g v}$$



Watt Balance

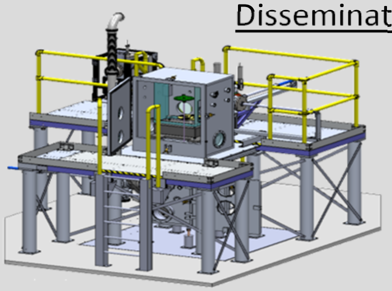
Realization of the kilogram in vacuum through a fixed Planck constant

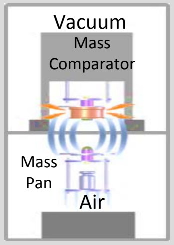
Mass Transport Vehicle (MTV) →



Direct traceability to SI ⟺ Vacuum artifacts

Dissemination





Vacuum-to-Air Transfer

Direct comparison of known mass in vacuum to unknown mass in air using magnetic suspension

Monitor Watt Balance stability

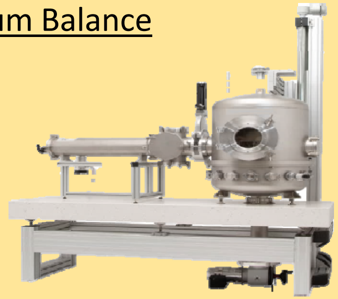
Vacuum artifacts

Check sorption artifact method

Vacuum Balance

Volume Artifacts

Surface Artifacts



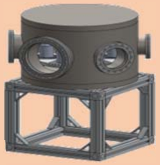
Surface and Volume Artifacts

Characterize sorption properties and air density for measurement of mass in vacuum and mass in air

Vacuum, air artifacts

Air artifacts

Vacuum and Air Storage



Vacuum

- Vacuum chamber pressure ~10^{-5} Pa
- Monitor pressure and gas composition of storage environment
- Load-lock to insert and remove artifacts with MTV

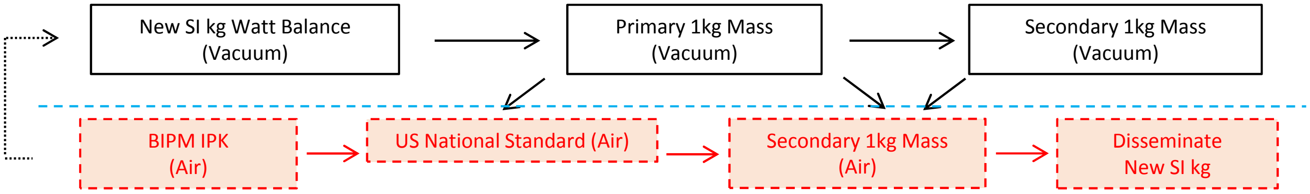
Air

- Constant flow of filtered room air
- Monitor temperature, pressure and humidity
- Load-lock to insert and remove artifacts with MTV

Artifact Pool

Dissemination from an ensemble of Pt-Ir and SS artifacts

Traceability and Dissemination



Magnetic Levitation Transfer

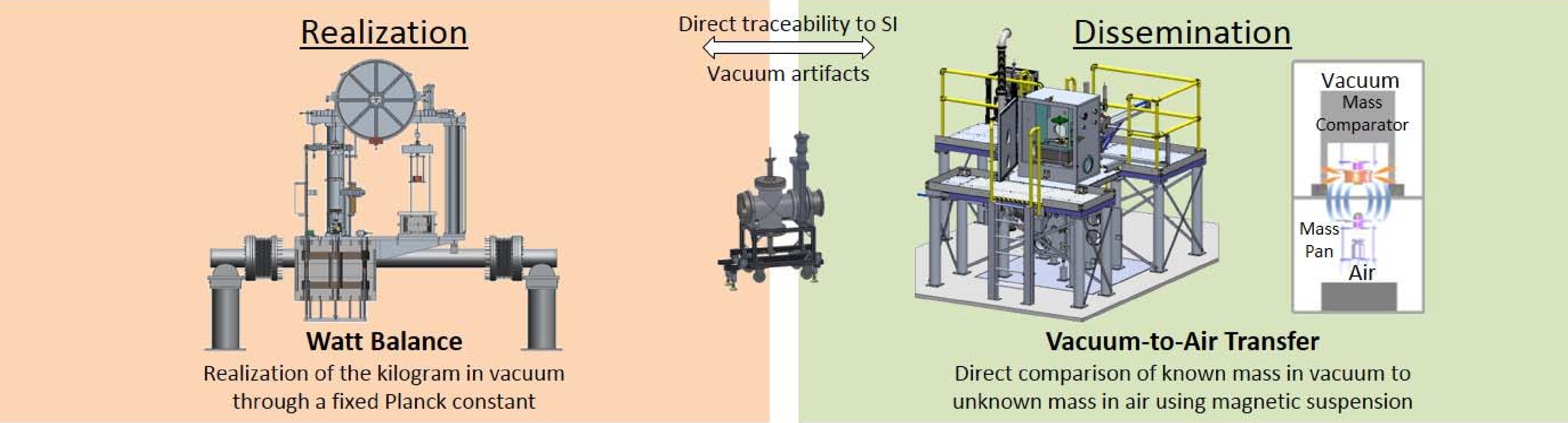
New SI kg Watt Balance (Vacuum) → Primary 1kg Mass (Vacuum) → Secondary 1kg Mass (Vacuum)

BIPM IPK (Air) → US National Standard (Air) → Secondary 1kg Mass (Air) → Disseminate New SI kg

Magnetic Levitation Transfer

Current System

From Watt Balance to Magnetic Suspension Mass Comparator (MSMC)
(Once *h* is fixed in 2018)



Watt Balance

Realization of the kilogram in vacuum through a fixed Planck constant

Vacuum-to-Air Transfer

Direct comparison of known mass in vacuum to unknown mass in air using magnetic suspension

Problems with present method

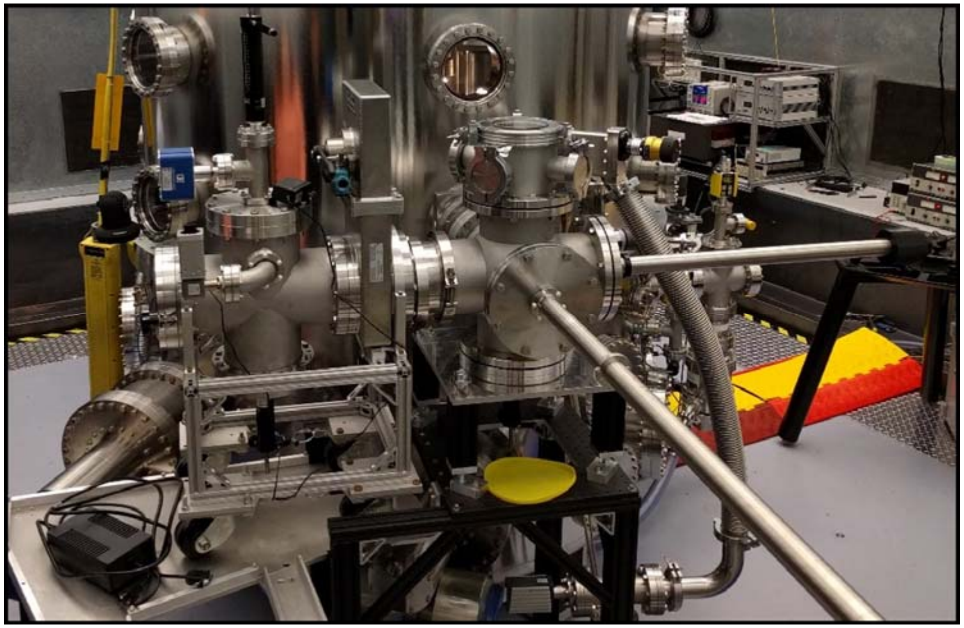
- Both WB and MSMC vacuum chambers must be vented, exposing the instruments to air and temperature shock
- Atmospheric contaminants adsorb onto the clean surface of the mass; measurable changes

Advantages with In-Vacuum method

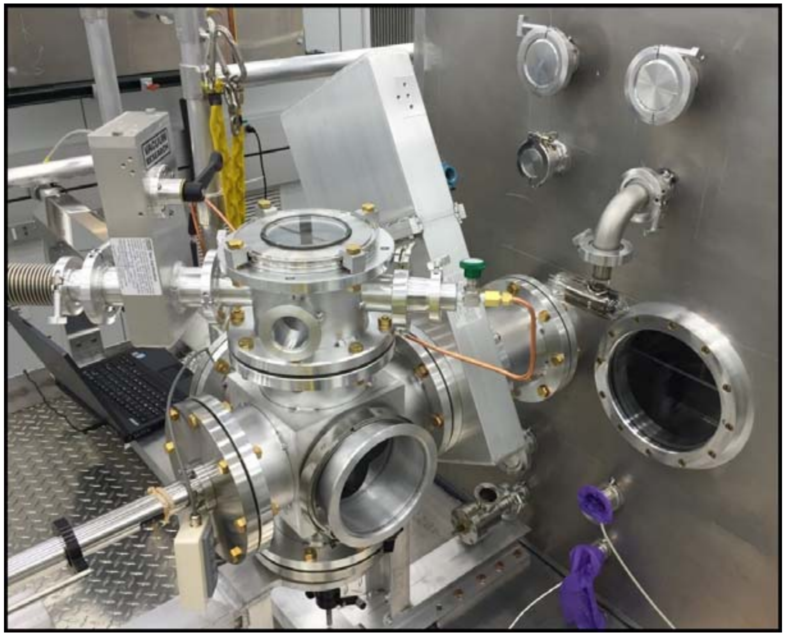
- No venting required for either chamber (reduce down time)
- Removal of temperature shock on magnets due to venting
- Riddance of surface sorption corrections and sources of uncertainty

Installed load lock for mass transfer in vacuum

Operation of the In-Vacuum Mass Transfer System from the WB to MSMC



Watt Balance Start Point



Magnetic Suspension Mass Comparator End Point

The Ampere

From

The ampere is that constant current which, if maintained in two straight parallel conductors of infinite length, of negligible circular cross section, and placed 1 meter apart in vacuum, would produce between these conductors a force equal to 2 x 10^{-7} newton per meter of length.

To

The ampere, symbol A, is the SI unit of electric current. It is defined by taking the fixed numerical value of the elementary charge *e* to be 1.602 176 620 8 $\times 10^{-19}$ when expressed in the unit C, which is equal to A s, where the second is defined in terms of $\Delta\nu_{Cs}$.

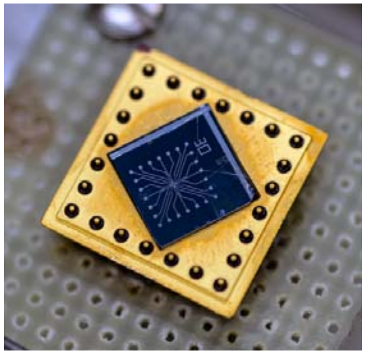
- Impossible to realize a physical conductor of infinite length and zero cross section, so ***definition isn't used***
- Since 1990 electrical standards are outside the SI
- Conventional electrical units employ quantum standards of voltage and resistance with ohm's law, V=I R

- Definition based on fixed value *e*
- *Can count electrons per unit time, e.g., SET charge pumps*

OR

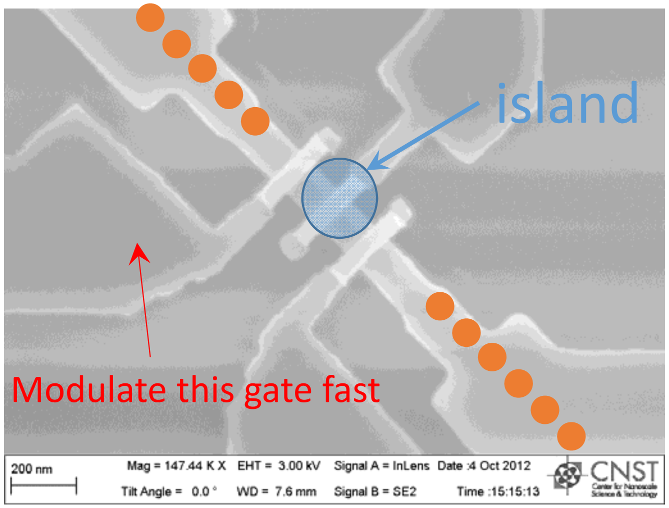
- *Quantum electrical standards of voltage and resistance with ohm's law are an SI unit!*

The Ampere at NIST by counting *e*

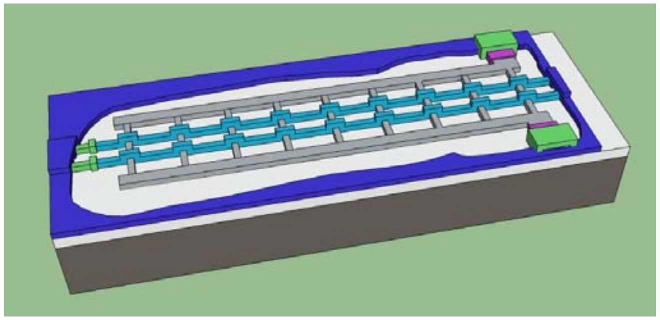


- Make devices to shuttle one electron at a time at a high frequency using physics of Coulomb blockade *(i.e., charge pump).*

$$I = \frac{dQ}{dt} = nef$$



Electrons shuttling through a Coulomb blockade device made at NIST



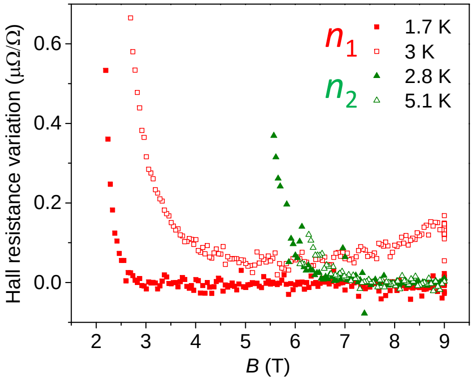
- Need lots of electrons to make a measureable current, so need many parallel pumps, like concept above
- An historic problem is that traditional metal gated pumps aren’t as stable as we would like
- NIST is developing an all silicon approach to solve this problem

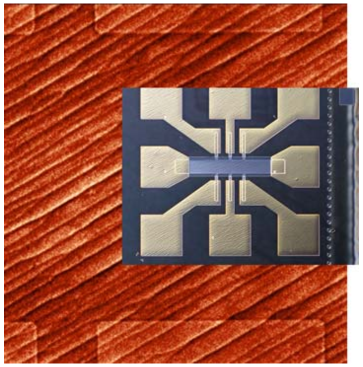
The Ampere at NIST by V/R

- Making SI voltage available through convenient instruments

Cryocooled NIST Programmable Josephson Voltage Standard system for realizing intrinsically accurate DC voltages from - 10V to +10V. Available as a NIST Standard Reference Instrument.

- Making SI ohm available through new devices based on graphene





NIST has developed novel techniques to grow graphene on Si C and to process the material into high current QHR devices. The devices are compatible with our existing highly customized measurement infrastructure, but can also be used directly with commercially available room temperature bridge systems, potentially revolutionizing the accessibility of this basic electrical standard.

The Kelvin

From

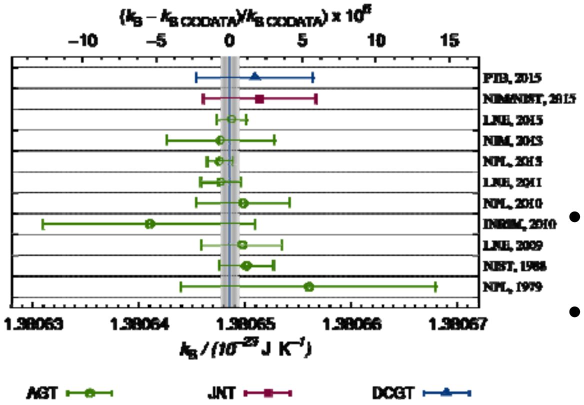
The kelvin, unit of thermodynamic temperature, is the fraction 1/273.16 of the thermodynamic temperature of the triple point of water.

Triple point cell

- Intrinsic standard
- Requires careful control of environmental factors
- Precision is limited

To

The kelvin, symbol K, is the SI unit of thermodynamic temperature. It is defined by taking the fixed numerical value of the Boltzmann constant *k* to be 1.380 648 52 $\times 10^{-23}$ when expressed in the unit J K^{-1} , which is equal to kg m^{2} s^{-2} K^{-1} , where the kilogram, metre and second are defined in terms of *h, c* and $\Delta\nu_{Cs}$.

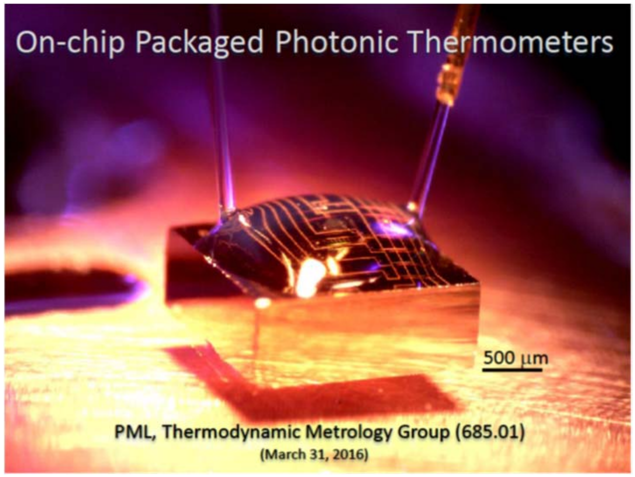


- Definition is based on fixing the Boltzman constant
- *Quantum noise becomes a potential absolute standard, paving the way for chip-based, self-calibrating sensors*
- *Triple point can still be used as convenient reference*
- Precision limited only by our imagination and quantum mechanics

Josephson voltage based Johnson noise thermometer

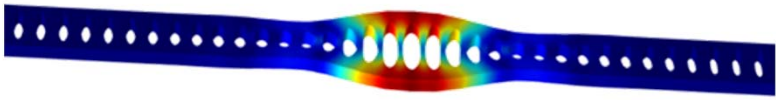
The Kelvin at NIST

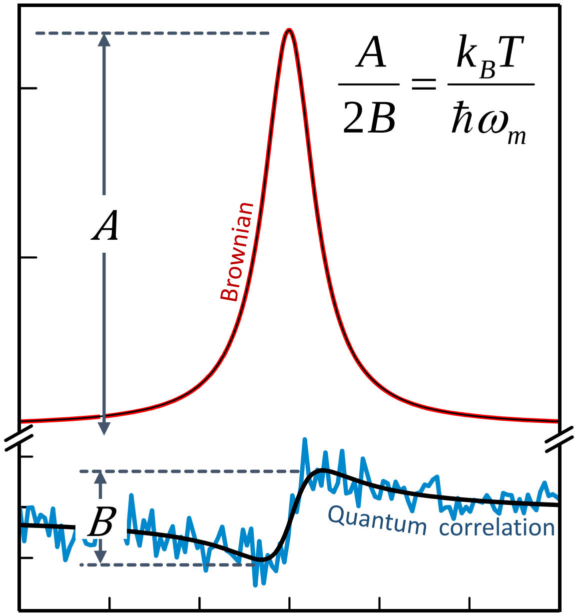
New photonic sensors



New approaches based on optomechanics

Si_3N_4 nanobeam optomechanical crystal





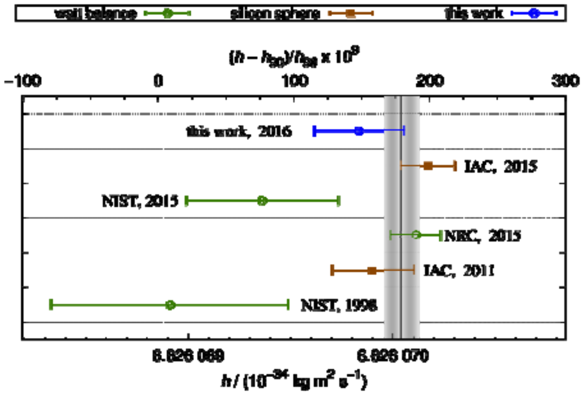
$$\frac{A}{2B} = \frac{k_B T}{\hbar \omega_m}$$

Improved Johnson Noise Thermometry

Redefinition of the Kg: What’s up?

Le Grand K (IPK)

- We are on schedule for the CIPM to ratify a redefinition in 2018!
- December 2013, International Prototype Kilogram (IPK) brought out for first time in 25 years: **Extraordinary Calibrations (Metrologia, March 2015)**
    - Result: BIPM mass scale found to be .037 mg too high relative to IPK (37 ppb)
    - This largely cancels the .045 mg shift NIST *accepted* in 2010
- All active Planck groups harmonized their mass to the Extraordinary Comparison in 2015
- NIST, PTB, NMIJ, and LNE reported new Planck values in 2016
- Agreement of Planck’s constant determinations is now sufficient to support redefinition (3 values within 50 ppb, 2 values below 20 ppb)
- Pilot study of the new kilogram is underway. BIPM is comparing artifacts from NIST, PTB, NMIJ and LNE realized directly from Kibble balances or X-ray crystal density method. Results to be announced early 2017.



Formation of CODATA

- 1966 –ICSU establishes the Committee on Data for Science and Technology (CODATA)
  - To strengthen international science for the benefit of society by promoting improved scientific and technical data management and use

ICSU
International Council for Science

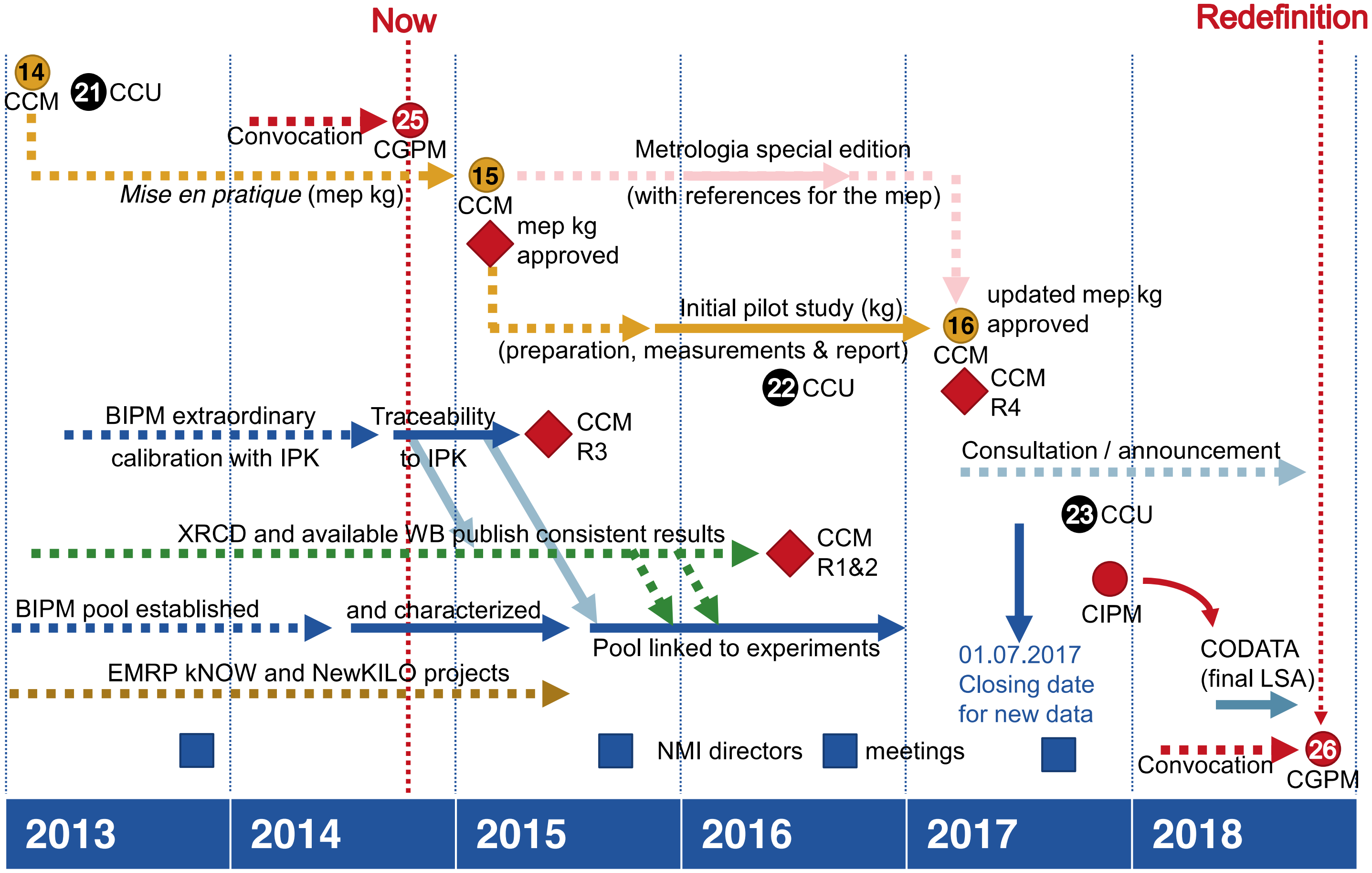
icsu.org

- **1969 CODATA establishes the Task Group on Fundamental Constants**
  - To periodically provide the scientific and technological communities with a self-consistent set of internationally recommended values of the basic constants and conversion factors of physics and chemistry based on all of the relevant data available at a given point in time.

codata.org

Near future: on the road to redefinition

Joint CCM and CCU roadmap for the new SI



Now

Redefinition

14 CCM

21 CCU

Convocation

25 CGPM

Mise en pratique (mep kg)

15 CCM

Metrologia special edition

(with references for the mep)

◆ mep kg approved

Initial pilot study (kg)

(preparation, measurements & report)

16 CCM

updated mep kg approved

22 CCU

◆ CCM R4

BIPM extraordinary calibration with IPK

Traceability to IPK

◆ CCM R3

Consultation / announcement

23 CCU

XRCD and available WB publish consistent results

◆ CCM R1&2

CIPM

BIPM pool established

and characterized

Pool linked to experiments

01.07.2017 Closing date for new data

CODATA (final LSA)

EMRP kNOW and NewKILO projects

NMI directors meetings

Convocation

26 CGPM

2013 | 2014 | 2015 | 2016 | 2017 | 2018

◆ Conditions from CCM Recommendation G1 (2013)

Critical Closing Date for Data

1 July 2017

Closing date for data for special CODATA constants adjustment to determine exact values of *h*, *e*, *k*, and N_A for 2018 revised SI (International System of Units).

BY this date data must be published or available in a preprint <u>accepted</u> for publication.

Critical Dates

31 December 2018

Closing date for data for first CODATA adjustment of the physical constants in the new SI

20 May 2019

2019 World Metrology Day – Proposed date of implementation of new SI

The last Planck must be in place July 2017

- The roadmap to redefinition goes through a final determination of the Planck constant
- Closing date for new data that will contribute to the CODATA special adjustment that will determine the exact value of the Defining Constants is 7/1/2017
- NIST is aiming to contribute a value with uncertainty below 20 ppb
- How will we get there?

Where does the uncertainty in NIST’s value come from?

Source	**Uncertainty (10^{-9})**
Statistical	24.9
Magnetic field	15.4
Electrical	10.9
Alignment	6.5
Mass metrology	6.3
Mathematical	5.0
Balance mechanics	5.0
Local acceleration, g	4.4
Velocity	1.7
Total relative uncertainty	**33.6**

Dominated by the Bl calibration in the velocity mode due to thermal drift and insufficient cancellation. Load lock will reduce drift. Have ideas to mechanically improve the IFOs. Realistic goal: **8 x 10^{-9}**.

Is limited by how well we can determine the quadratic effect of the current on the magnetic field, i.e., weighing at different mass values.
We hope to get this down to **10 x 10^{-9}**.

Dominated by time dependent leakage, which needs further investigation. Realistic target: **6 x 10^{-9}**.

It should be possible to get a combined relative uncertainty of **20 x 10^{-9}**.

Final Steps – Education and Communication

- Full analysis completed on the impact on all NIST calibration services and published
- NIST participation in international education and publicity efforts
- NIST participation in final development of *mise en pratiques*
- Multiple presentations on the status and anticipated impact

- Finally, developing materials for direct communication with customers

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

Questions?