Future impact of the new definitions on NMIs and the BIPM

M. Stock, BIPM
NMI Directors' Meeting
October 2019

The revised SI – based on a set of seven defining constants

The International System of Units, the SI, is the system of units in which:

$\Delta\nu_{Cs}$ = 9 192 631 770 Hz

c = 299 792 458 m/s

h = 6.626 070 15 x 10^{-34} Js → kg

e = 1.602 176 634 x 10^{-19} C → A

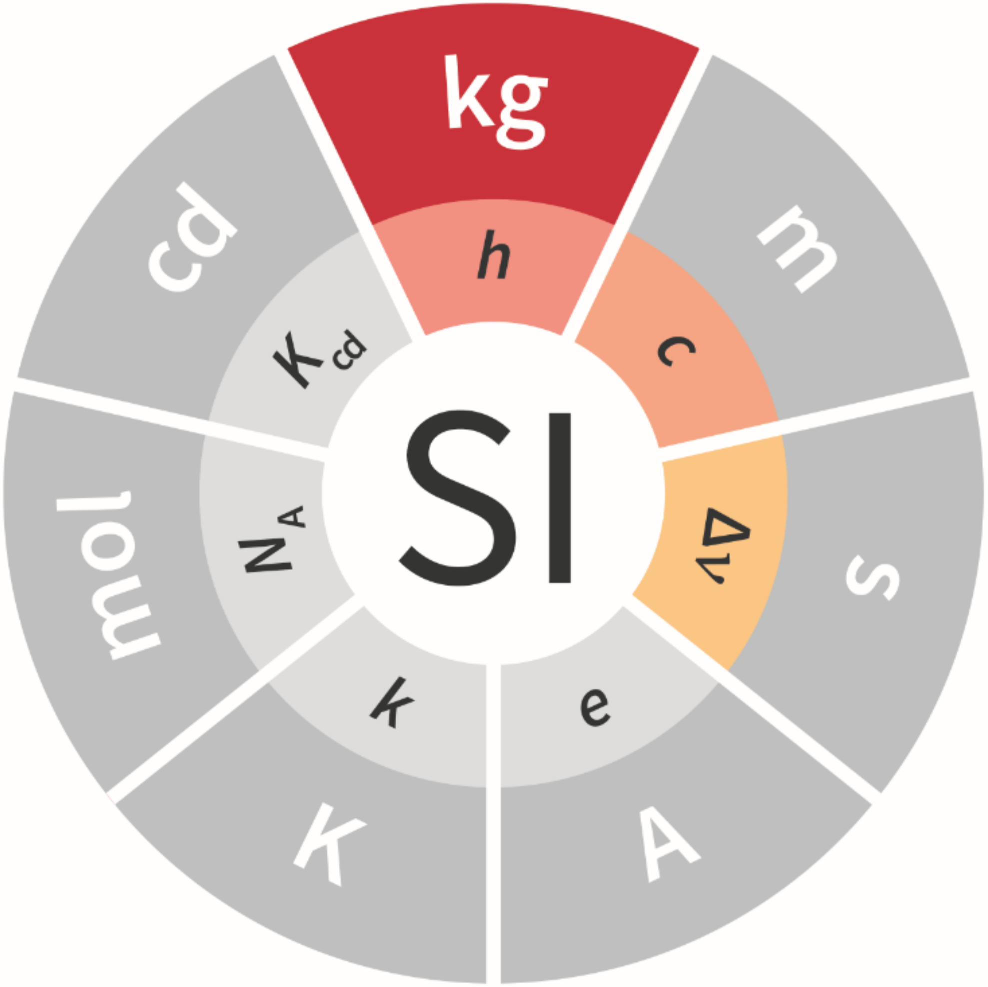
k = 1.380 649 x 10^{-23} J/K → K

N_A = 6.022 140 76 x 10^{23} mol^{-1} → mol

K_{cd} = 683 lm/W

Impact of the new definition of the kilogram

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 $\Delta\nu_{Cs}$.



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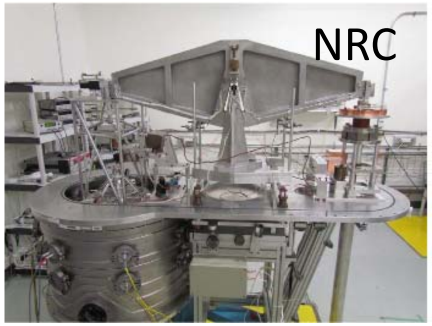
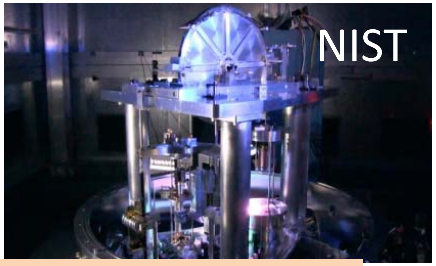
New definition makes kilogram universally available

1 kg = m (IPK)

h = 6.62607015 × 10^{-34} J s

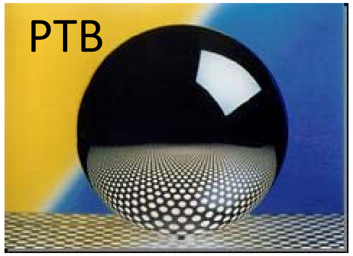
Kibble balances



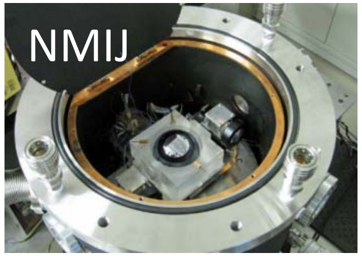


KRISS
LNE
METAS
MSL
NIM
NPL
PTB
UME
…
…

$$1\ \text{kg} = \frac{h}{6.62607015 \times 10^{-34}}\,\text{m}^{-2}\text{s}$$



XRCD-method



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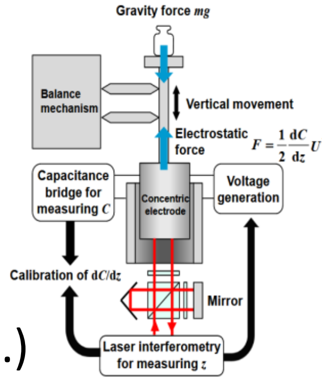
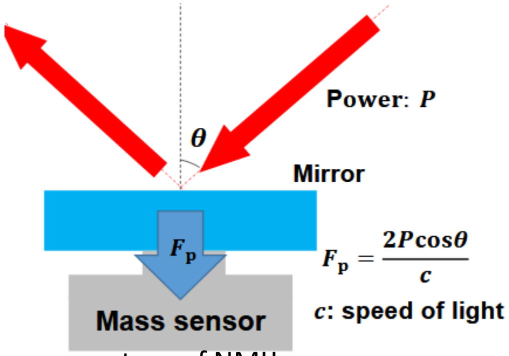
What does the new definition bring?



courtesy of NMIJ

- In principle any NMI can realize the kilogram (but there is no obligation to do so !)
- The mass unit can be realized at any particular value, 1 kg no longer has special status
- Lower uncertainties for “small” masses (mg-range) than before (electrostatic force bal.)
- 2 orders of magnitude lower uncertainties for atomic masses from h/m_u (atomic recoil, H/D-spectr.)
- Optical radiation pressure for (very) small mass measurement: 1 W –> 7 nN –> 0.7 µg
- Force, torque, pressure can be derived from electrical quantities instead of mass, with potentially smaller uncertainty (independent on *g*)



courtesy of NMIJ

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The future of the realization experiments

- Simpler and cheaper Kibble balances at NMIs working at the highest level: around 1 part in 10^8 uncertainty, possibly working around 100 g
- much smaller, simpler and cheaper Kibble balances, possibly for industrial use, working over a range of masses at uncertainties around 1 ppm, eliminating need for sets of calibrated weights: “self-calibrating balances”
- Kibble balances (MEMS-style) in µg to mg range, for research purposes, with reduced uncertainty, and eliminating calibration with extremely delicate mass standards, e.g. for gene therapy, personalized medicine (source: NPL), micro-force measurements on bio molecules
- Use of ^{nat}Si-spheres to realize kilogram (PTB), based on density comparison with ^{28}Si-sphere, requires volume determination of ^{nat}Si-sphere, avoiding high cost of ^{28}Si: “quasi primary realization”

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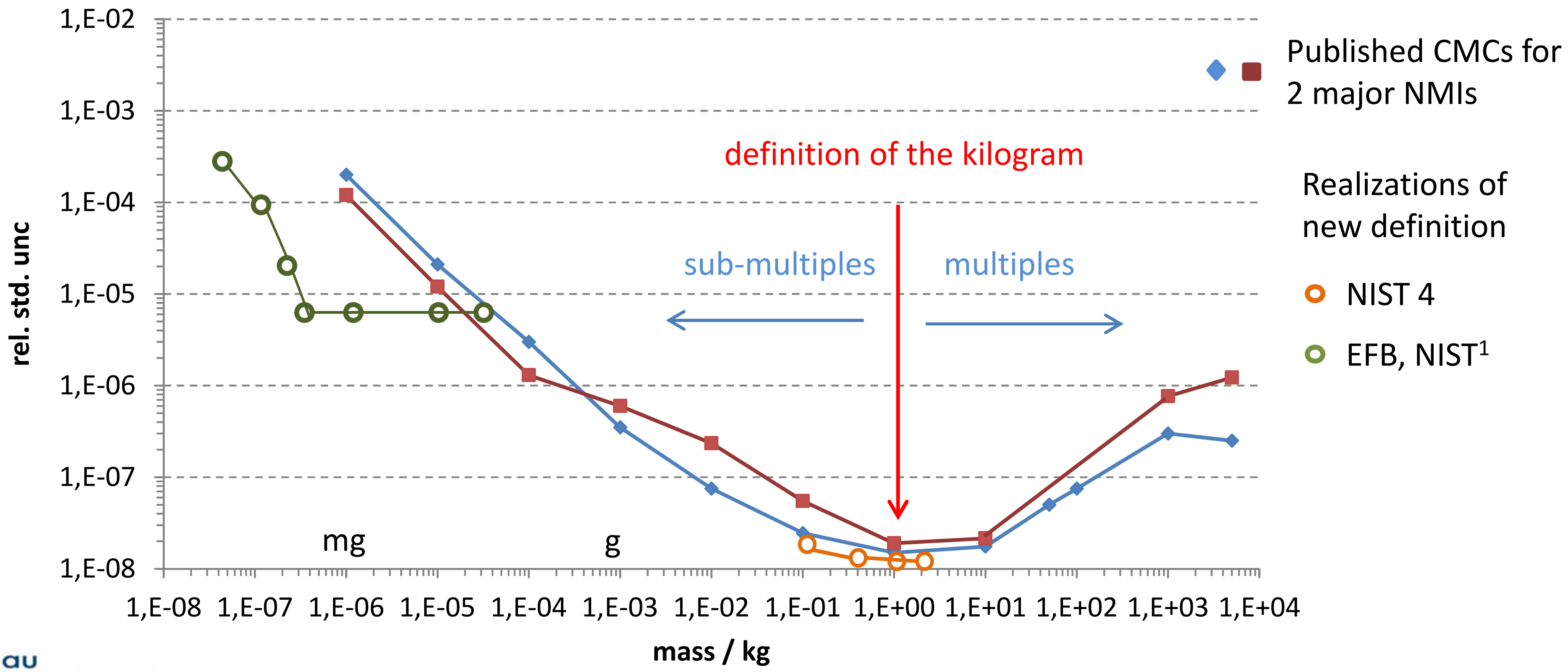
Improved uncertainties for masses below 1 kg



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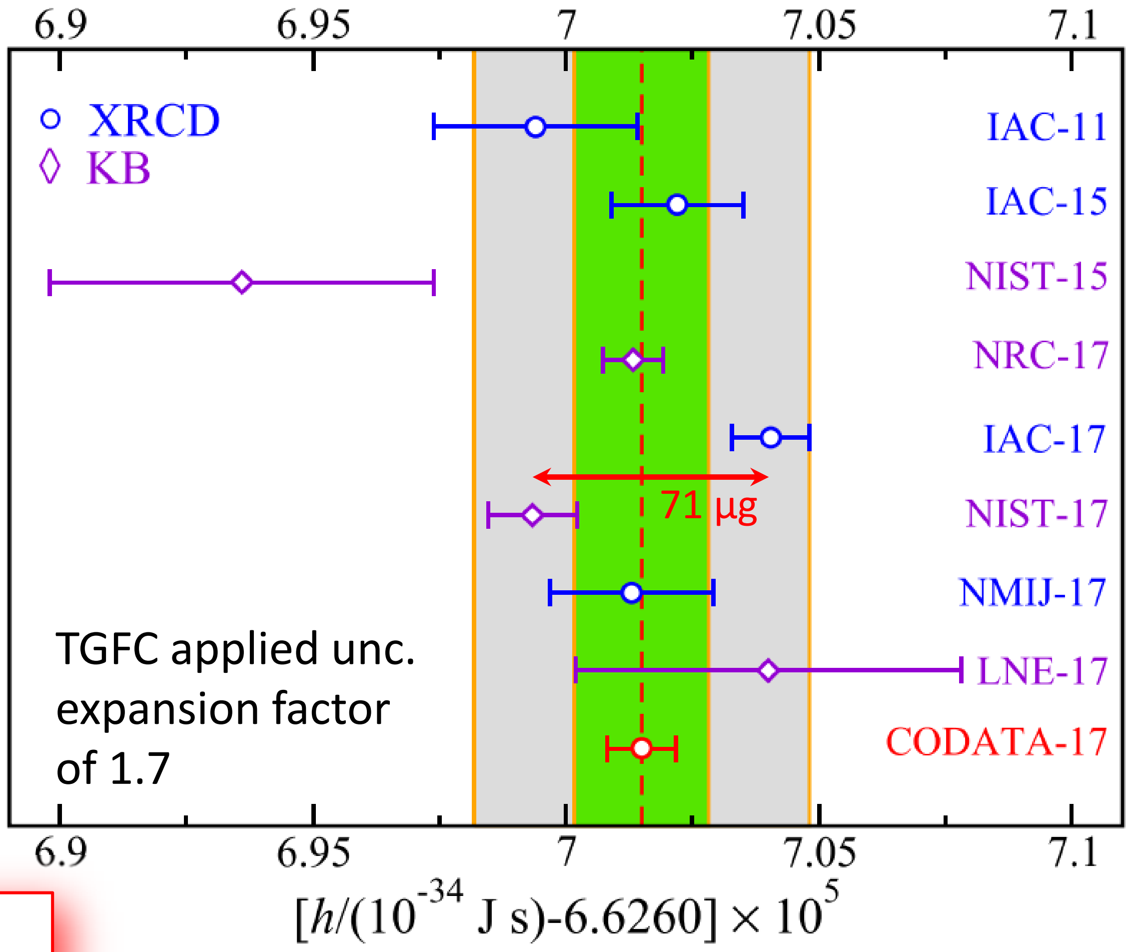
[1] Accepted for publication in *IEEE Trans. Instrum. Meas.* 2019

Values for *h* from realisation experiments contributing to CODATA 2017

- Experiments which contributed values to CODATA 2017 are not in ideal agreement
- CCM conditions for redefinition:
  - Three independent determinations of *h* with rel. unc. ≤ 5 x 10^{-8}
  - Two different methods
  - 1 determination of *h* with rel. unc. ≤ 2 x 10^{-8}
  - Consistent results
- While it can be argued that the conditions have been met the situation is not fully satisfactory
- At the 2017 meeting of the CCM decided the use of an **interim Consensus Value** for the kilogram until such time that enough repeated experiments have demonstrated consistency and temporal stability

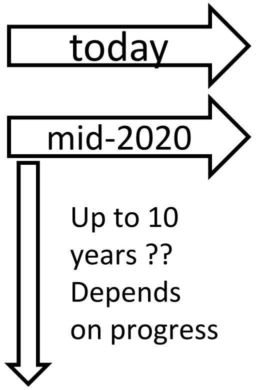
internationally coordinated dissemination of the kilogram



TGFC applied unc. expansion factor of 1.7

The four phases for the dissemination of the kilogram

CCM TG on the phases of the dissemination of the kilogram



Up to 10 years ?? Depends on progress

Phase	Time scale	Description	Source of traceability	Uncertainty of BIPM mass calibrations	Dissemination of mass from NMIs with realization experiments
0	Until 20 May 19	**Traceability to the IPK**	$m_{\mathrm{IPK}} \equiv 1$ kg $u_{m_{\mathrm{IPK}}} \equiv 0$	$u_{\mathrm{stab}}(t)$	Dissemination from national prototype traceable to IPK
1	20 May 19 - date 1	Traceability to the Planck constant via the IPK, with additional uncertainty from the (new) definition	$m_{\mathrm{IPK}} = 1$ kg $u_{m_{\mathrm{IPK}}} = 10\ \mu g$	$\approx \sqrt{u^2_{m_{\mathrm{IPK}}} + u^2_{\mathrm{stab}}(t)}$	Dissemination from national prototype traceable to IPK, with 10 µg added uncertainty
2	date 1 – date 2	**Traceability to the Planck constant, dissemination from a consensus value (CV)**	Consensus value (CV)	$\approx \sqrt{u^2_{\mathrm{CV}} + u^2_{\mathrm{stab}}(t)}$	Dissemination from consensus value with uncertainty $\approx \sqrt{u^2_{\mathrm{CV}} + u^2_{\mathrm{stab.NMI}}(t)}$
3	from date 2	**Traceability to the Planck constant, dissemination by individual realizations**	Fixed value of h $u(h) \equiv 0$	Uncertainty of BIPM realization experiment	Dissemination from realization experiments with the uncertainty of the experiment.

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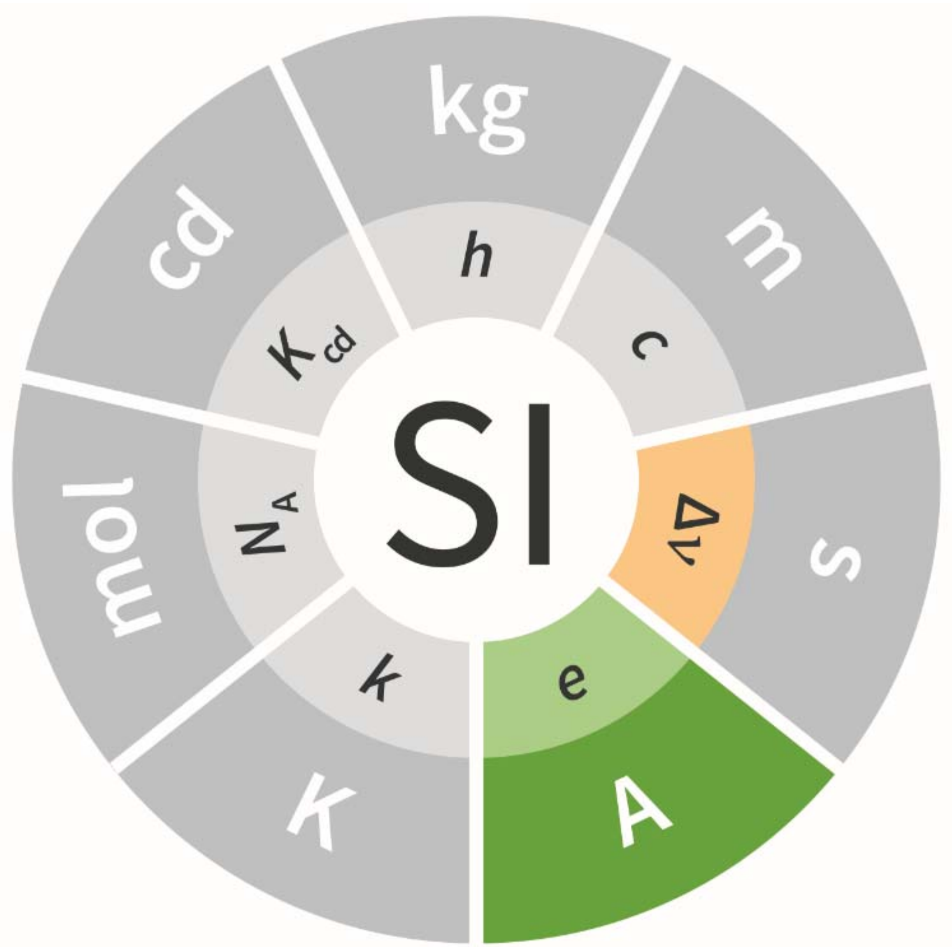
Impact of the new definition of the ampere

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 1.602 176 634 × 10^{-19}** when expressed in the unit C, which is equal to A s, where the second is defined in terms of $\Delta\nu_{Cs}$.



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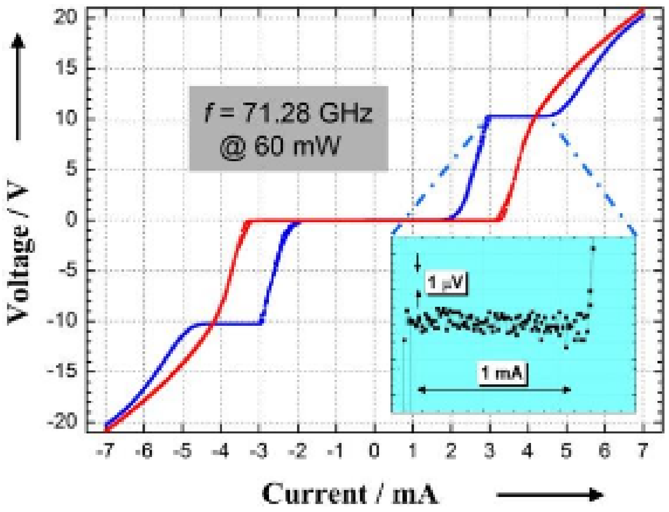
Electrical quantum standards “brought into the SI”

Josephson voltage standard



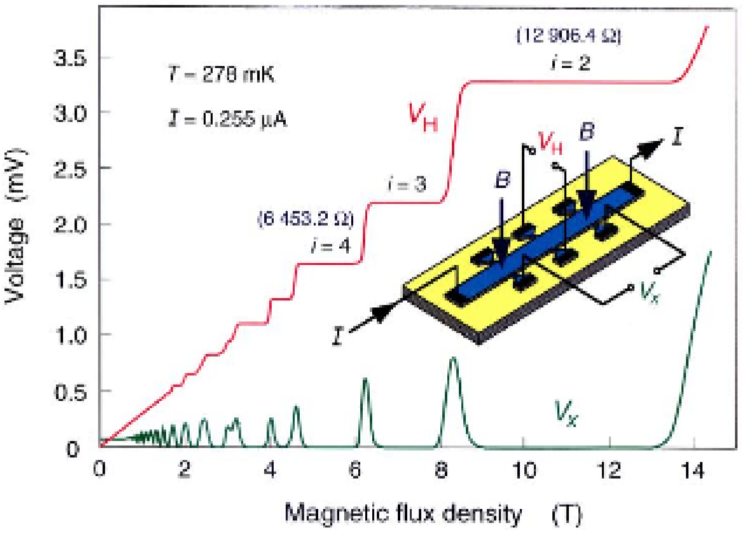
$$V = n \cdot (h/2e) \cdot f$$

$$\nwarrow \xcancel{K_{\text{J-90}}}$$

$$R = (h/e^2) \cdot 1/n$$

$$\nwarrow \xcancel{R_{\text{K-90}}}$$

Quantum Hall resistance standard

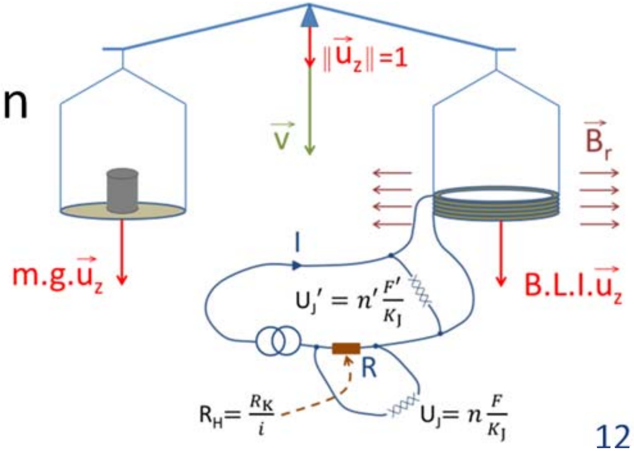


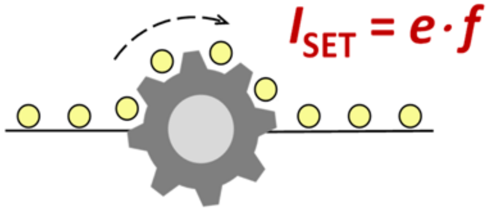
- Conventional values $K_{\text{J-90}}$ and $R_{\text{K-90}}$ used since 1990 -> parallel electric unit system
- Revised SI: K_{J} and R_{K} calculated from fixed numerical values of h and e

$K_{\text{J}} = h/2e = 483\,597.848\,416\,984\ldots$ GHz/V
$R_{\text{K}} = h/e^2 = 25\,812.807\,459\,3045\ldots\ \Omega$

Electrical quantum standards “brought into the SI”

- No fundamental change in technology, electrical quantum standards already in use since many years
- Transition from conventional constants to SI brings step changes of volt and ohm
  - ➢ CCEM has issued guidance document
- More versatile and easier-to-use quantum standards needed for wider uptake of Kibble balances, e.g. quantum voltage references operating at LN_2 temperature, easy-to-use quantized Hall resistance standards (graphene)
- Accurate SET current standard needed for a direct realization of the definition of ampere





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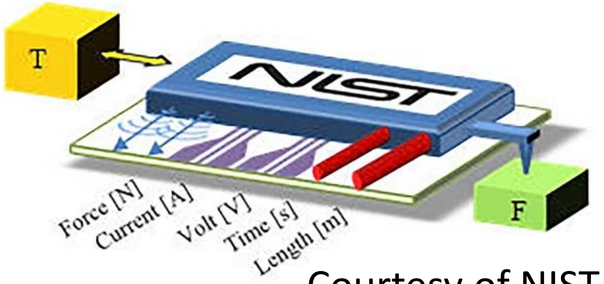
“Quantum SI” in the context of a wider development of quantum technologies

- Research on embedded measurements, based on quantum standards and sensors: self-calibrating , multi-functional, low-cost, not requiring traditional calibration
  - future role of NMIs ?
  - who takes responsibility for correct operation ?

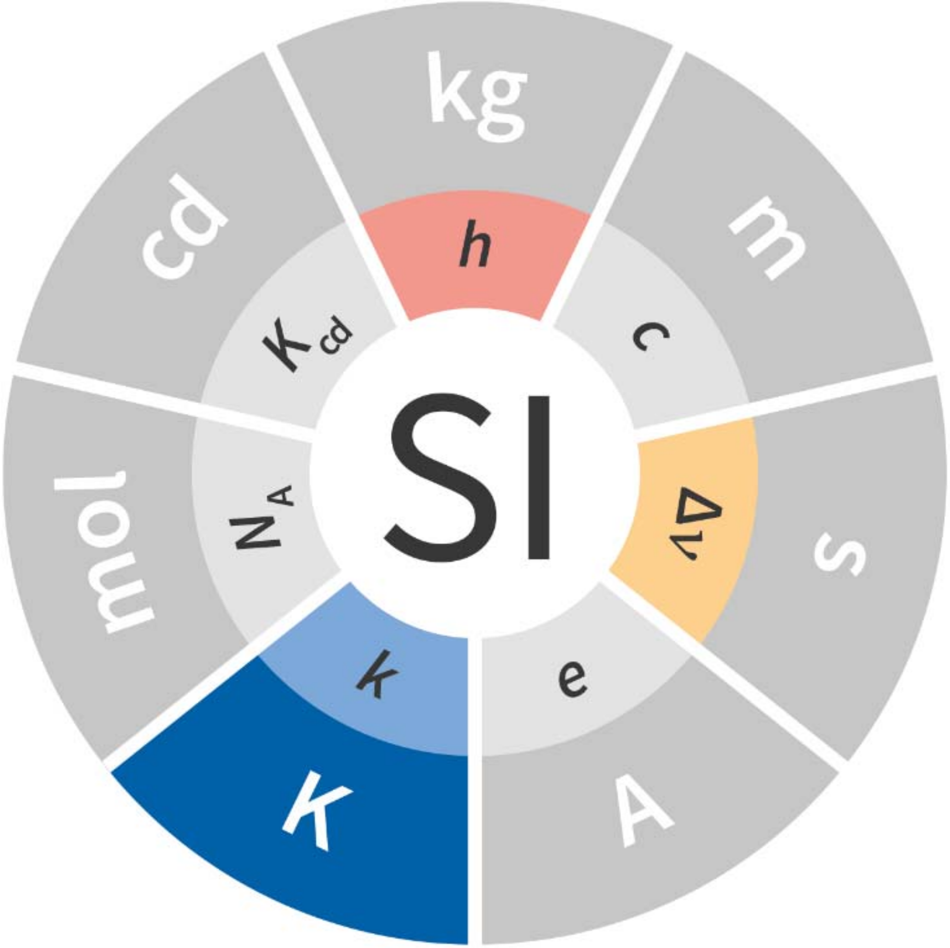


Courtesy of NIST

- EU quantum flagship program (€ 1B, over 10 years)
  - includes projects on development of quantum-enabled-sensors (atomic vapour cells realized as MEMS) and quantum clocks
  - Similar projects in US (NQI) and China

Impact of the new definition of the kelvin

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 1.380 649 × 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 $\Delta\nu_{Cs}$

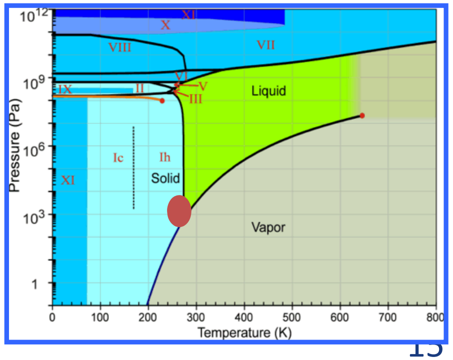


Temperature measurement is difficult

Temperature is the only base quantity which is not additive (intensive quantity):

Complex primary thermometers necessary to obtain “thermodynamic” temperatures: Absolute gas thermometer, radiation thermometer, noise thermometer,…

In “old Si” all measurements had to be referenced to water triple point 273.16 K, inconvenient for very high and very low temperatures



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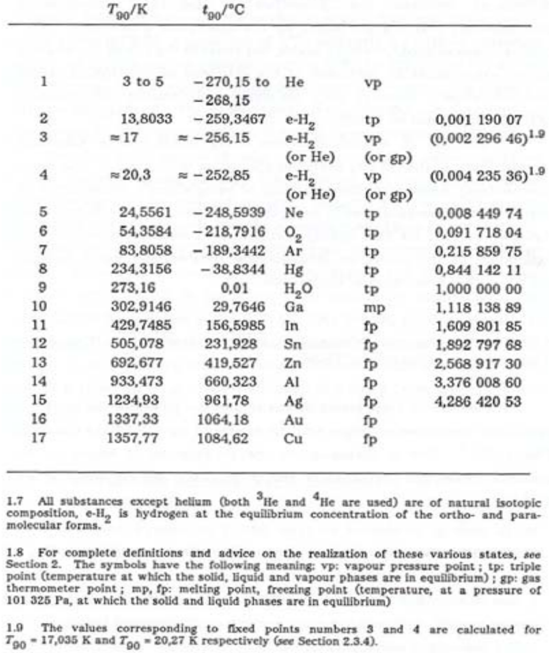
International temperature scale ITS-90

fixed points



Number	Temperature		Sub-stance$^{1.7}$	State$^{1.8}$	$W_r(T_{90})$
	T_{90}/K	t_{90}/°C			
1	3 to 5	−270,15 to −268,15	He	vp	
2	13,8033	−259,3467	e-H_2	tp	0,001 190 07
3	≈ 17	≈ −256,15	e-H_2 (or He)	vp (or gp)	(0,002 296 46)$^{1.9}$
4	≈ 20,3	≈ −252,85	e-H_2 (or He)	vp (or gp)	(0,004 235 36)$^{1.9}$
5	24,5561	−248,5939	Ne	tp	0,008 449 74
6	54,3584	−218,7916	O_2	tp	0,091 718 04
7	83,8058	−189,3442	Ar	tp	0,215 859 75
8	234,3156	−38,8344	Hg	tp	0,844 142 11
9	273,16	0,01	H_2O	tp	1,000 000 00
10	302,9146	29,7646	Ga	mp	1,118 138 89
11	429,7485	156,5985	In	fp	1,609 801 85
12	505,078	231,928	Sn	fp	1,892 797 68
13	692,677	419,527	Zn	fp	2,568 917 30
14	933,473	660,323	Al	fp	3,376 008 60
15	1234,93	961,78	Ag	fp	4,286 420 53
16	1337,33	1064,18	Au	fp	
17	1357,77	1084,62	Cu	fp	

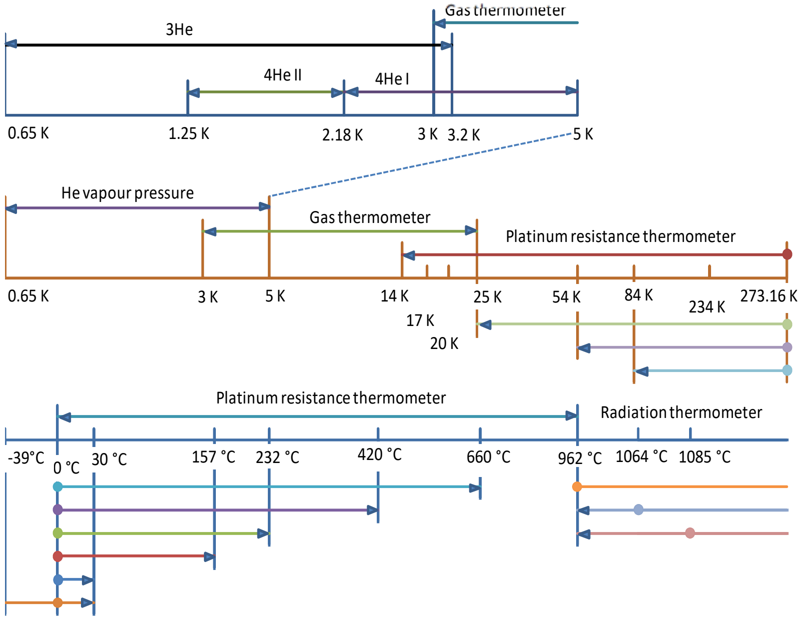
1.7 All substances except helium (both ^{3}He and ^{4}He are used) are of natural isotopic composition, e-H_2 is hydrogen at the equilibrium concentration of the ortho- and para-molecular forms.

1.8 For complete definitions and advice on the realization of these various states, *see* Section 2. The symbols have the following meaning: vp: vapour pressure point ; tp: triple point (temperature at which the solid, liquid and vapour phases are in equilibrium) ; gp: gas thermometer point ; mp, fp: melting point, freezing point (temperature, at a pressure of 101 325 Pa, at which the solid and liquid phases are in equilibrium)

1.9 The values corresponding to fixed points numbers 3 and 4 are calculated for T_{90} = 17,035 K and T_{90} = 20,27 K respectively (*see* Section 2.3.4).

+

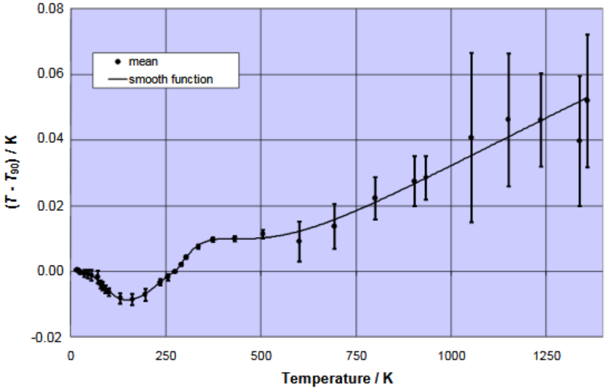
interpolation



= T_{90}

Conversion to thermodyn. temp.

$T - T_{90}$



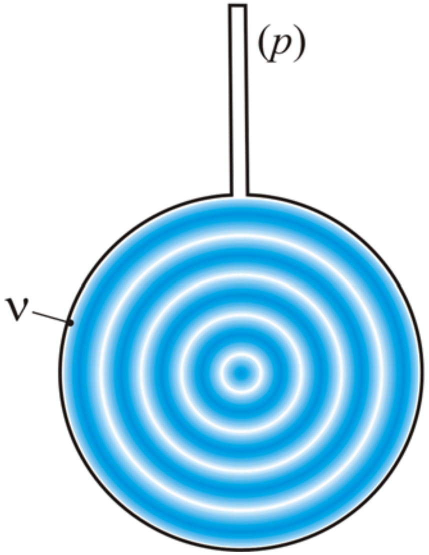
CCT WG4
J. Fischer et al.,
Int. J. Thermophys. 32,12-25 (2011)

Most temperature measurements are made in terms of the ITS-90, not in the SI.

For *T* < 1K PLTS-2000 is the defined scale.

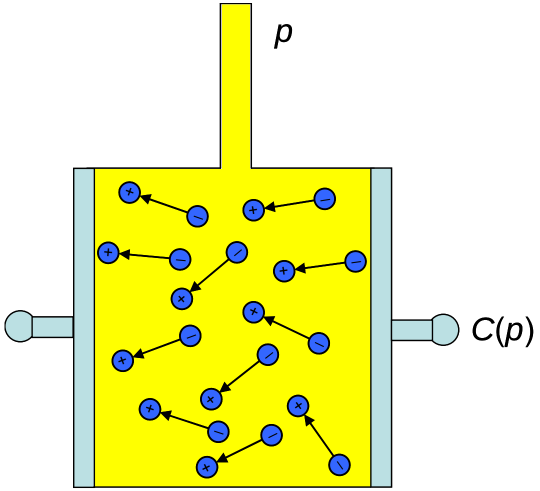
Direct determination of thermodyn. temperature making use of new definition of kelvin

$k = 1.380\,649 \times 10^{-23}$ J/K



AGT

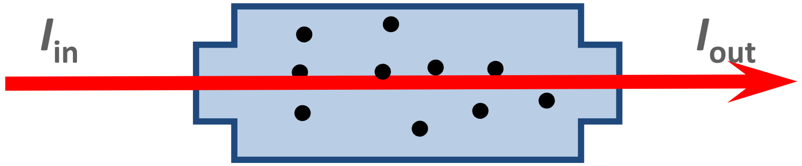
$$u_0^2 = \gamma\, kT/\, m$$
$$\gamma = c_p/c_V$$



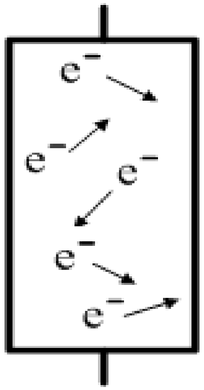
DCGT

$$p = kT\,\varepsilon_0\,(\varepsilon_r - 1)/\alpha_0$$

$$\Delta\nu_D = [2\,kT/(mc_0^2)]^{1/2}\cdot\nu_0$$



DBT



JNT

$$\langle U^2\rangle = 4\,kT\,R\,\Delta f$$

+RT

Courtesy of PTB

Practical implications of redefined kelvin

Short-term

- ITS-90 and PLTS-2000 will continue to be used for realization and dissemination
- Primary thermometers expected to be more widely developed and used at NMIs

CCT Recommendation T1 (2017):

“that Member State NMIs take full advantage of the opportunities for the realization and dissemination of thermodynamic temperature afforded by the kelvin redefinition and the *mise en pratique* for the definition of the kelvin.”

Medium–term (5-10 years)

- primary thermometry expected to achieve comparable or lower uncertainties than ITS-90 for $T > 1300$ K and $T < 1$ K
- High temperature part of ITS-90 might be abandoned in practice

Long-term (speculative)

- PLTS-2000 to be superseded by primary Johnson Noise Thermometry
- ITS-90 progressively superseded by primary thermometry

Conclusions

- In principle any NMI can realize the kilogram (but there is no obligation to do so !)
- The mass unit can be realized at any particular value, in particular at lower masses
- Until satisfactory agreement of sovereign kg realizations: internationally coordinated dissemination of kilogram
- More versatile and easier-to-use quantum standards needed for wider uptake, in industry and for realization of kg
- Development of self-calibrating embedded measurement systems
- Primary thermometers expected to be more widely used at NMIs, progressively superseding defined temperature scales

Transition to the use of individual realisation experiments

a) A minimum of five consistent realization experiments which:

  I. Achieve Key Comparison results with a relative standard uncertainty of 40 parts in 10^9 or better

  II. Demonstrate consistency with the KCRV

  III. Demonstrate stability by producing consistent (equivalent) results for two consecutive Key Comparisons

b) At least two of the realization experiments meeting the above criteria should have uncertainties less than 20 parts in 10^9.

c) The consistent set of experiments must include two independent methods of realizing the SI unit of mass (e.g. Kibble balance and X-ray crystal density experiments)

d) The difference between the Consensus Value for the kilogram (determined from three last 3 Key Comparison results) and the KCRV for the final Key Comparison is less than 5 parts in 10^9.

How will a Consensus Value for the kilogram work?

Requirements

- Consistency with IPK, linked to all available realization experiments, temporal stability, easy access for dissemination

Determination

- KCs for the realization experiments will take place every 2 years
- CV will be based on an average of the last 3 KCRVs (to ensure temporal stability)
- Initial value with be based on: IPK, Pilot study result (2016), KCRV of first KC (2019/20)

Dissemination

- KCs will be piloted by the BIPM
- CV will be maintained and disseminated by the BIPM using their Pt-Ir standards
- BIPM will continue to provide calibrations for NMIs but traceability will switch from the IPK to the CV following the completion of the first KC of realisation experiments

Uncertainty

- It is proposed that the standard uncertainty in the consensus value be 20 µg

Impact for NMIs

Adjustments

- Care has been taken to ensure that the value of the kilogram remains constant across all the phases of the implementation of the new definition so no adjustments to national mass scales will be necessary

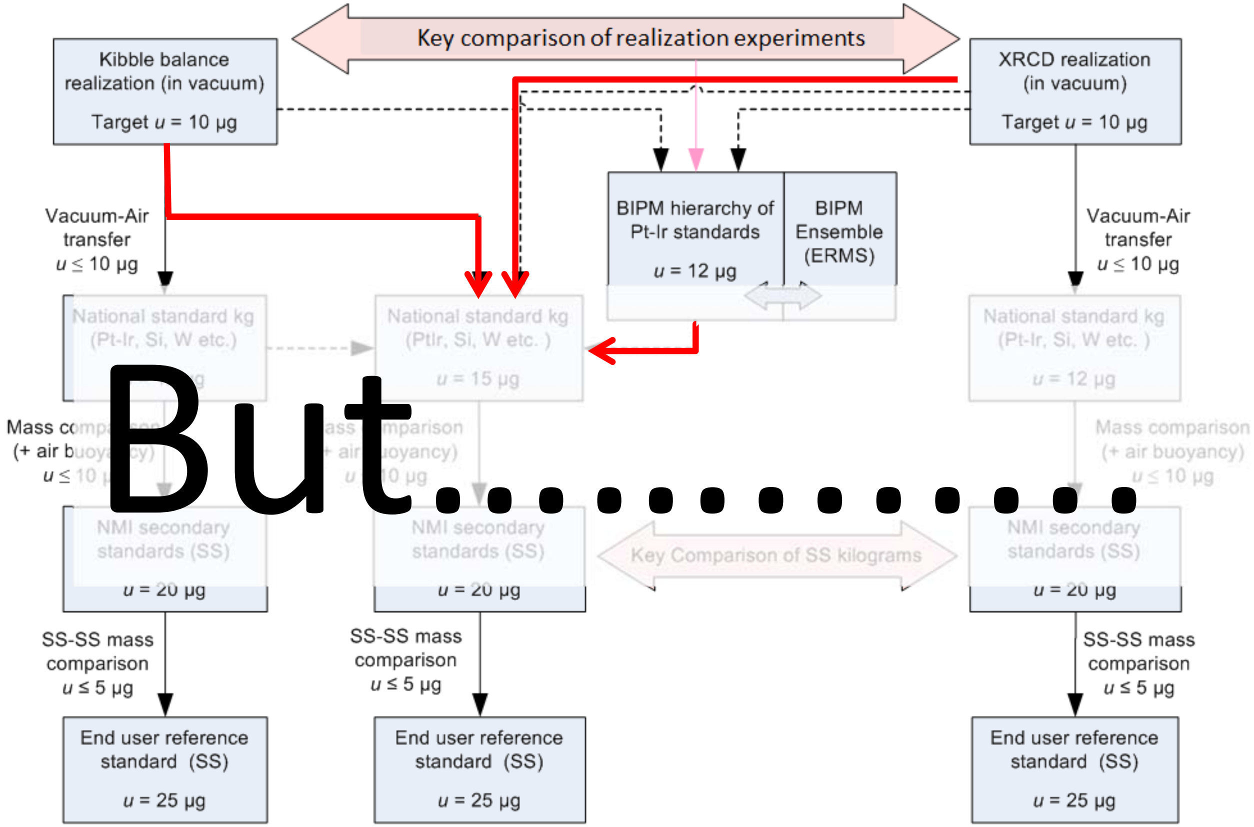
Uncertainties and CMCs

- CMCs will need to be reviewed to take into account the additional (10 µg) uncertainty in the IPK after redefinition (20 May 2019)
- BIPM has issued guidance on how the uncertainties on their previous calibrations will change
- As a guide only uncertainties of about 25 µg (*k*=1) or lower (at 1 kg) will need to be increased as a result of the redefinition (25 µg -> 27 µg)

Traceability

- NMIs can continue to take traceability from the BIPM.
- BIPM traceability will initially be to the IPK (with the additional uncertainty) and then, after the completion of the first KC of realisation experiments, to the Consensus Value

Multiple traceability paths after the redefinition



But……….

BIPM will keep a very important role after the redefinition:

- organizing **key comparisons** of realizations of the kilogram (next 2019/20) and of stainless steel kilograms providing a **stable mass reference**
- ensuring **worldwide uniform** and **stable dissemination** of kilogram
- providing **mass calibrations**

M. Stock, S. Davidson, H. Fang, M. Milton, E. de Mirandés, P. Richard, C. Sutton, “Maintaining and disseminating the kilogram following its redefinition” *Metrologia* **54** (2017) S99, open access

“2017 Highlight of Metrologia”