Frontiers of Characterization and Metrology for Nanoelectronics

Purpose:

The 2015 International Conference on Fr... f Characterization and Metrology for ... s (FCMN) will be held at the Hilt... in Dresden, Germany, April ...

The 10th World Conference

Conferences at NIST in:
1995, 1998, 2000, 2007 and 2013

While a city of notable art treasure, architectur... pe, Dresden also has largest hub of microelectronics in ... aterials science and engineering (more than 2000 materi... Dresden and in several institutes).

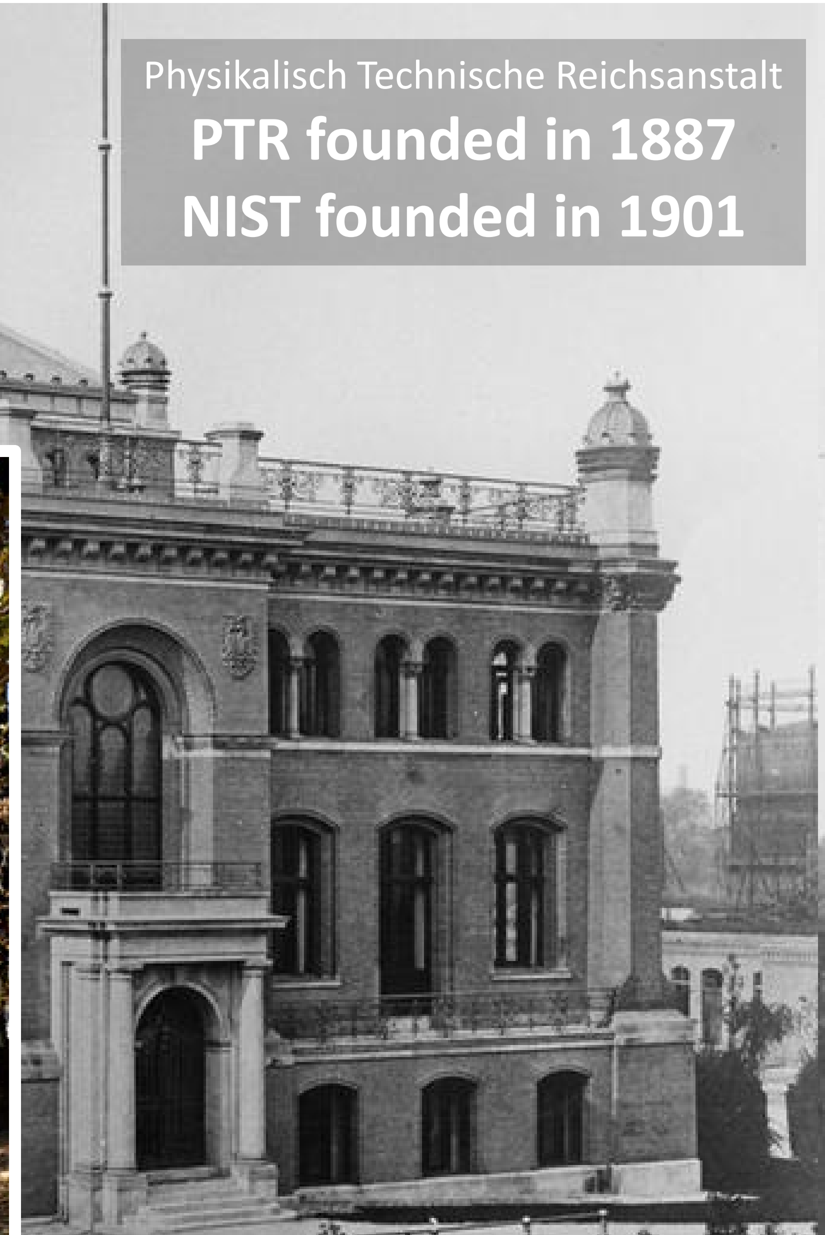
The FCMN brings together scientists ... ed in all aspects of the characterization technology needed fo... ic materials and device research, development, and manufacturing.

The conference will consist of formal invit... presentation sessions and poster sessions for contributed papers. The poster papers will cover new developments in characterization and metrology especially at the nanoscale.

The conference series began at NIST in 1995.

Welcome in Germany

The country where the first metrology institute was founded



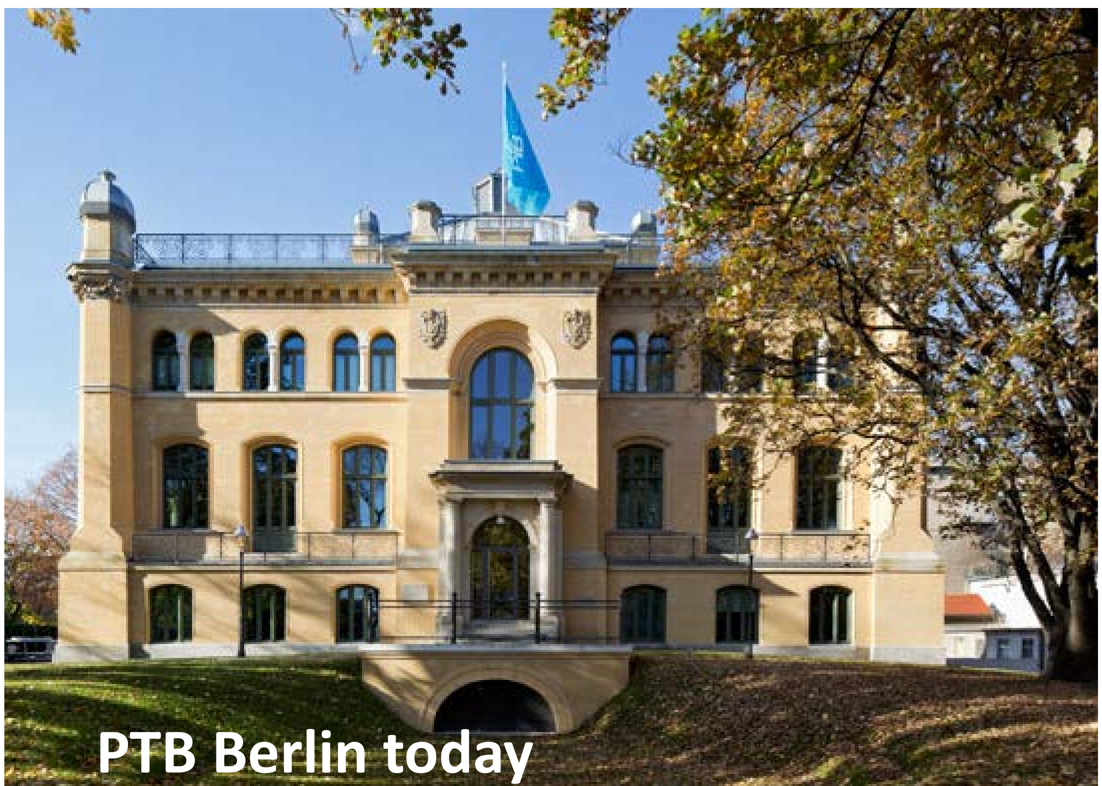
Physikalisch Technische Reichsanstalt Berlin

First Laboratory of PTR in 1891

Physikalisch Technische Reichsanstalt

PTR founded in 1887

NIST founded in 1901



PTB Berlin today

2015 Frontiers of Characterization and Metrology for Nanoelectronics

April 14-16, 2015

Hilton Dresden, An der Frauenkirche 5, 01067 Dresden, Germany

Tuesday, April 14

Conference Opening

Keynote Talks

Session Chair: David Seiler, NIST

9:00

Characterization Challenges In The 28 nm Technology Node

Hubert Lakner, Executive Director, Fraunhofer Institute for Photonic Microsystems

9:45

Wide Perspective on Today's Semiconductor Industry

Suresh Venkatesan, Senior Vice President, Technology Development, Global Foundries

10:30

Coffee Break and Poster Viewing

11:00

Nanoelectronics for Metrology

Klaus von Klitzing, Max-Planck-Institut FKF

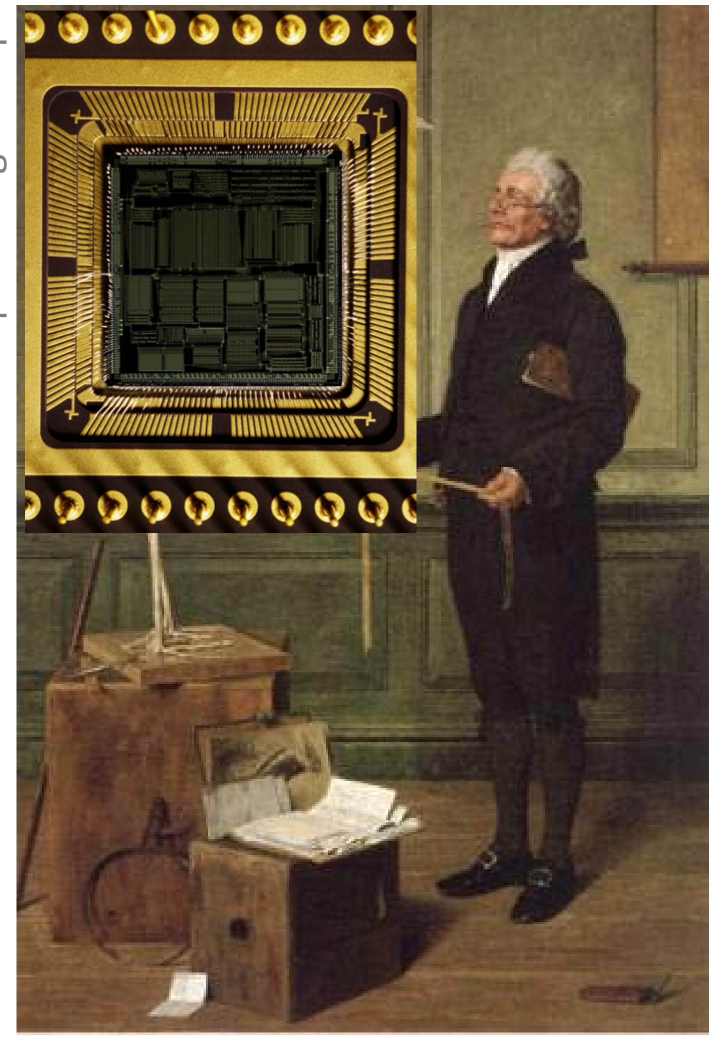
129 years ago

Lord Kelvin (William Thomson)
6.May 1886

..I often said that when you can measure what you are speaking about, and can express it in numbers, you know something about it.

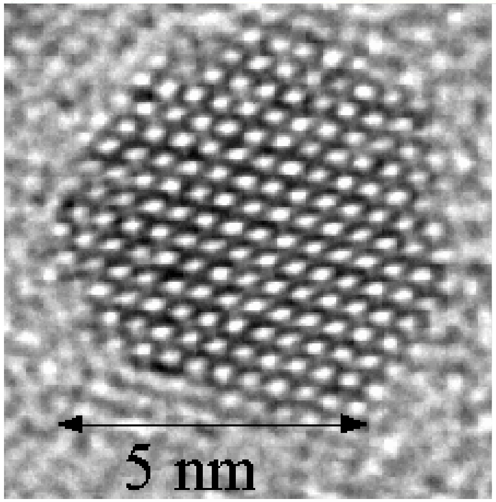
*...So therefore, if **science is measurement**, then*
without metrology there can be no science

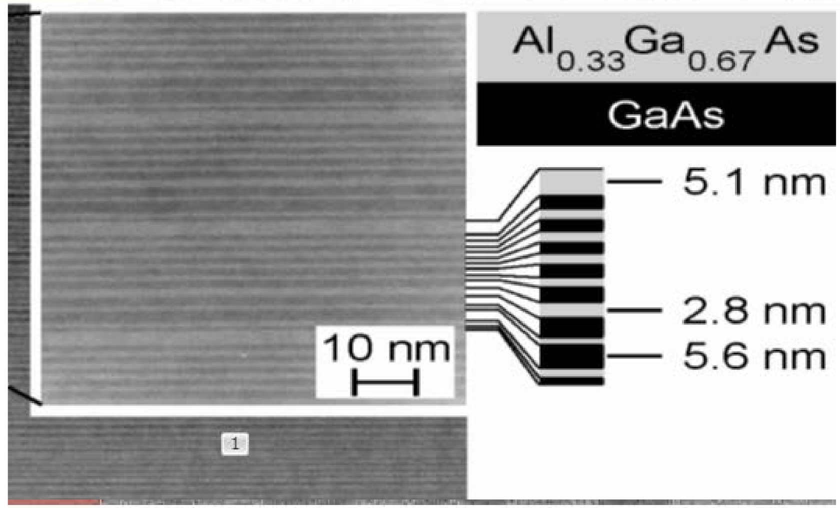
"Science is Measurement"
Henry Marks (1829 – 1898)

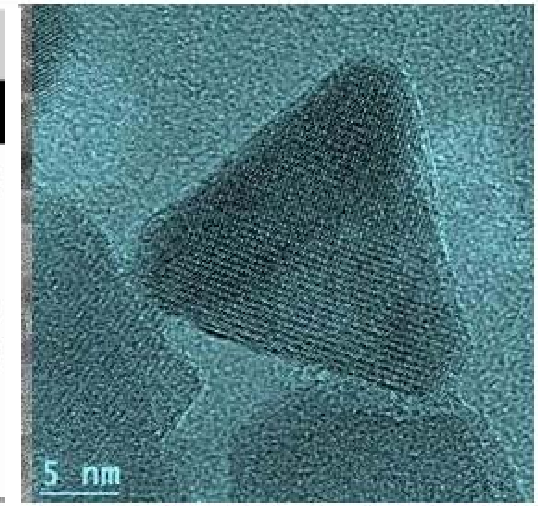


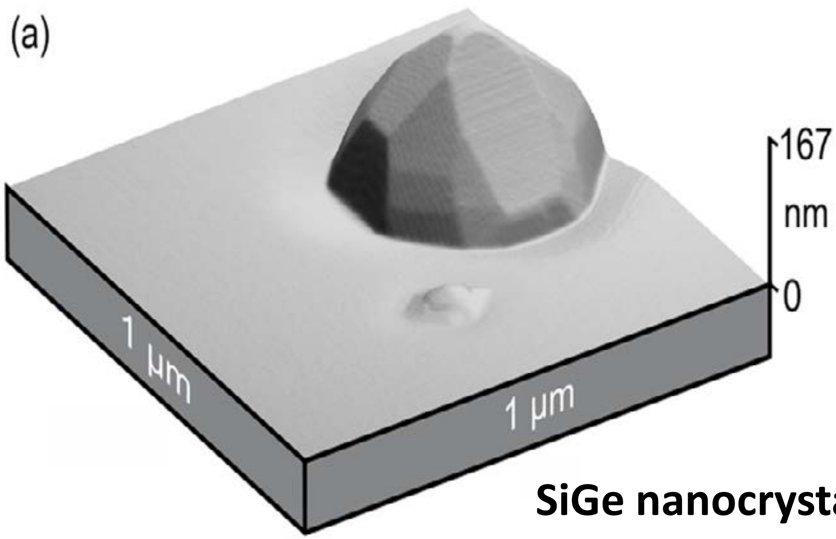
With this painting, Henry Marks became member of the Royal Academy, London

Nanoscience:
Dimension → Function









SiGe nanocrystals on silicon

group O.G.Schmidt,

Institute for Integrative Nanosciences Dresden

The Story of the Egyptian Cubit

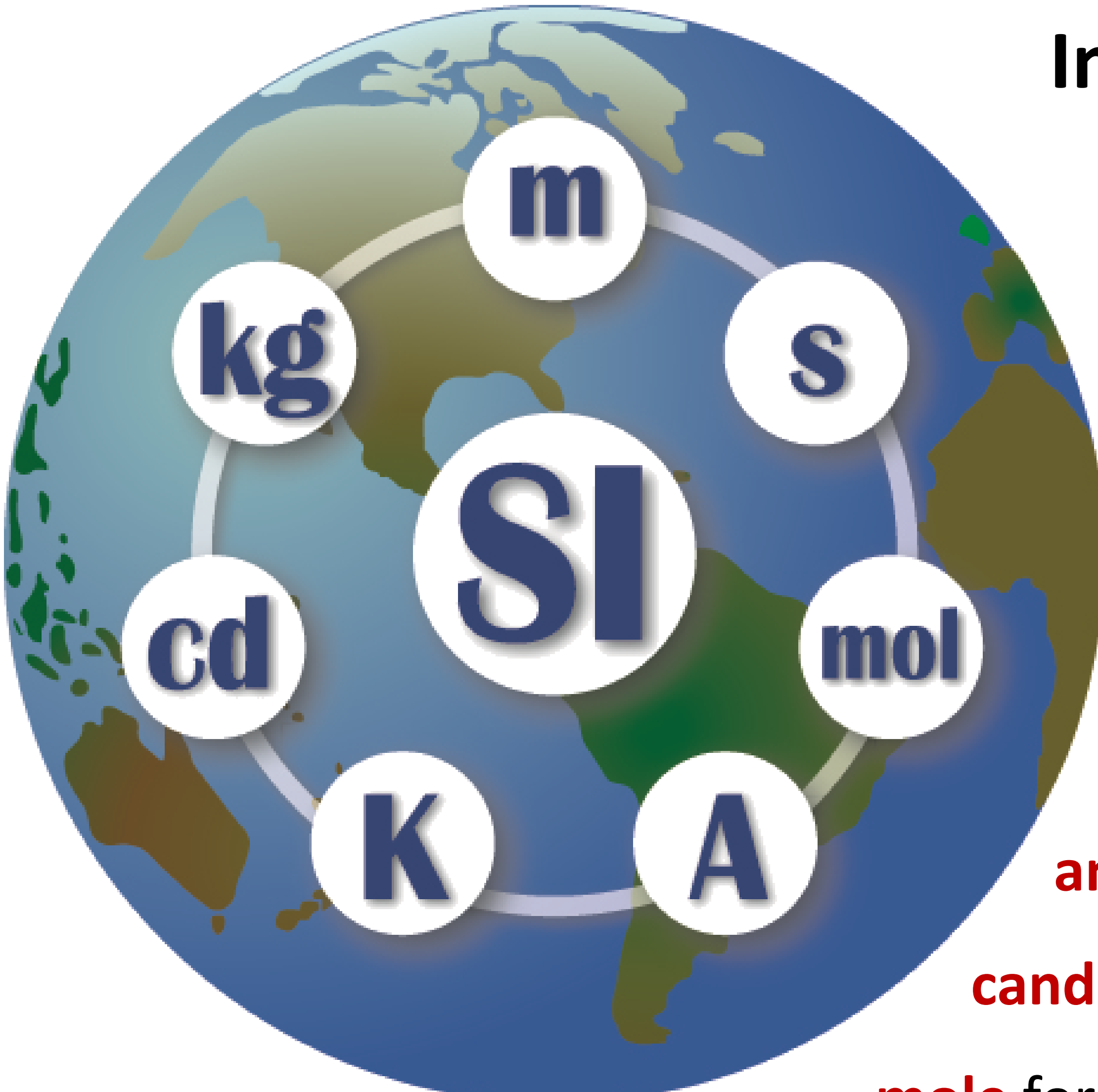
It is believed that about 3,000 years B.C., the Egyptian unit of length was established. The Royal Egyptian Cubit was decreed to be equal to the length of the forearm from the bent elbow to the tip of the extended middle finger plus the width of the palm of the hand of the Pharoah ruling at that time. The Royal Cubit Master was carved from a block of black granite to endure for all time. Workers building tombs, temples and pyramids were supplied with cubit sticks made of wood or granite. The Royal Architect or foreman of each construction site was responsible for maintaining and transferring the unit of length to the workers' cubit sticks. It was required that the cubit sticks be brought at each full moon to be compared to the Royal Cubit Master. Failure to do so was punishable by death.

Though the punishment prescribed was severe, the ancient Egyptians had anticipated the spirit of the present day system of legal metrology, standards, traceability and calibration recall. With this standardization and uniformity of length, they achieved amazing accuracy. The Great Pyramid of Giza was constructed to stand roughly 756 feet or 9,069.4 inches. Using cubit sticks, the builders were within 4.5 inches — an accuracy of 0.05%.

This story of the Egyptian cubit was presented to Ed Nemeroff, NCSL Vice President - International Division
by Professor, Dr. Mohamed El-Fiki, President of the Egyptian National Institute for Standards
in commemoration of the United States - Egypt Bilateral Workshop on Metrology, Standards & Conformity Assessment
Jointly sponsored by the United States National Institute of Standards and Technology and the Egyptian National Institute for Standards
Alexandria, Egypt
1996

National Conference of Standards Laboratories • 1800 30th Street, Suite 305B • Boulder, CO 80301 • USA • Phone (303) 440-3339 • Fax (303) 440-3384 • ncsl-staff@ncsl-hq.org • http://www.ncsl-hq.org

GLOBAL UNITS USED TODAY:



International System of 7 Base Units

second for time

metre for length

kilogram for mass

kelvin for temperature

ampere for electric current

candela for luminous intensity

mole for the amount of substance

http://www.nist.gov

UNIVERSAL SET OF UNITS

(established at the time of the French revolution)

22.8.1790: Working Group for an

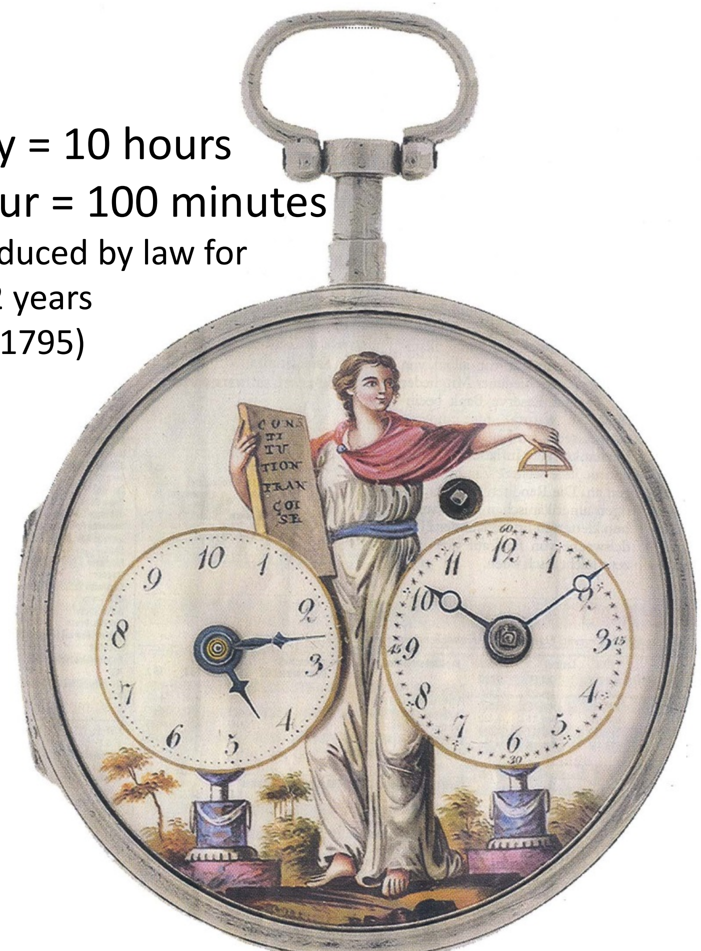
UNIVERSAL SET OF UNITS

Introduction of „Metric System“ by French Academy of Science

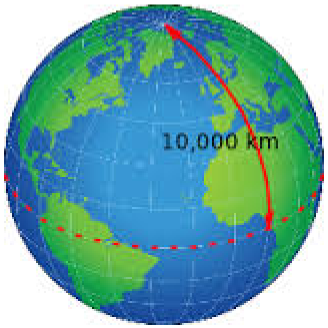
1 day = 10 hours

1 hour = 100 minutes

(introduced by law for only 2 years 1793-1795)



1799:
Year of birth of Métre et Kilogramme „des Archives“



The metre is equal to one ten millionth part of the quarter of the terrestrial meridian

The kilogram is equal to the mass of a decimetre cube of water at the temperature of melting ice


Photo Terry Quinn

Meter Convention 20.5.1875

METRIC SYSTEM
Meter Kilogram Second
signed by **17** countries

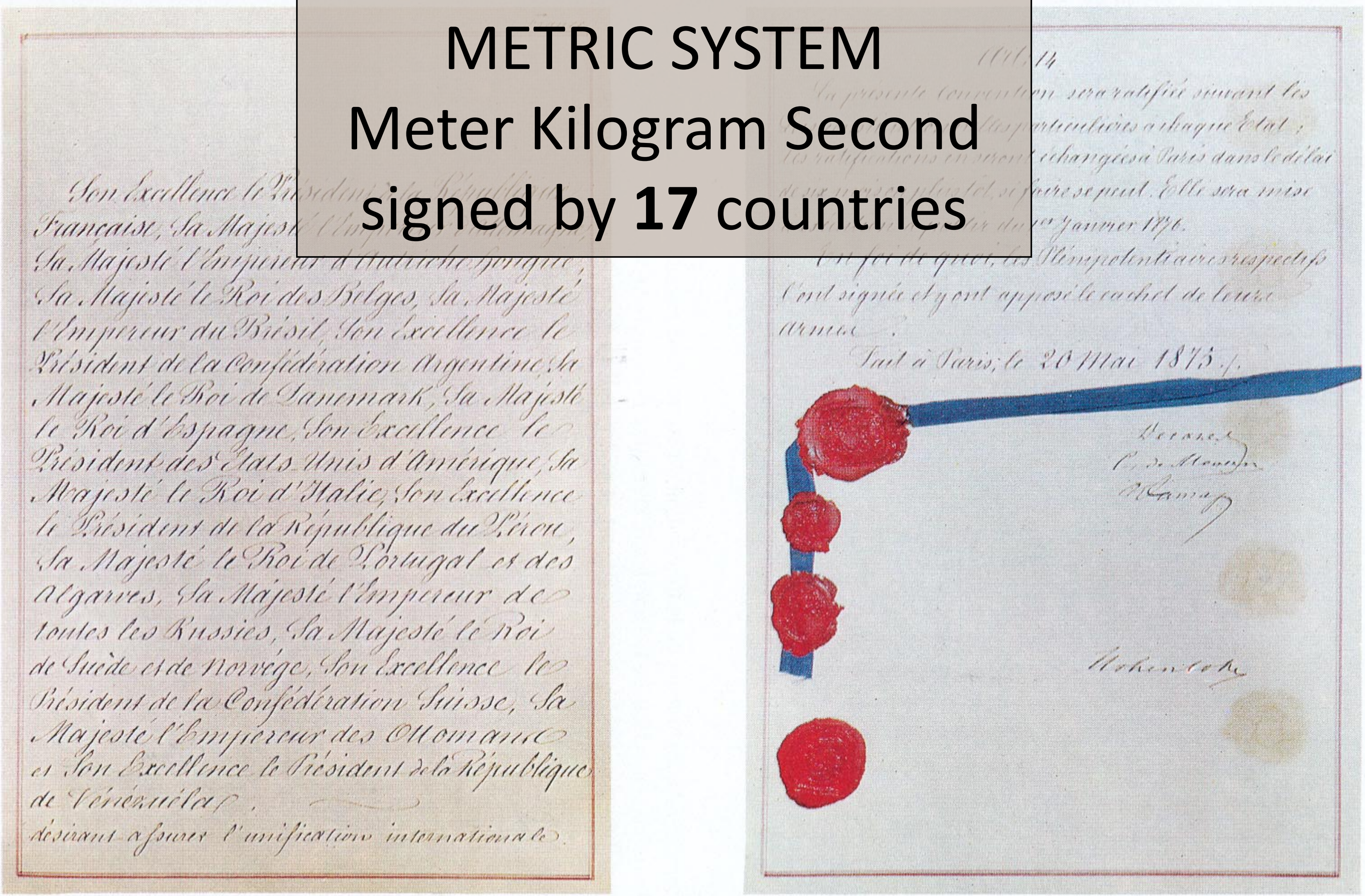
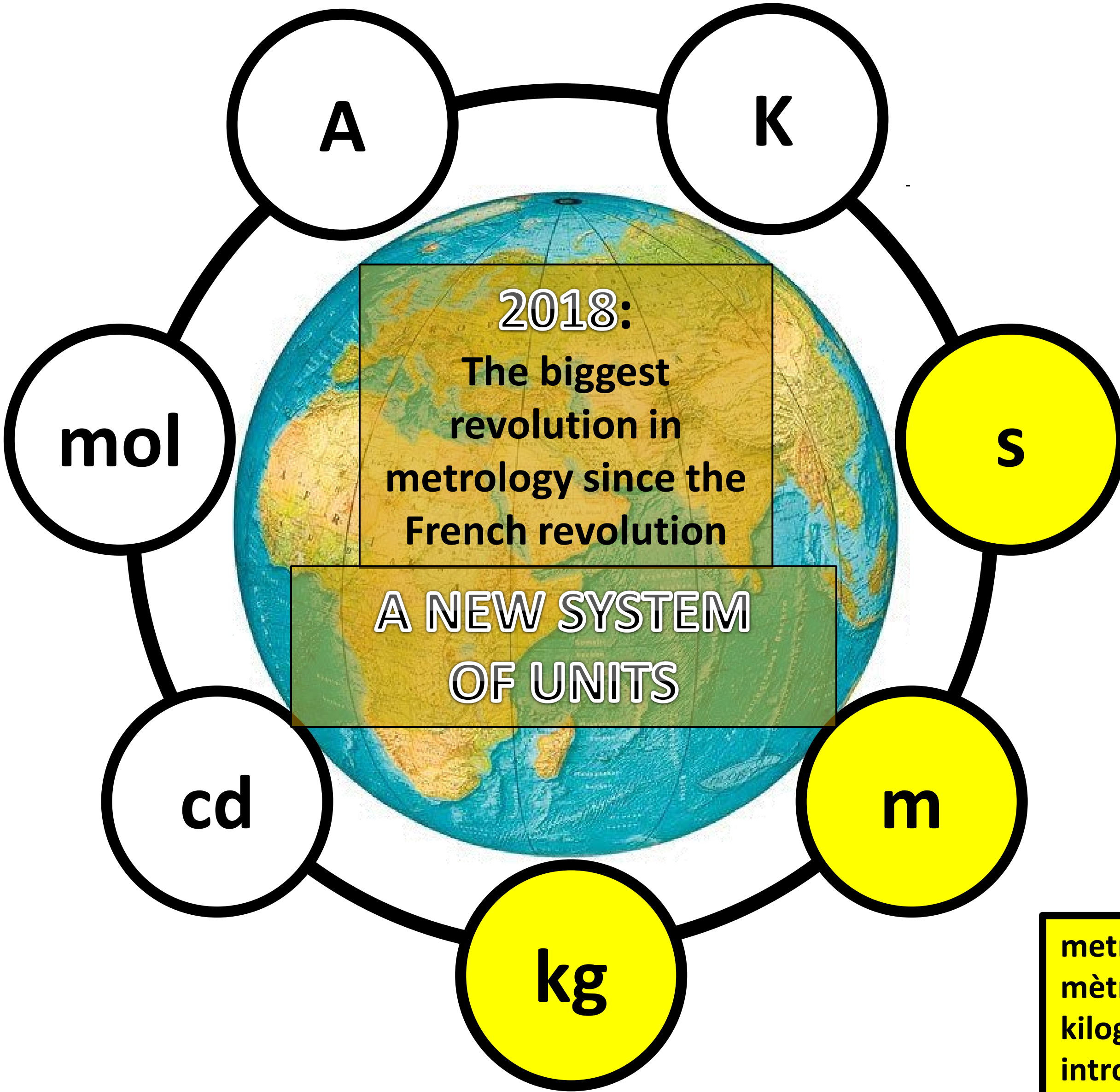


Fig. 3. — La Convention du Mètre (1875).
Première page et premières signatures de l'exemplaire manuscrit déposé dans les Archives du Gouvernement français (Format original : environ 19,5 cm × 31 cm).

Properties of the Earth were used to introduce a Global Sytem of Units



SI Base Units

metric system based on the mètre des archives and the kilogramme des archives introduced by France in 1799

A NEW SYSTEM OF UNITS (SI UNITS)

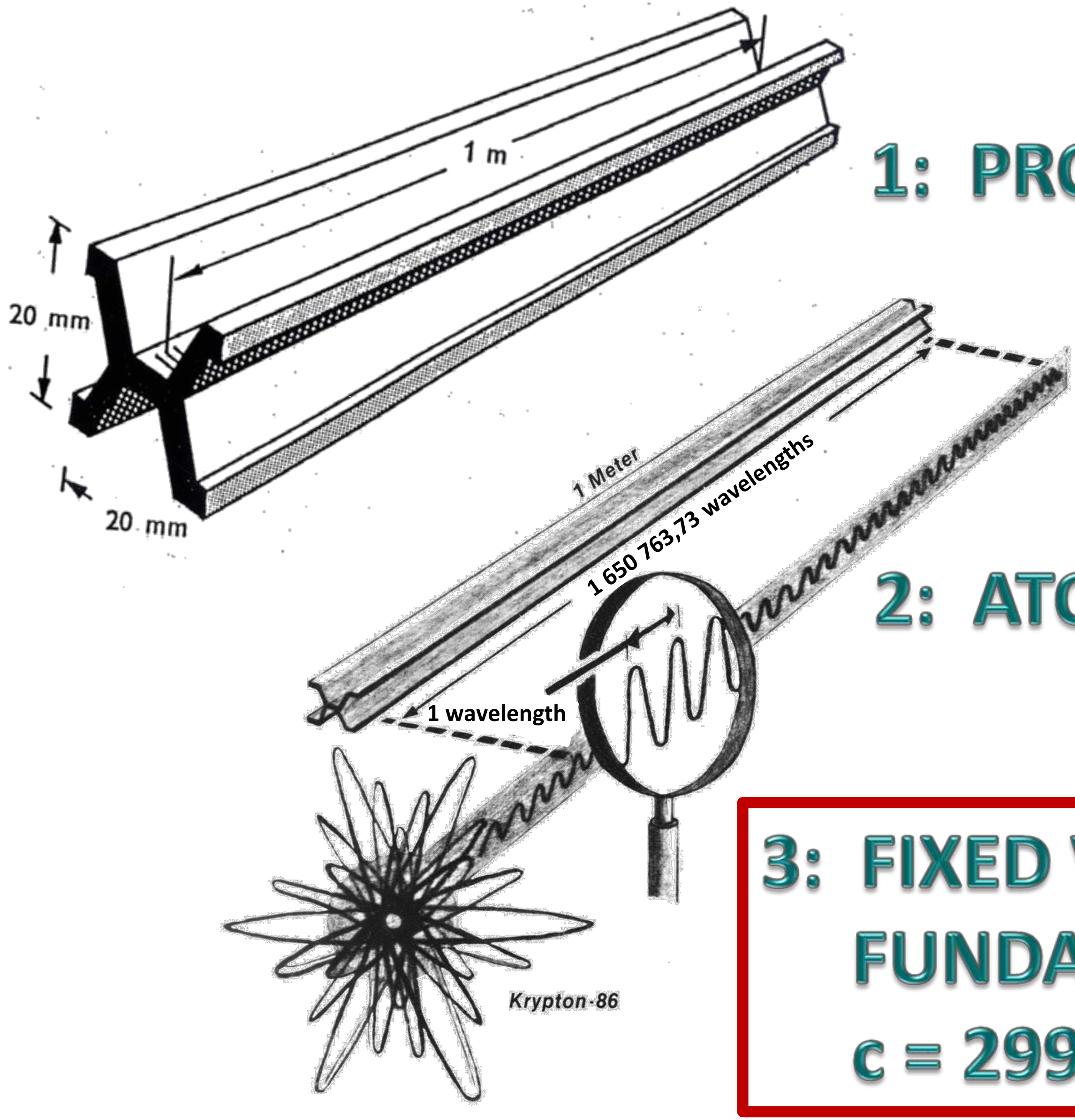
Don't worry:
The units will be exactly identical with our present units at the time of the introduction of the new International System of Units

(no change at all for length units)

(...but more stable!)

Kilogram
Ampere, Ohm, Volt
Kelvin
Mol

Development of „METER"-definition



1: PROTOTYPE

2: ATOMIC WAVELENGTH (1960-1983)

3: FIXED VALUE FOR FUNDAMENTAL CONSTANT $c = 299792458$ m/s

Official definition of the length unit 1 meter
(since 1983)

The meter is defined as the length of the path travelled by light in vacuum in 1⁄299,792,458 of a second.

FIXED VALUE OF A FUNDAMENTAL CONSTANT AS BASIS FOR AN INTERNATIONAL UNIT

(original idea of Max Planck)

1900: Max Planck

(Theory of Black Body Radiation)

Birth of quantum mechanics

$$E(\lambda,T) = \frac{2hc^2}{\lambda^5}\frac{1}{e^{hc/\lambda kT}-1}$$

Ann.Physik 1, 69-122 (1900)

"....with the help of fundamental constants we have the possibility of establishing units of length, time, mass, and temperature, which necessarily retain their significance for all cultures, even unearthly and nonhuman ones."

even Aliens understand the universal language of science and fundamental constants

Max Planck and his Universal Units

$$Planck\ \ length\ \ \ l_P = \sqrt{\frac{\hbar G}{c^3}} \approx 1.6 \cdot 10^{-35}\, m$$

$$Planck\ mass\ \ \ \ m_P = \sqrt{\frac{\hbar c}{G}} \approx 2.18 \cdot 10^{-8}\, kg$$

$$Planck\ time\ \ \ t_P = \sqrt{\frac{\hbar G}{c^5}} \approx 5.39 \cdot 10^{-44}\, s$$

$$Planck\ temperature\ \ T = \sqrt{\frac{\hbar c^5}{G {k_B}^2}} = 1.42 \cdot 10^{32}\, K$$

Unfortunately, Planck units are useless for practical applications

5 month ago:
25th meeting of the
Conférence générale des poids et mesures

Tuesday 18 November 2014 at 9:30

at the **Palais des Congrès de Versailles**,

10 rue de la Chancellerie,

78000 Versailles, Yvelines, France.

1st General Conference on Weights and Measures: 1889

Constitution of the General Conference on Weights and Measures

Metre Convention (1875): Article 3*

"The International Bureau** shall operate under the exclusive direction and supervision of an *International Committee for Weights and Measures****, itself placed under the authority of a *General Conference on Weights and Measures*****, consisting of the delegates of all the contracting Governments."

Regulations annexed to the Metre Convention (1875): Article 7*

"The General Conference, mentioned in Article 3 of the Convention, shall meet in Paris, on the convocation of the International Committee at least once every six years.

5 month ago:
25th meeting of the *Conférence générale des poids et mesures*

List of Draft Resolutions of the General Conference on Weights and Measures (25th meeting)

A	On the future revision of the International System of Units, the SI
B	On the election of the International Committee for Weights and Measures
C	On the Pension and Provident Fund of the BIPM
D	Dotation of the BIPM for the years 2016 to 2019
E	On the importance of the CIPM Mutual Recognition Arrangement

Proposal for a new SI system

Base Unit		***Reference constants used to define the unit***		
		in* the *current SI	**reference constant *in the new SI***	
second,	s	$\Delta\nu(^{133}\mathrm{Cs})_{\mathrm{hfs}}$	$\Delta\nu(^{133}\mathrm{Cs})_{\mathrm{hfs}}$	Cs hyperfine splitting
metre,	m	c	c	speed of light in vacuum
kilogram,	kg	$m(\mathcal{K})$	h	Planck constant
ampere,	A	μ_0	e	elementary charge
kelvin,	K	T_{TPW}	k	Boltzmann constant
mole,	mol	$M(^{12}\mathrm{C})$	N_A	Avogadro constant
candela,	cd	K_{cd}	K_{cd}	luminous efficacy of a 540 THz source

Resolution at the Last CGPM

Resolution A

The General Conference on Weights and Measur… 25th meeting,

encourages

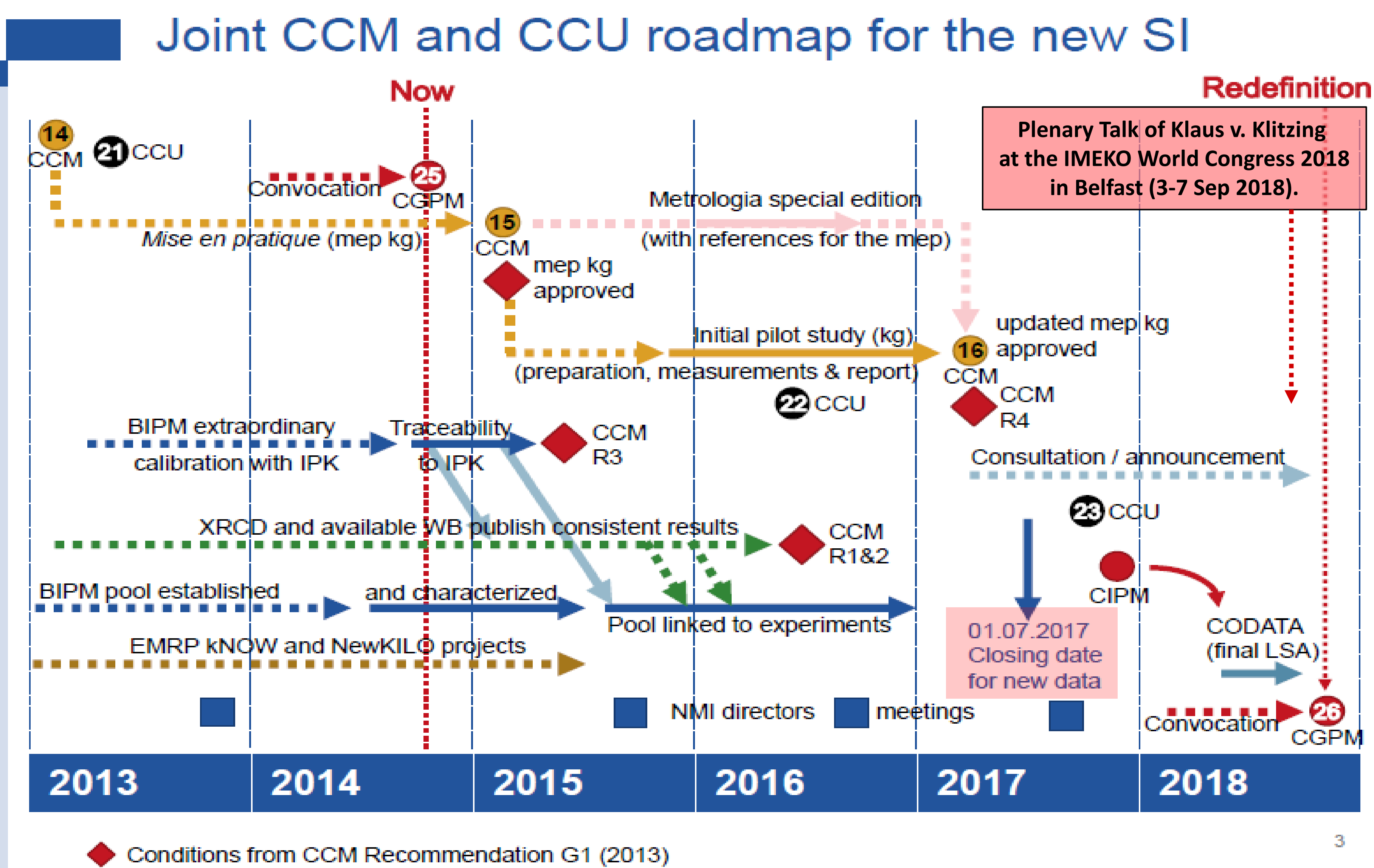
continued effort by the CIP… …nsultative Committees, the NMIs, the BIPM, a… …s such as the International Organization of Le… …, to complete all work necessary for the CGPM … …dopt a resolution that would replace the current … SI, provided the amount of data, their uncert… …nsistency are deemed satisfactory.

NOT BEFORE 2018

next relevant meeting of the

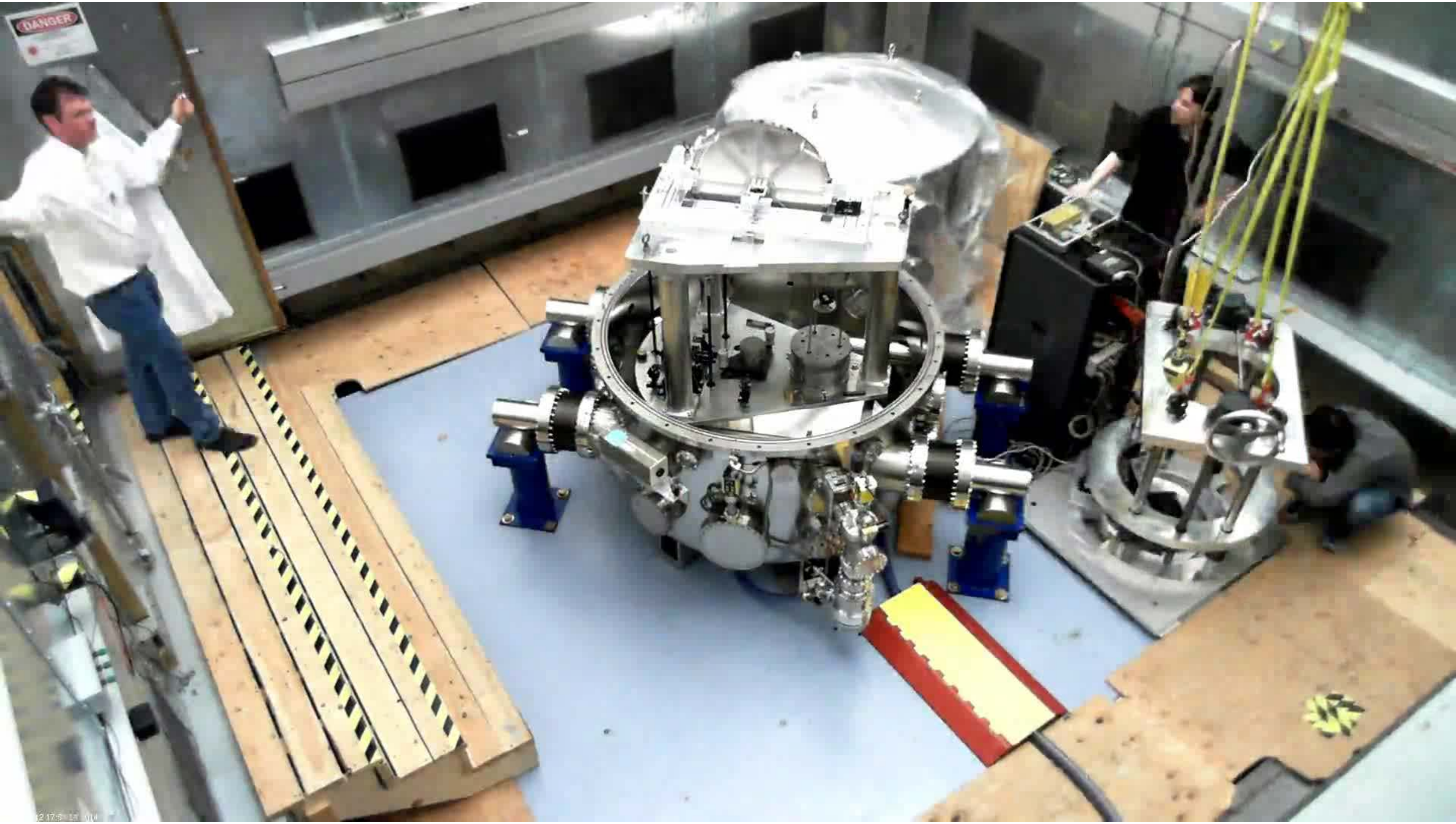
Conférence Générale des Poids et Mesures (CGPM)

Roadmap Until Next CGPM Meeting



Activities at NIST in 2014

FOR A NEW KILOGRAM



Physics Today July 2014

A more fundamental International System of Units

David B. Newell

The kilogram will be replaced by a fixed value of the Planck constant *h*

The universally accepted method of expressing physical measurements for world commerce, industry, and science is about to get a facelift, ...

Although the present International System of Units (SI, from the French Système International d'Unités) was officially established in 1960, its origin goes back to the creation of the metric system during the French Revolution. Following an idea proposed a century earlier by John Wilkins,[1] the new system of weights and measures took as its starting point a single universal measure—the meter—and used it to define length, volume, and mass. The meter came from a perceived constant of nature: one ten-millionth of the distance along Earth's meridian through Paris from the North Pole to the equator.[2] Definitions for the units of volume and mass followed, with the liter being 0.001 m^3 and the kilogram the mass of 1 liter of distilled water at 4 °C. Subsequently, in 1799, two platinum artifact standards for length and mass based on those definitions were deposited in the Archives de la République in Paris. In the words of the Marquis de Condorcet, a new system of measurement "for all time, for all people" was born.

Seventy-six years later, the signing of the Meter Convention in 1875 established three international organizations: the General Conference on Weights and Measures (CGPM), the International Committee for Weights and Measures (CIPM), and the International Bureau of Weights and Measures (BIPM). They were formally tasked with maintaining the SI and continue to do so.

The SI is a living, evolving system, changing as new knowledge and measurement needs arise, albeit sometimes slowly when measured against the rapid pace of scientific progress. For example, in the 18th and 19th centuries when natural philosophers and scientists tried to apply the system of length, mass, and time—with time defined by astronomical observations—to quantify newly discovered phenomena such as magnetism and electricity and the concept of energy, they also discovered the need for

David Newell is a physicist at the National Institute of Standards and Technology in Gaithersburg, Maryland, and chair of the CODATA Task Group on Fundamental Constants.

Basic research on

SILICON FIELD EFFECT TRANSISTORS

initiated the expected change in the definition of our SI base units

for the discovery of the Quantum Hall Effect

The QHE has Initiated the Development of a New SI System

QHE symposium (MPI Stuttgart, June 2013)

Invited Talk 1

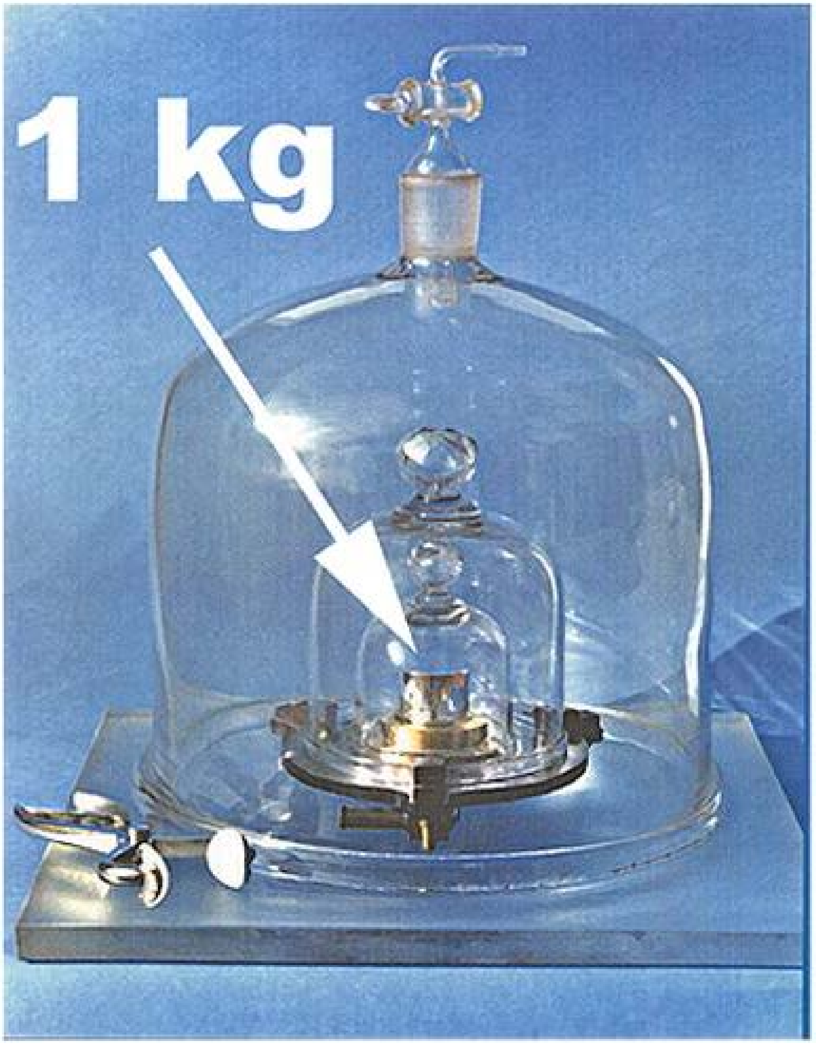
The quantum-Hall effect – the key to the New SI

Terry Quinn

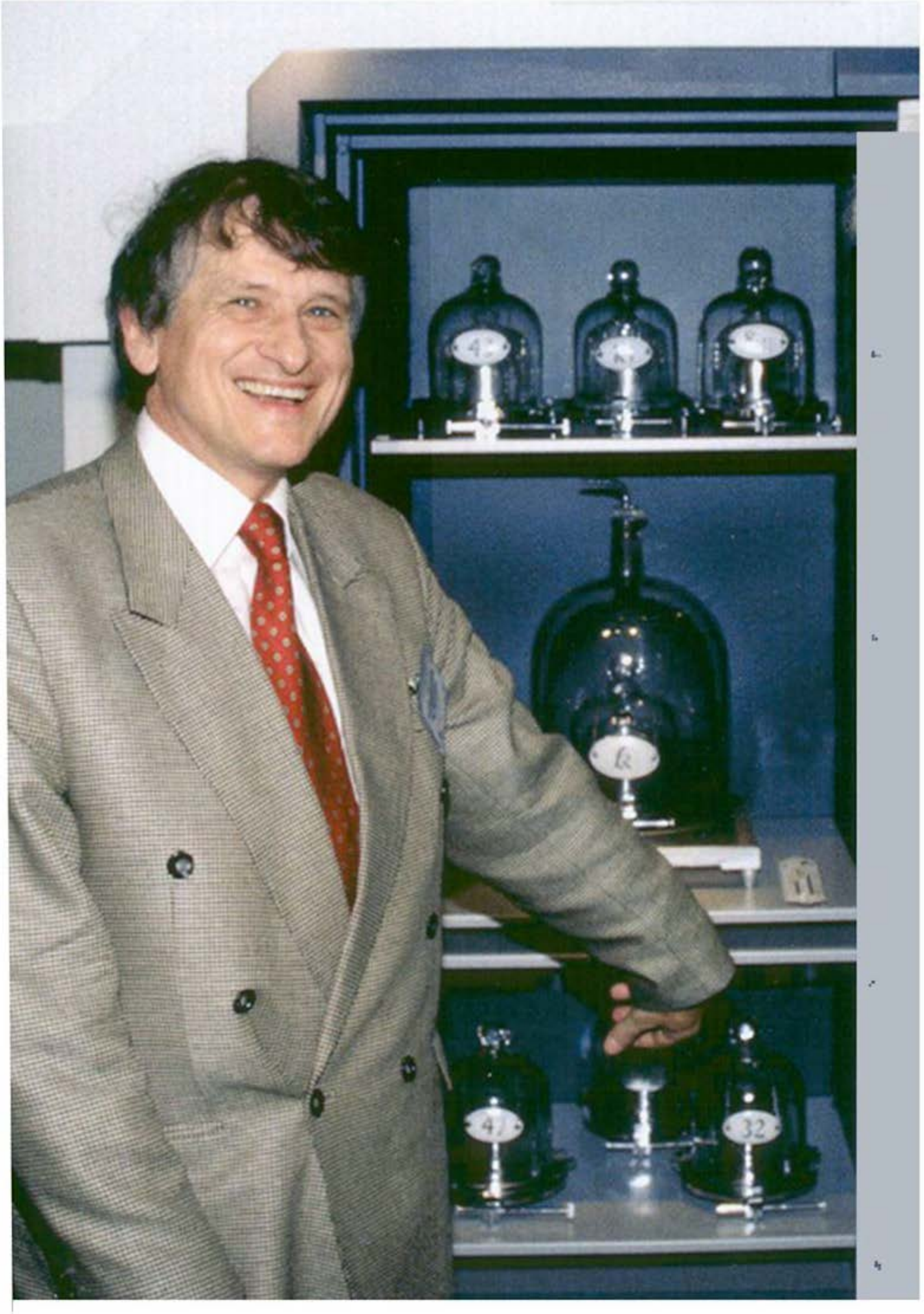
Emeritus Director, International Bureau of Weights and Measures, Paris, France

The New SI is a revision of the International System of Units in which each of the seven base units, second, metre, kilogram, ampere, kelvin, mole and candela, will be defined in terms of a fixed numerical value of a fundamental constant or constant of nature. It was adopted in principle by the 24th General Conference on Weights and Measures in 2011 to be implemented when certain experimental data are finally approved. Key to the New SI will be the redefinition of the kilogram in terms of a fixed numerical value for the Planck constant. Such a definition only became possible with the discovery of the quantum-Hall effect.

Problems with our present kilogram !

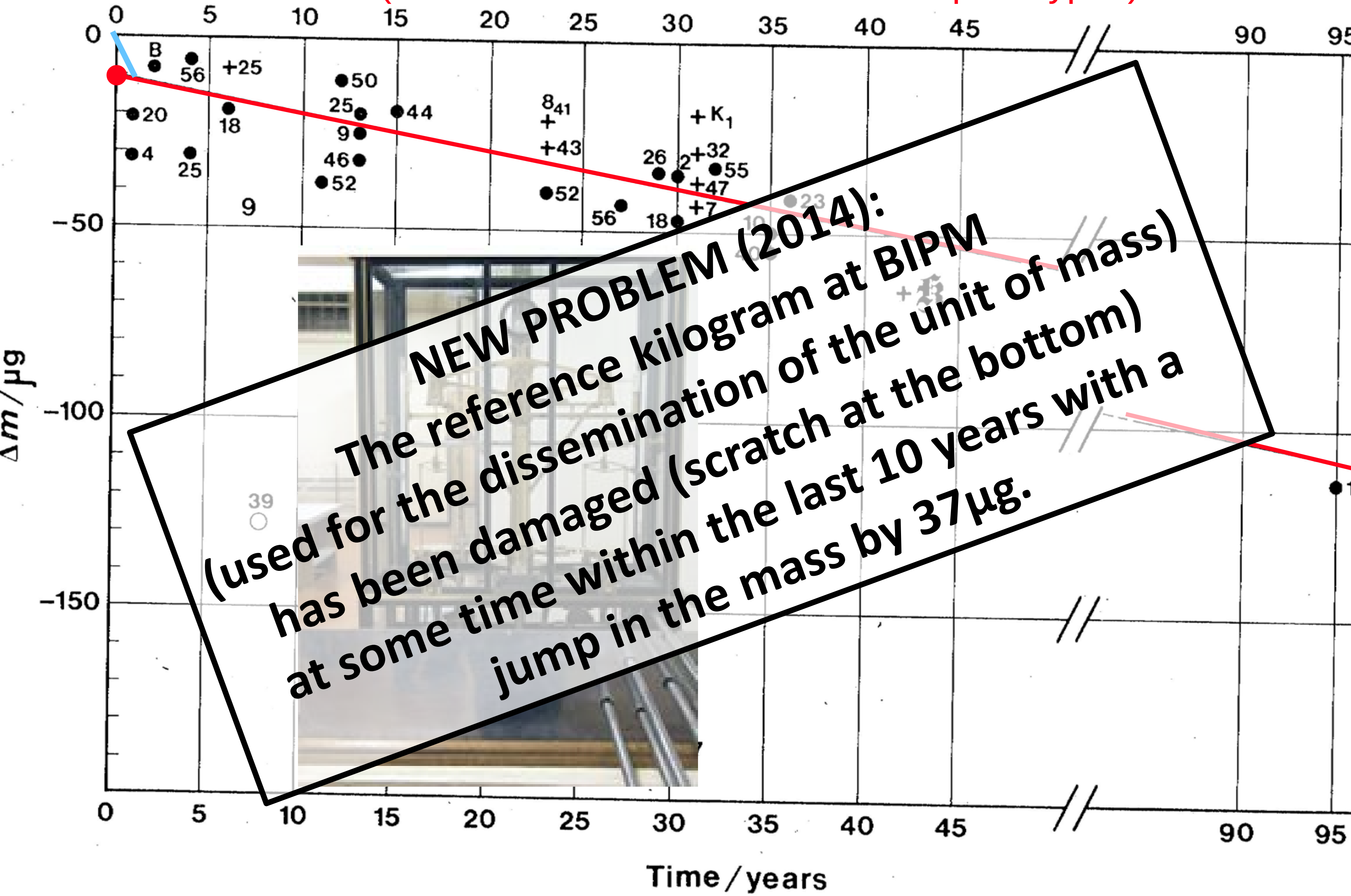


The kilogram prototype in Sèvre



the mass of the prototype changes with time

(relative to mean value of national prototypes)



NEW PROBLEM (2014):
The reference kilogram at BIPM
(used for the dissemination of the unit of mass)
has been damaged (scratch at the bottom)
at some time within the last 10 years with a
jump in the mass by 37μg.

Official prototype of kilogram mysteriously losing weight

Posted 9/12/2007 1:27 PM | Comments 27 | Recommend 6

Enlarge By Jacques Brinon, AP

A copy of a 118-year-old cylinder that has been the international prototype for the metric mass. American physicist Richard Davis said the reference kilo appears to have lost 50 micrograms compared to the average of dozens of copies.

By Jamey Keaten, Associated Press

PARIS — A kilogram just isn't what it used to be.

The 118-year-old cylinder that is the international prototype for the metric mass, kept tightly under lock and key outside Paris, is mysteriously losing weight — if ever so slightly. Physicist Richard Davis of the International Bureau of Weights and Measures in Sevres, southwest of Paris, says the reference kilo appears to have lost 50 micrograms compared with the average of dozens of copies.

"The mystery is that they were all made of the same material, and many were made at the same time and kept under the same conditions, and yet the masses among them are slowly drifting apart," he said. "We don't really have a good hypothesis for it."

The kilogram's uncertainty could affect even countries that don't use the metric system — it is the ultimate weight standard for the U.S. customary system, where it equals 2.2 pounds. For scientists, the inconstant metric constant is a nuisance, threatening calculation of things like electricity generation.

INSTITUTE OF PHYSICS PUBLISHING METROLOGIA

Metrologia **42** (2005) 71–80 doi:10.1088/0026-1394/42/2/001

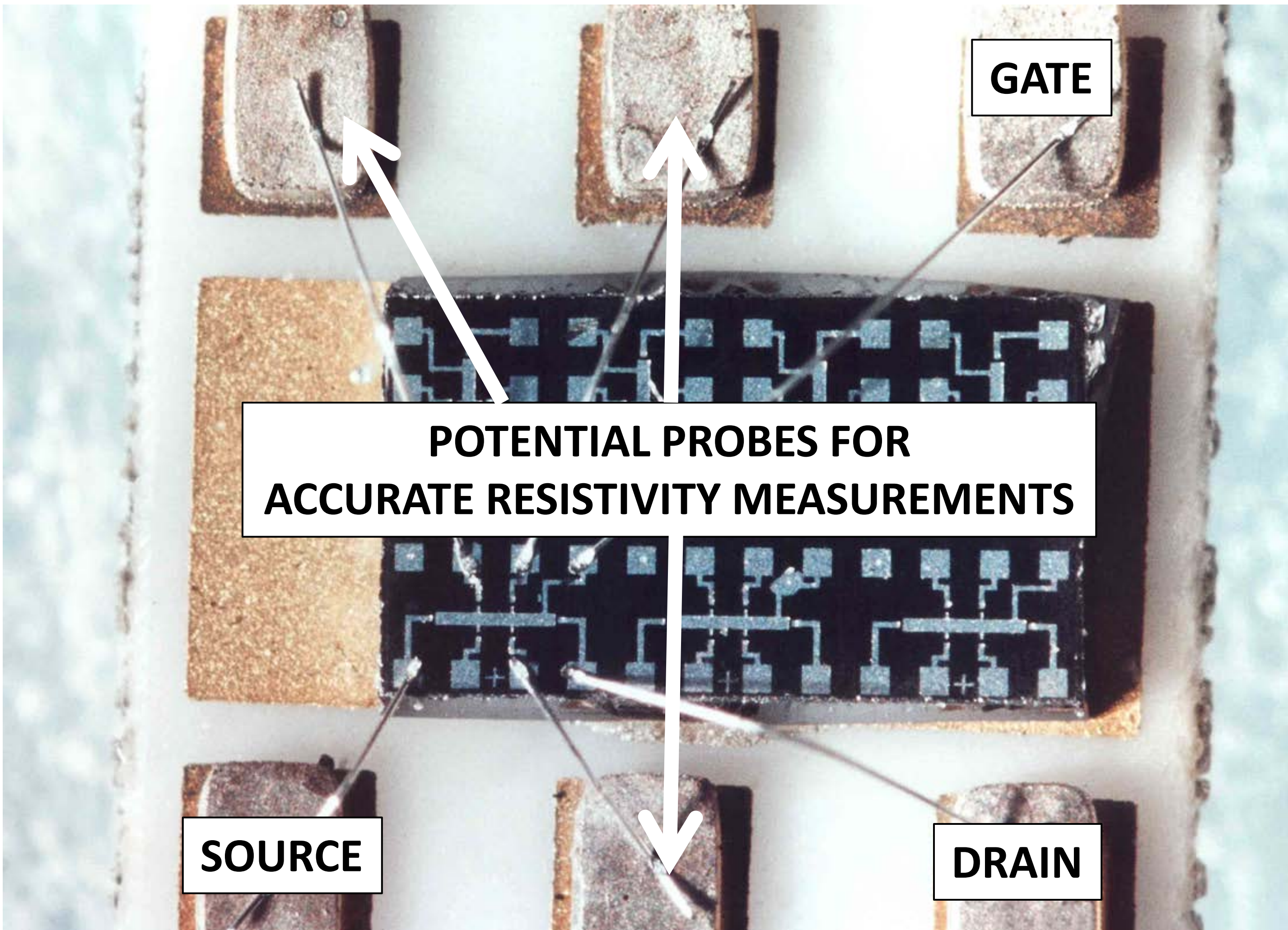
Redefinition of the kilogram: a decision whose time has come

Ian M Mills[1], Peter J Mohr[2], Terry J Quinn[3], Barry N Taylor[2] and Edwin R Williams[2]

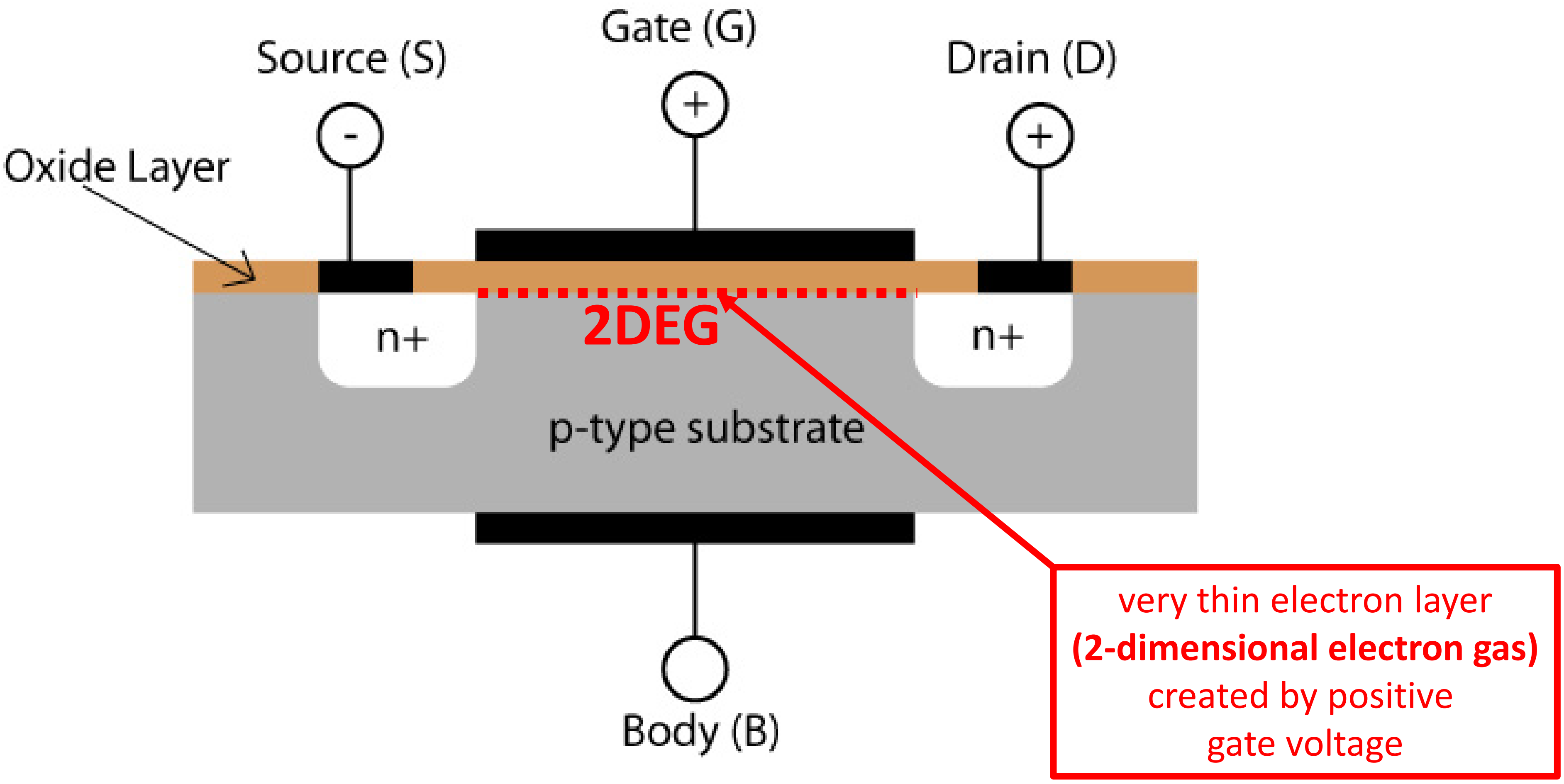
My Nobel Prize discovery
(Quantum Hall Effect)
plays an important role !

My Nobel Prize is connected with basic research on the most important device in electronics:

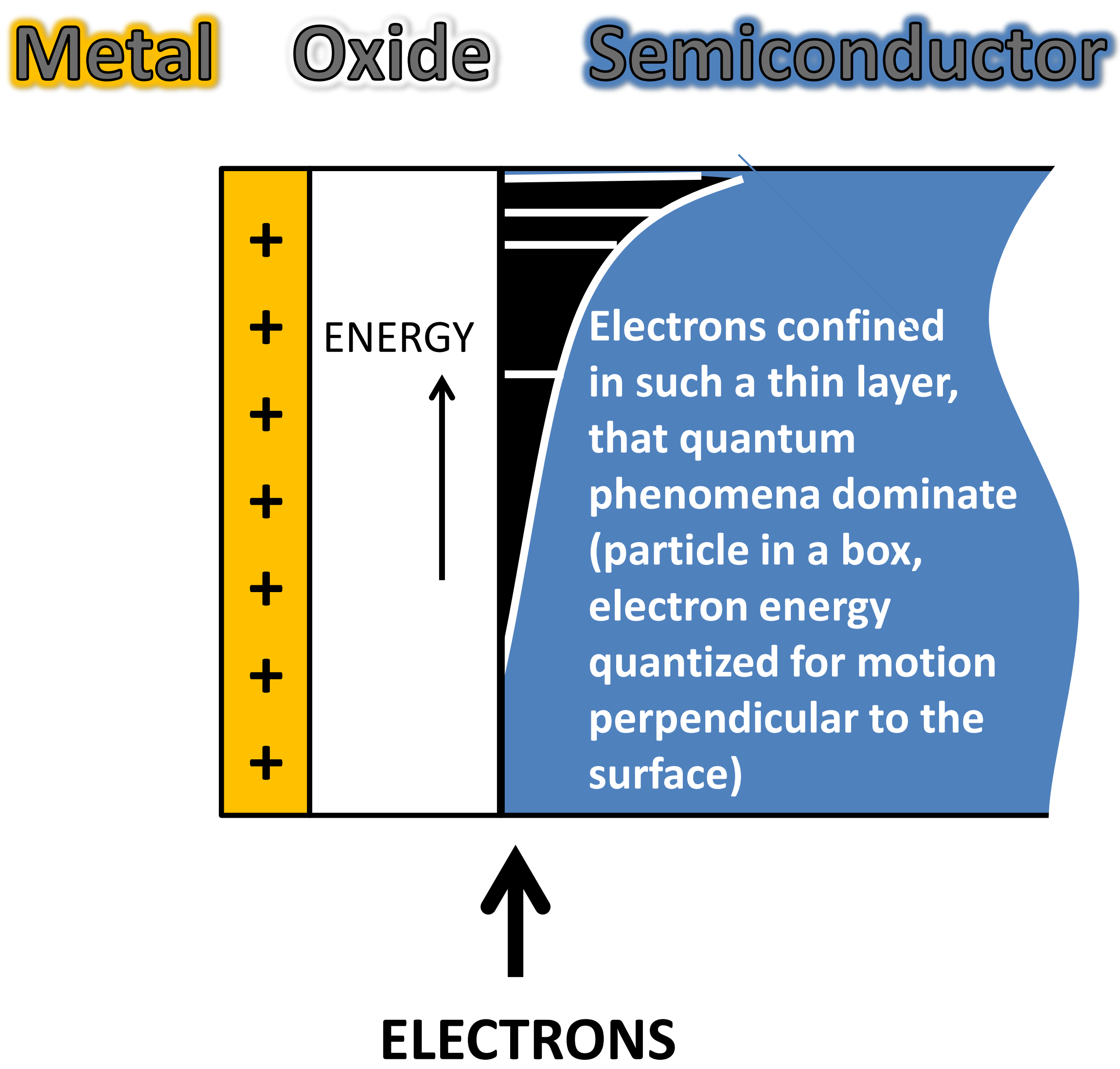
MOS field effect transistor



Field Effect Transistor, the Backbone of Electronics



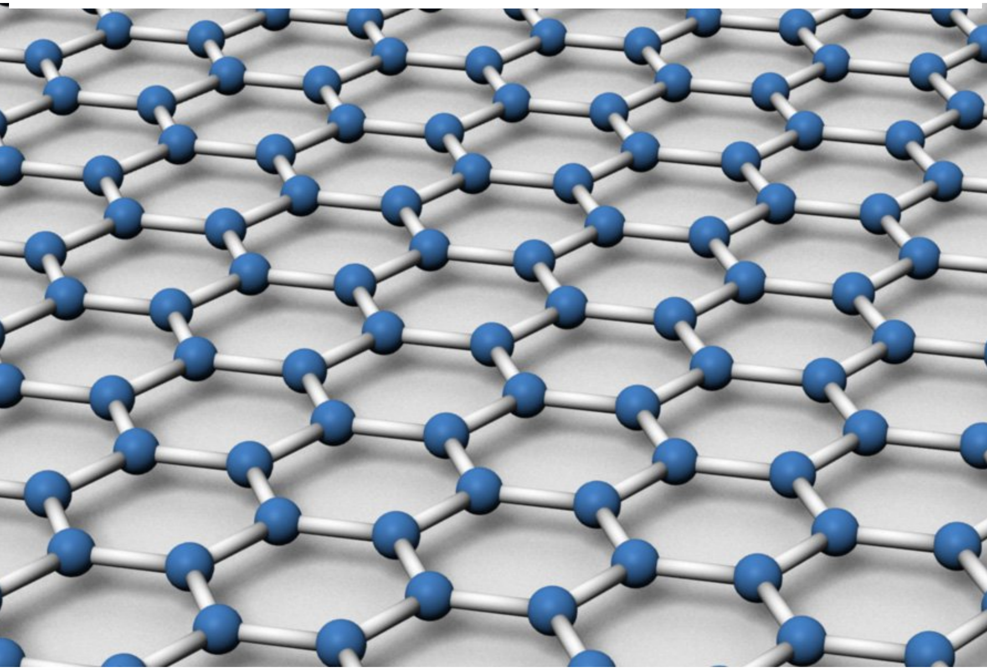
Two-Dimensional Electron Gas

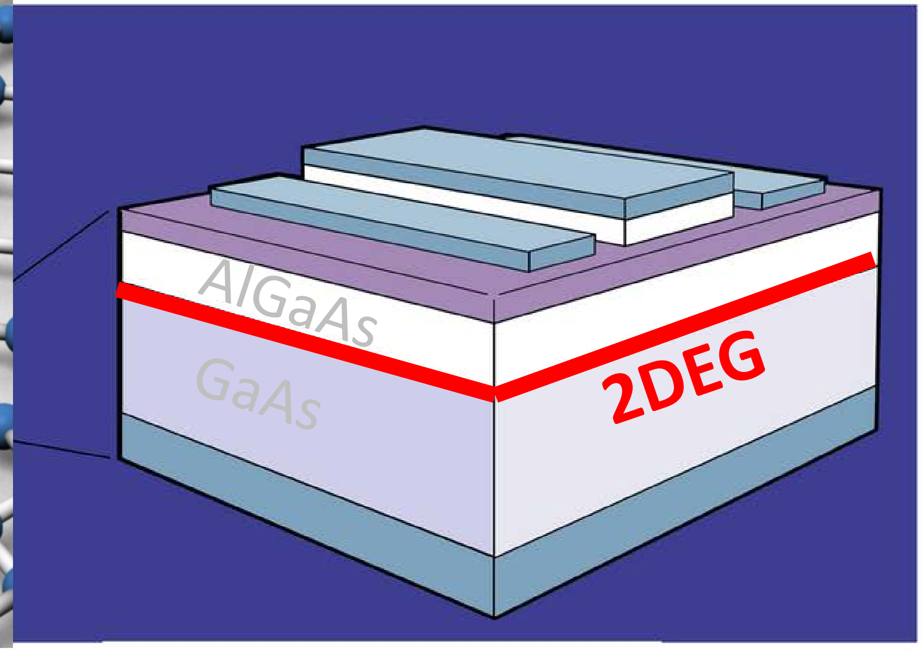


Nobel Prize 2010 Nobel Prize 2000

Graphene: The ideal 2DEG

Modern version of Si MOSFET

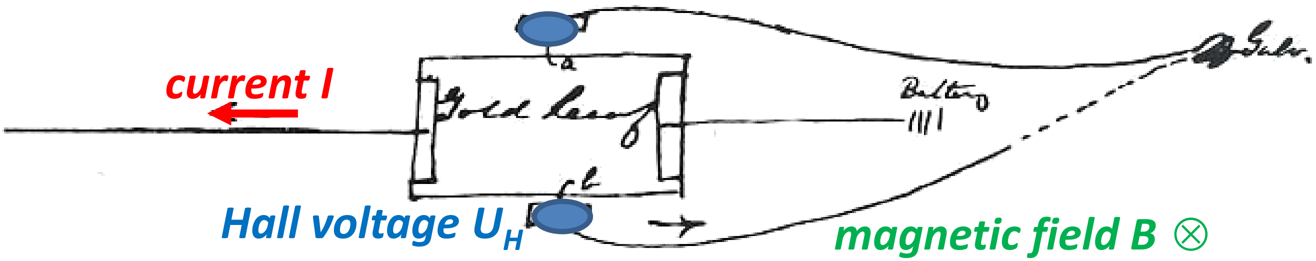


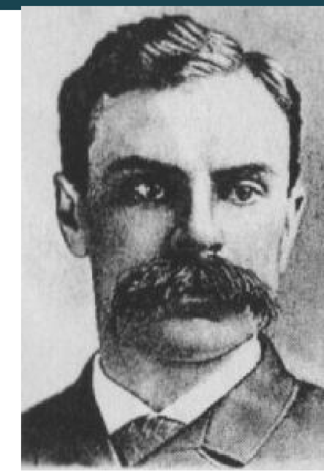


Heterostructures for fast electronics:

HEMT (2DEG for High Electron Mobility Transistor

1879: Discovery of the Hall effect




Edwin Hall (1855-1938)

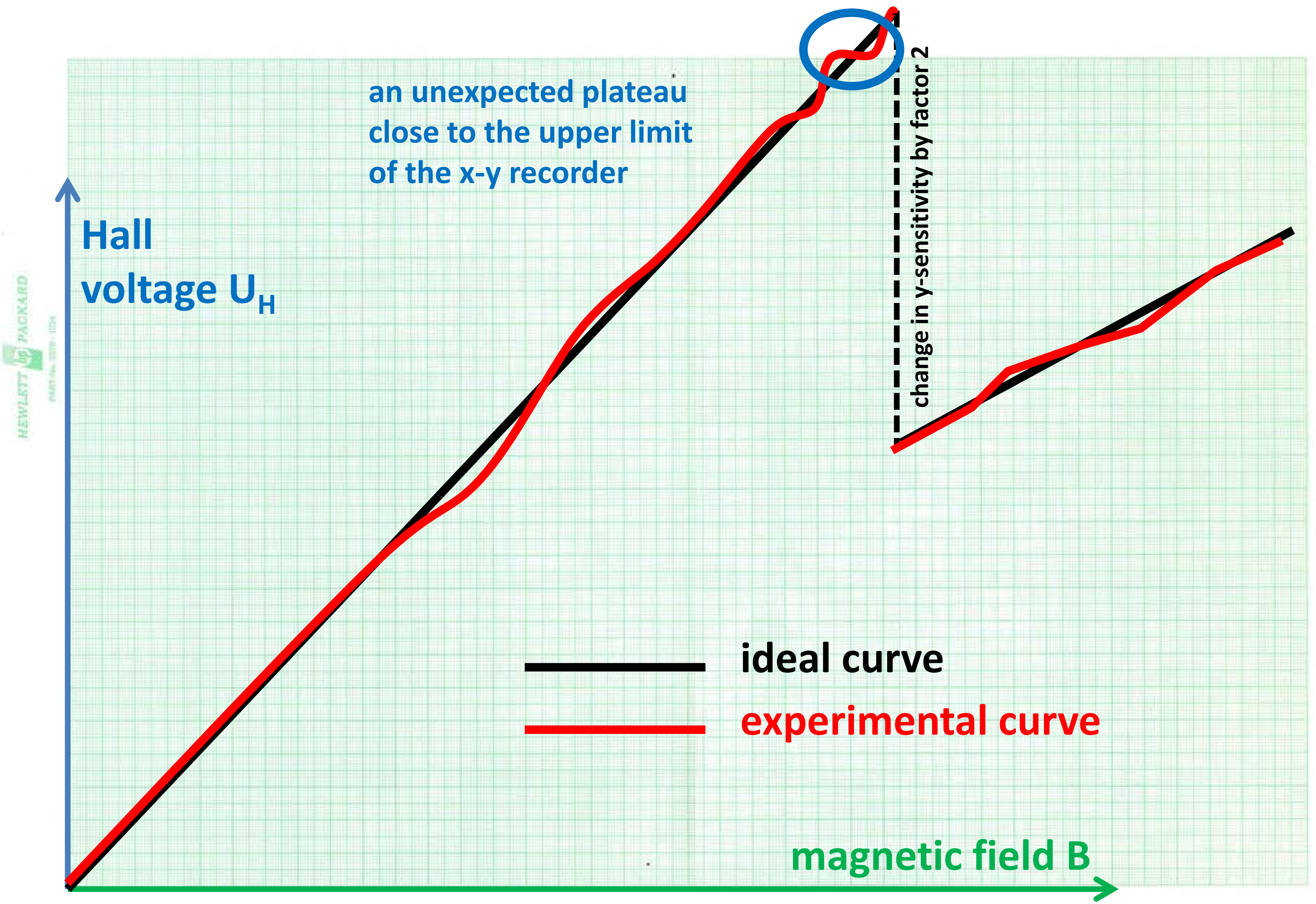
The results obtained are as follows:

Type equation here.

Current through gold leaf strip. C.	Strength of Magnetic field. M.	Current through Thomson galvanometer. c.	$\frac{C \times M}{c}$
·0616	11420 H	·00000000232	303000000000·
·0249	11240 "	·00000000085	329000000000·
·0389	11060 "	·00000000135	319000000000·
·0598	7670 "	·00000000147	312000000000·
·0595	5700 "	·00000000104	326000000000·

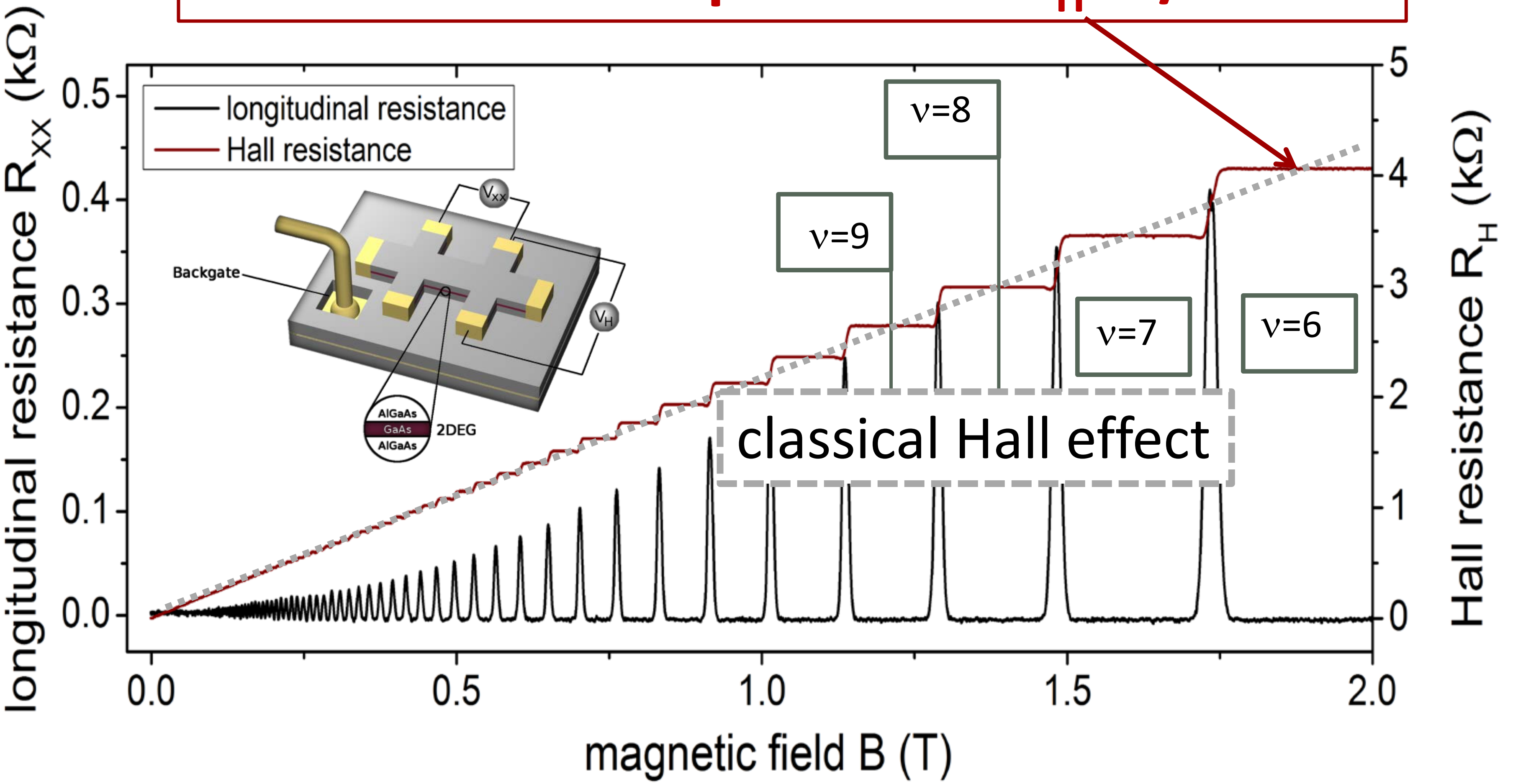
$$U_H \sim B \cdot I$$

Proportional constant gives information about electron concentration


an unexpected plateau
close to the upper limit
of the x-y recorder
Hall
voltage U_H
change in y-sensitivity by factor 2
ideal curve
experimental curve
magnetic field B

Integer Quantum Hall Effect for GaAs/AlGaAs Heterostructure

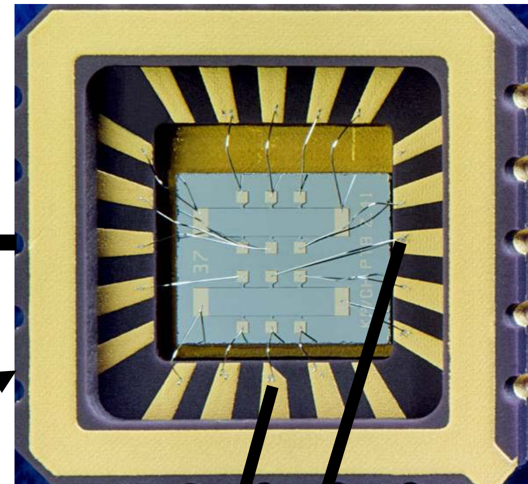
Hallresistance is quantized: $R_H = h/\nu e^2$



Unexpected Result

Quantum Hall Effect (QHE)

current I



2-dimensional electron system in strong magnetic fields

voltage V

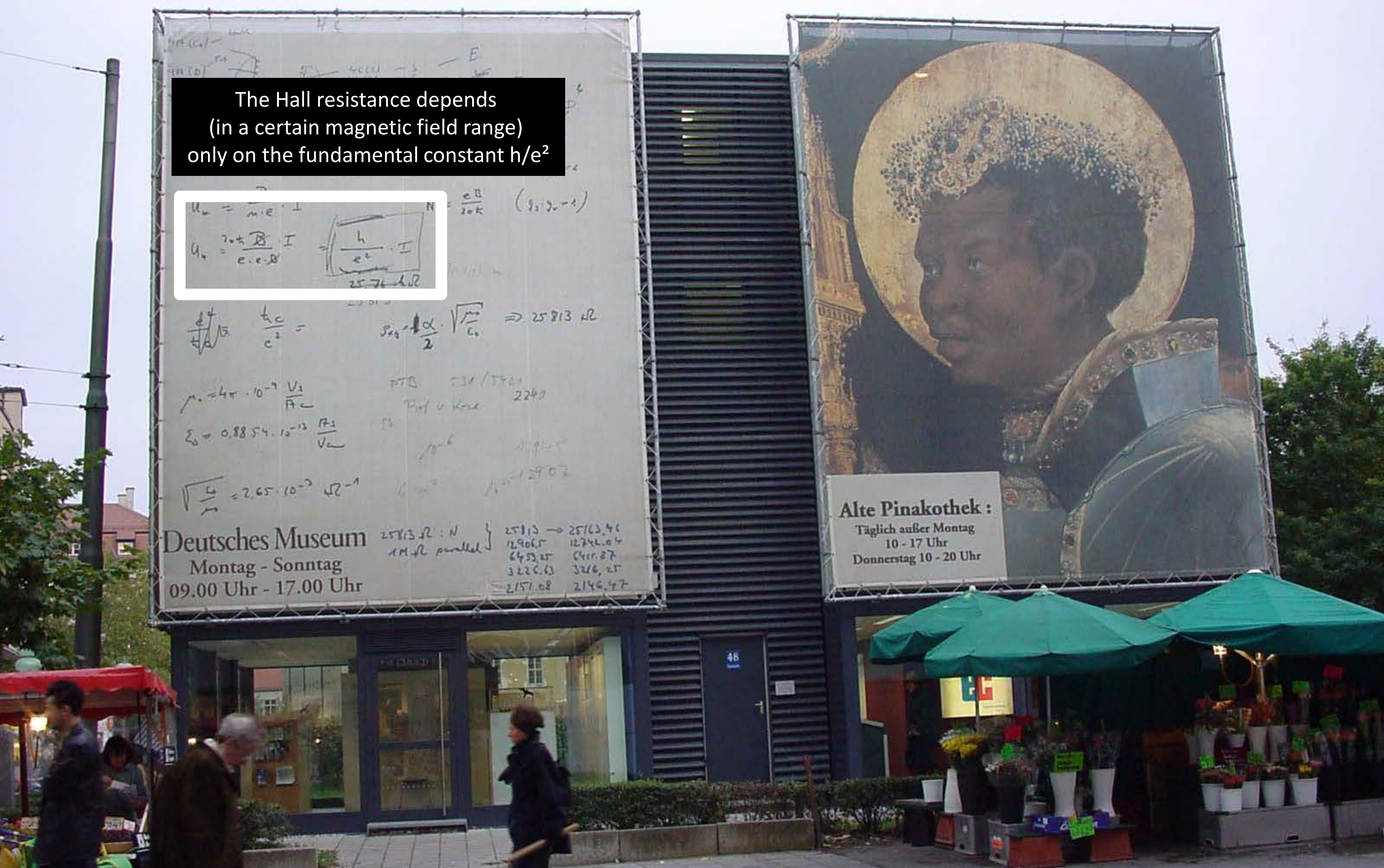
Ohm's law:

$$V = R \cdot I$$

Under QHE condition, this resistance has always the fundamental value

$$R = 25812{,}807\ldots\Omega = h/e^2$$

Memos from 5.2.1980



The Hall resistance depends
(in a certain magnetic field range)
only on the fundamental constant h/e^2

First draft of the "NOBEL" publication

(submitted 30.5.1980 to PRL)

Realization of a resistance standard based on natural constants

K. v. Klitzing, Physikalisches Institut der Universität Würzburg, D-8700 Würzburg, FRG

G. Dorda, Forschungslaboratorien der Siemens AG, D-8000 München

and M. Pepper, Cavendish Laboratory, University of Cambridge, Cambridge, U.K.

Abstract

Measurements of the Hall voltage of a two dimensional electron gas, realized with a silicon MOS fieldeffect transistor, show, that the Hall resistance at experimentally well defined surface carrier concentrations has a fixed value which depends only on natural constants and which is insensitive to the geometry of the device.

Reaction from PRL (20.6.1980)

has been reviewed by our referee(s). On the basis of the resulting report(s), we judge that the paper is not suitable for publication in Physical Review Letters in its present form, but might be made so by appropriate revision. Pertinent criticism extracted from the report(s) is enclosed. While we cannot made a definite commitment, the probable course of action if you choose to resubmit is indicated below.

( ) Acceptance, if the editors can judge that all or most of the criticism has been met.
( ) Return to the original referee(s) for judgement.
(✓) Submittal to new referee(s) for judgement.

Please accompany your resubmittal by a summary of the changes made, and a brief response to any criticisms you have not attempted to meet. Do not ask us to make changes in the manuscript, but send us either a new copy or revised pages for substitution.

CAUTION!
PLEASE STAY WITHIN ALLOWED LENGTH WHENEVER ADDITIONS OR MODIFICATIONS ARE MADE.

Sincerely yours,

George Basbas
Editor (Associate)

enc.
GB/vm

QUANTIZED HALL RESISTANCE IN SI OHM

(data collected until 1988)

CSIRO, Australia	25 812.809 (2) Ω
NPL, UK	25 812.809 (1) Ω
BNM-LCIE, France	25 812.802 (6) Ω
ETL, Japan	25 812.806 (6) Ω
NIST, USA	25 812.807 (1) Ω
VNIIM, Russia	25 812.806 (8) Ω
VSL, Netherland	25 812.802 (5) Ω
NRC, Canada	25 812.814 (6) Ω
EAM, Switzerland	25 812.809 (4) Ω
PTB, Germany	25 812.802 (3) Ω
NIM, China	25 812.805 (16) Ω
CSIRO/BIPM	25 812.809 (2) Ω
CSIRO/Japan	25 812.813 (2) Ω

BEST VALUE (1990): R_K=25 812.807 (5) Ω

limitations due to calibration of reference resistor

BIPM

Bureau International des Poids et Mesures

→ Representation of the ohm by means of the quantum Hall effect*

1988

The Comité International des Poids et Mesures,

acting in accordance with instructions given in **Resolution 6** of the 18th Conférence Générale des Poids et Mesures concerning the forthcoming adjustment of the representations of the volt and the ohm,

considering

- that most existing laboratory reference standards of resistance change significantly with time,
- that a laboratory reference standard of resistance based on the quantum Hall effect would be stable and reproducible,
- that a detailed study of the results of the most recent determinations leads to a value of 25 812.807 Ω for the von Klitzing constant, R_K, that is to say, for the quotient of the Hall potential difference divided by current corresponding to the plateau i = 1 in the quantum Hall effect,
- that the quantum Hall effect, together with this value of R_K, can be used to establish a reference standard of resistance having a one-standard-deviation uncertainty with respect to the ohm estimated to be 2 parts in 10^7, and a reproducibility which is significantly better,

recommends

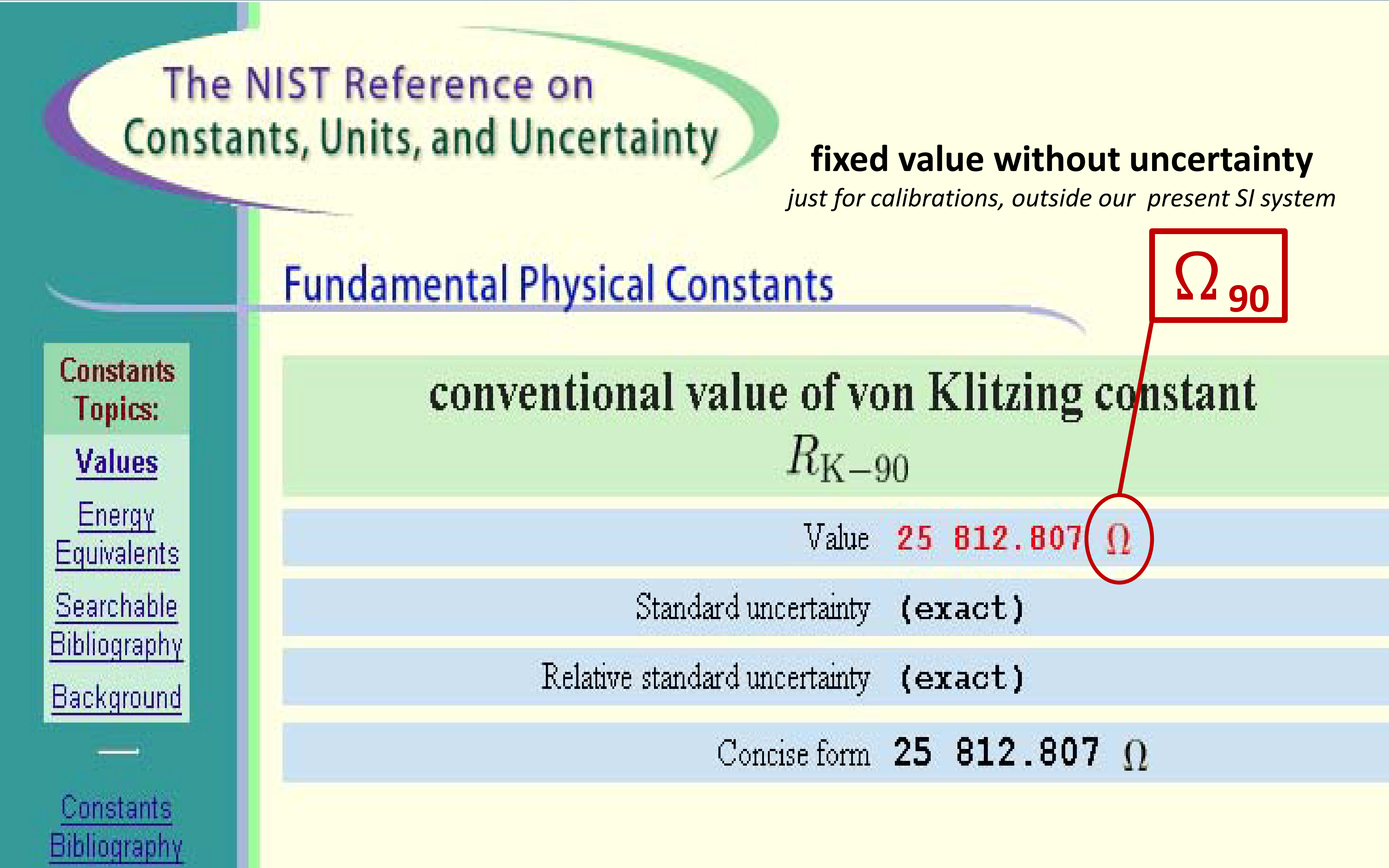
- that 25 812.807 Ω exactly be adopted as a conventional value, denoted by R_{K-90}, for the von Klitzing constant, R_K,
- that this value be used from 1 January 1990, and not before, by all laboratories which base their measurements of resistance on the quantum Hall effect,

http://physics.nist.gov/cuu/Constants/index.html

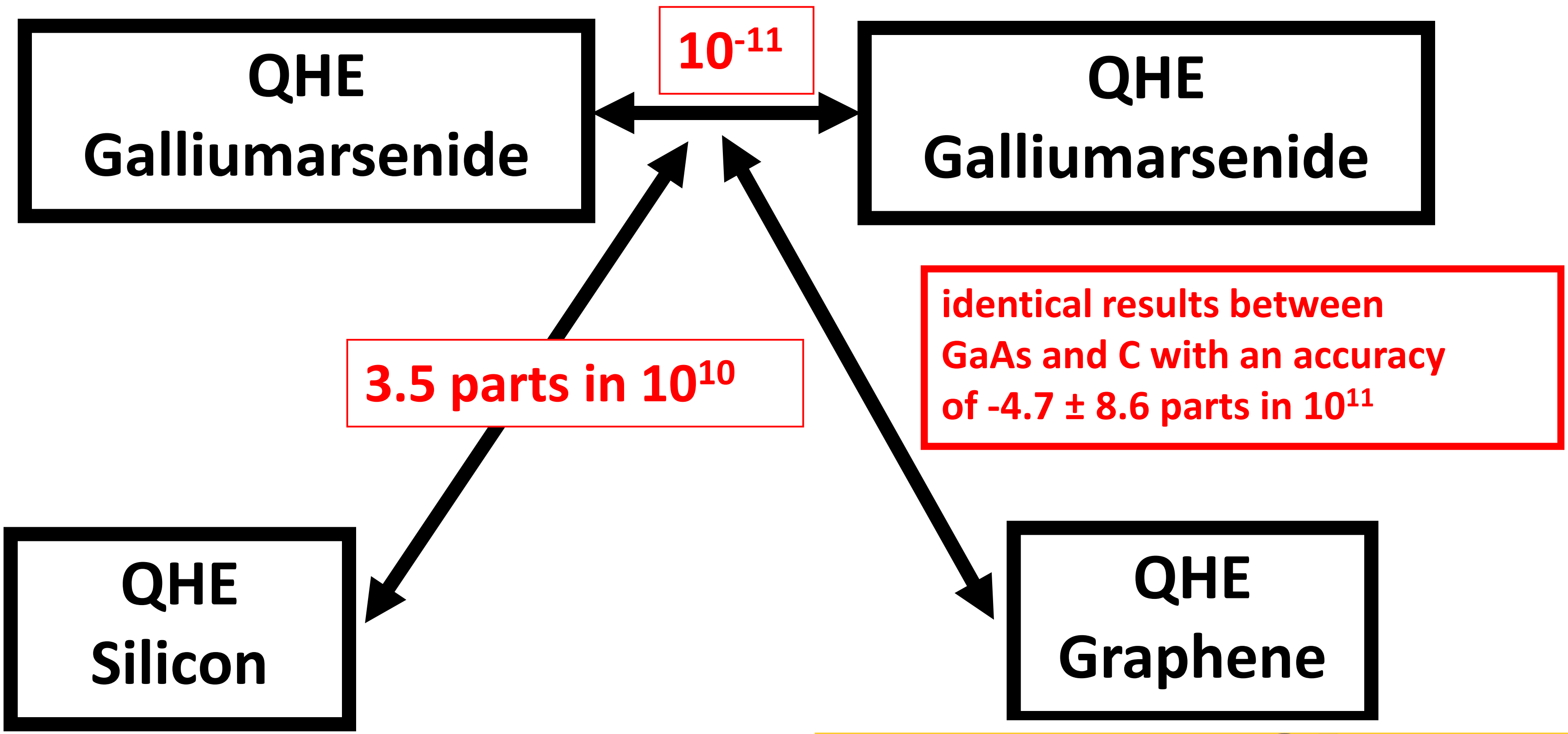
fixed value without uncertainty

just for calibrations, outside our present SI system

Ω_{90}



Quantized Hall Resistance for Different Materials



PHYSICAL REVIEW LETTERS

VOLUME 66 | 25 FEBRUARY 1991 | NUMBER 8

Direct Comparison of the Quantized Hall Resistance in Gallium Arsenide and Silicon

A. Hartland, K. Jones,[a] and J. M. Williams
National Physical Laboratory, Teddington TW11 0LW, United Kingdom

B. L. Gallagher and T. Galloway
Department of Physics, The University, Nottingham NG7 2RD, United Kingdom

(Received 16 November 1990)

Using an ultrasensitive, cryogenic, current-comparator bridge the quantized Hall resistance $R_H(2)$ in a GaAs/AlGaAs heterostructure has been compared directly with $R_H(4)$ in a silicon MOSFET. The measurements show that $R_H(2;\mathrm{GaAs})/R_H(4;\mathrm{Si}) = 2[1 - 0.22(3.5) \times 10^{-10}]$. Within the 1σ combined uncertainty of $\pm 3.5 \times 10^{-10}$ the result suggests that the quantized Hall resistance is a universal quantity, independent of the host lattice and Landau-level index, and is probably equivalent to h/e^2, the relationship predicted theoretically.

New Journal of Physics
The open-access journal for physics

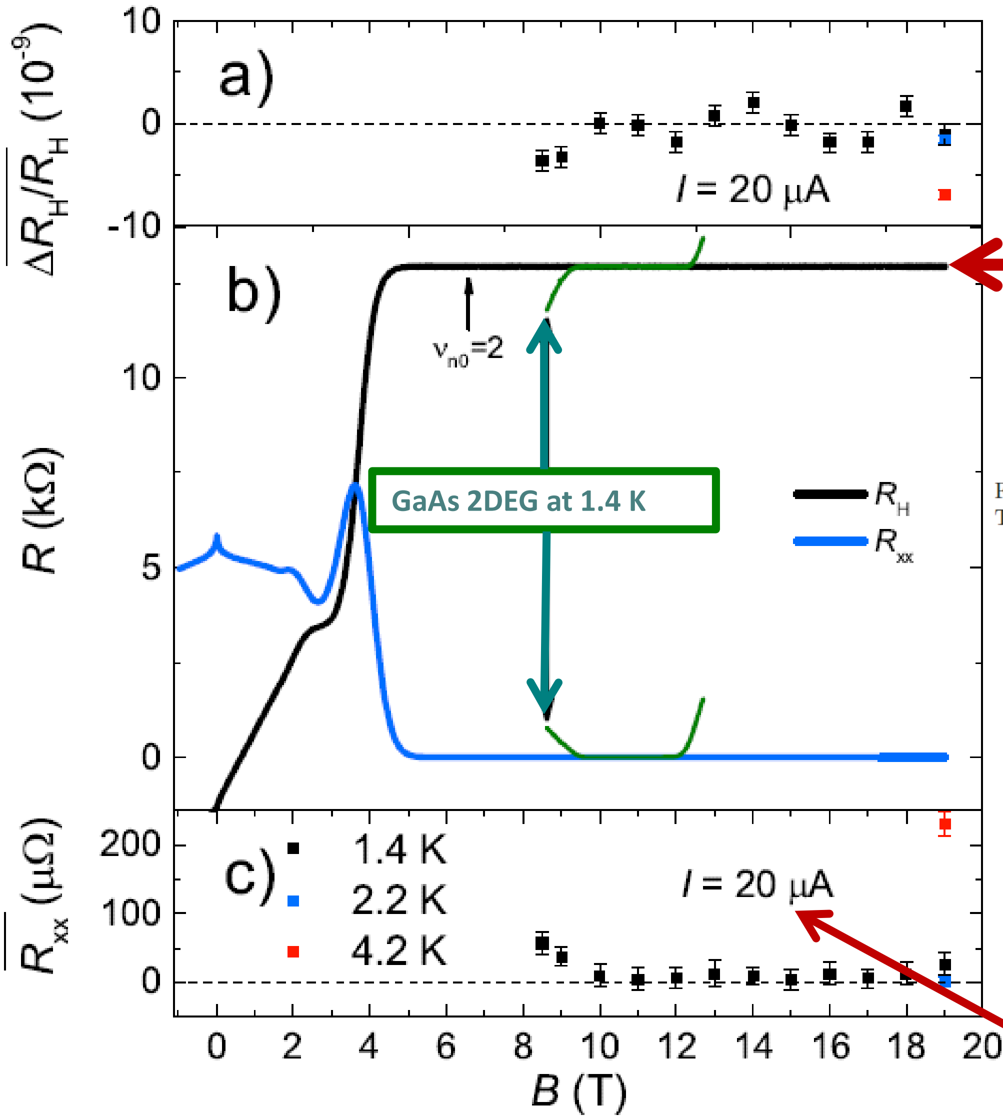
13 (2011) 093026

Graphene, universality of the quantum Hall effect and redefinition of the SI system

T J B M Janssen[1,6], N E Fletcher[2], R Goebel[2], J M Williams[1], A Tzalenchuk[1], R Yakimova[3], S Kubatkin[4], S Lara-Avila[4] and V I Falko[5]

Very Wide QHE Plateau for CVD Grown Graphene on SiC

http://arxiv.org/abs/1407.3615v1



Hallplateau from 5 Tesla- 20 Tesla
1 part in 10^9

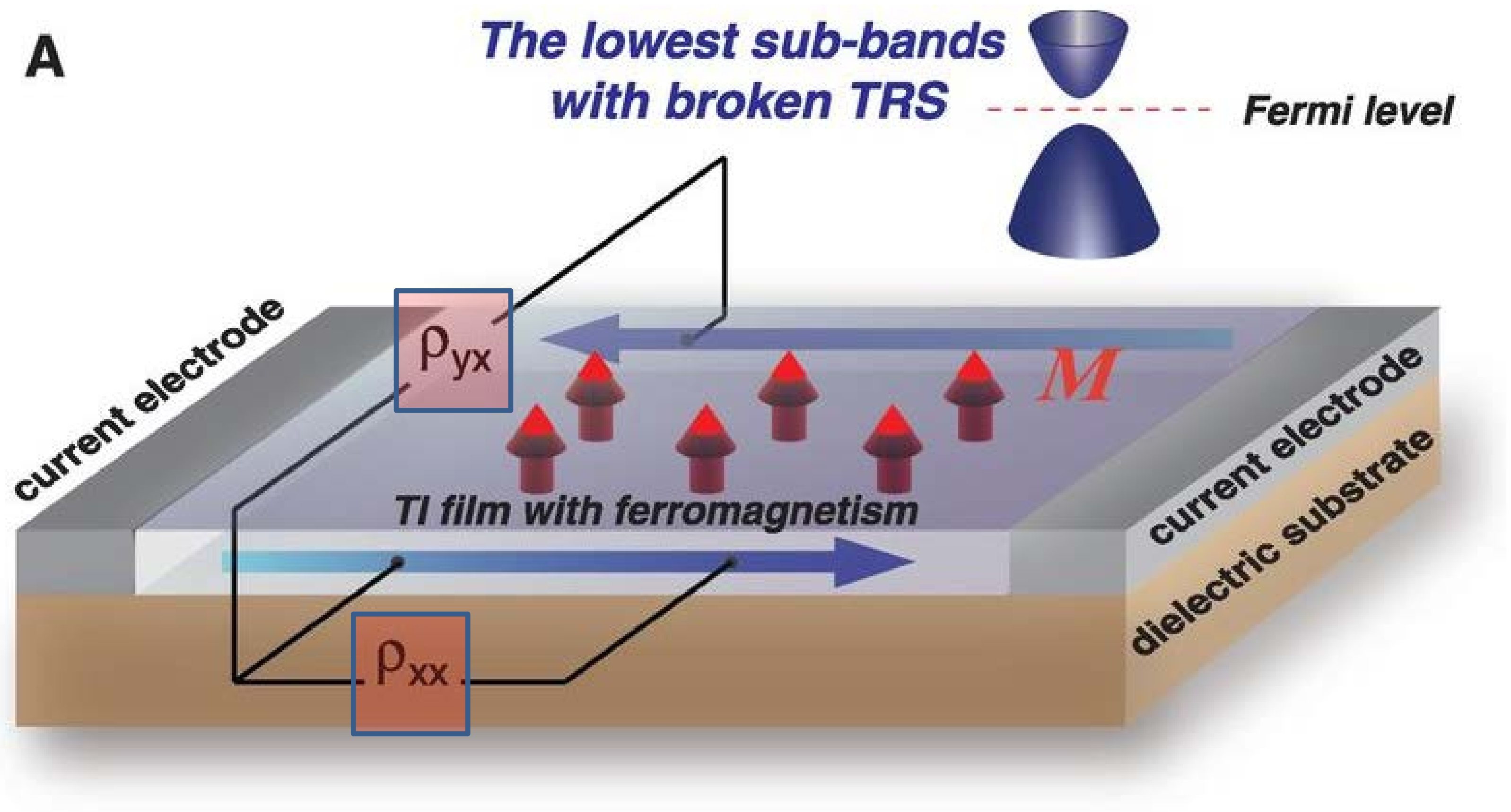
Quantum Hall resistance standard based on graphene grown by chemical vapor deposition on silicon carbide

F. Lafont[1], R. Ribeiro-Palau[1], D. Kazazis[2], A. Michon[3], O. Couturaud[4], C. Consejo[4], T. Chassagne[5], M. Zielinski[5], M. Portail[3], B. Jouault[4], F. Schopfer[1] and W. Poirier[1*]

FIG. 1. a) Hall resistance deviation $\overline{\Delta R_H/R_H}$ *versus* magnetic field B. b) Longitudinal (R_{xx}) and transversal (R_H) resistances (measured with a 100 nA current) as a function of B varying from 0 T to 19 T for the graphene sample (blue curve) and varying from 8 T to 13 T for the GaAs sample (green curve). ν_{n0} is the Landau level filling factor calculated from the carrier density n_0 determined at low magnetic fields. c) Longitudinal resistance $\overline{R_{xx}}$ *versus* B. Error bars correspond to one standard deviation (1σ).

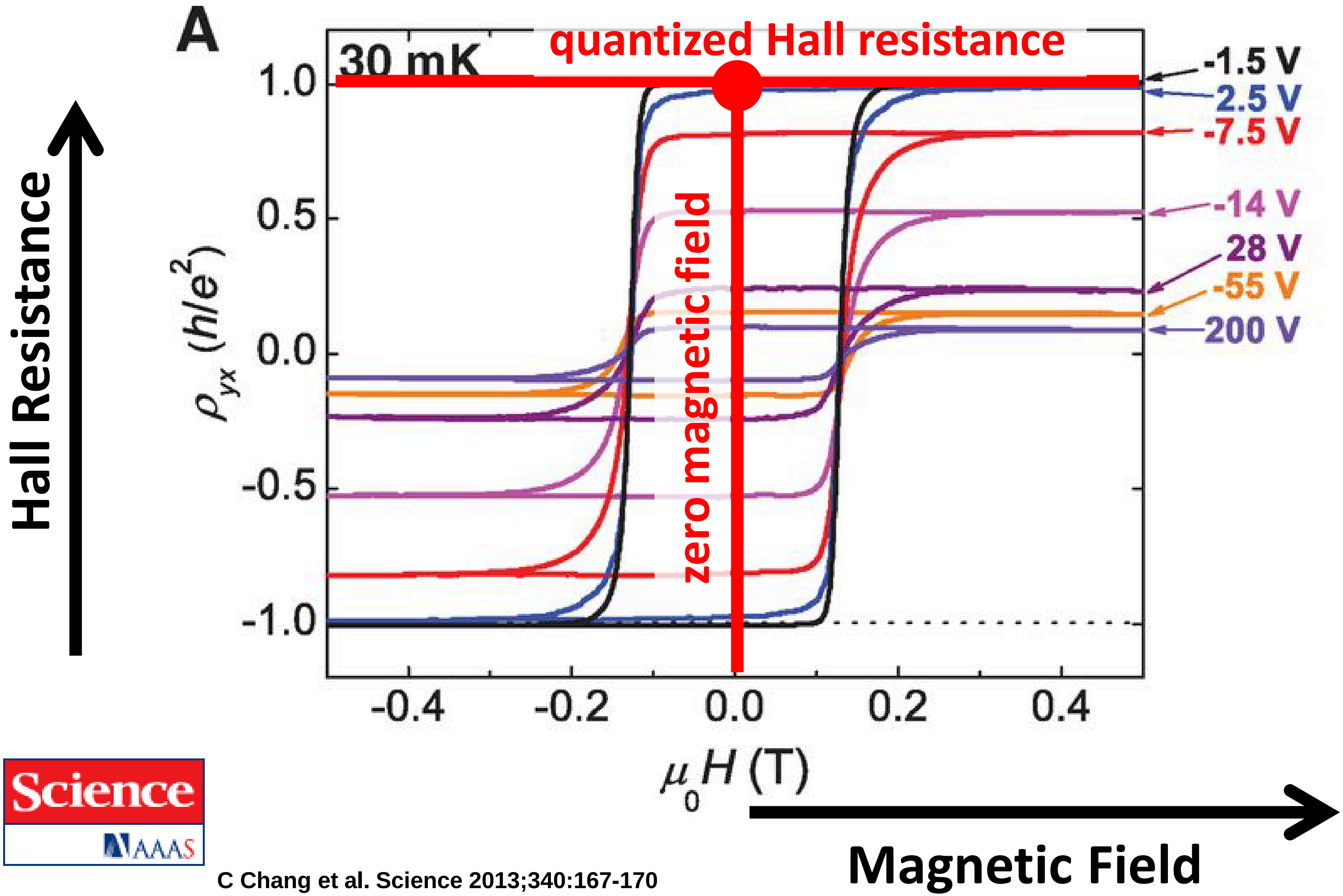
Hall voltage >250 mV

QAH (2013): Quantum Hall Effect without Magnetic Field



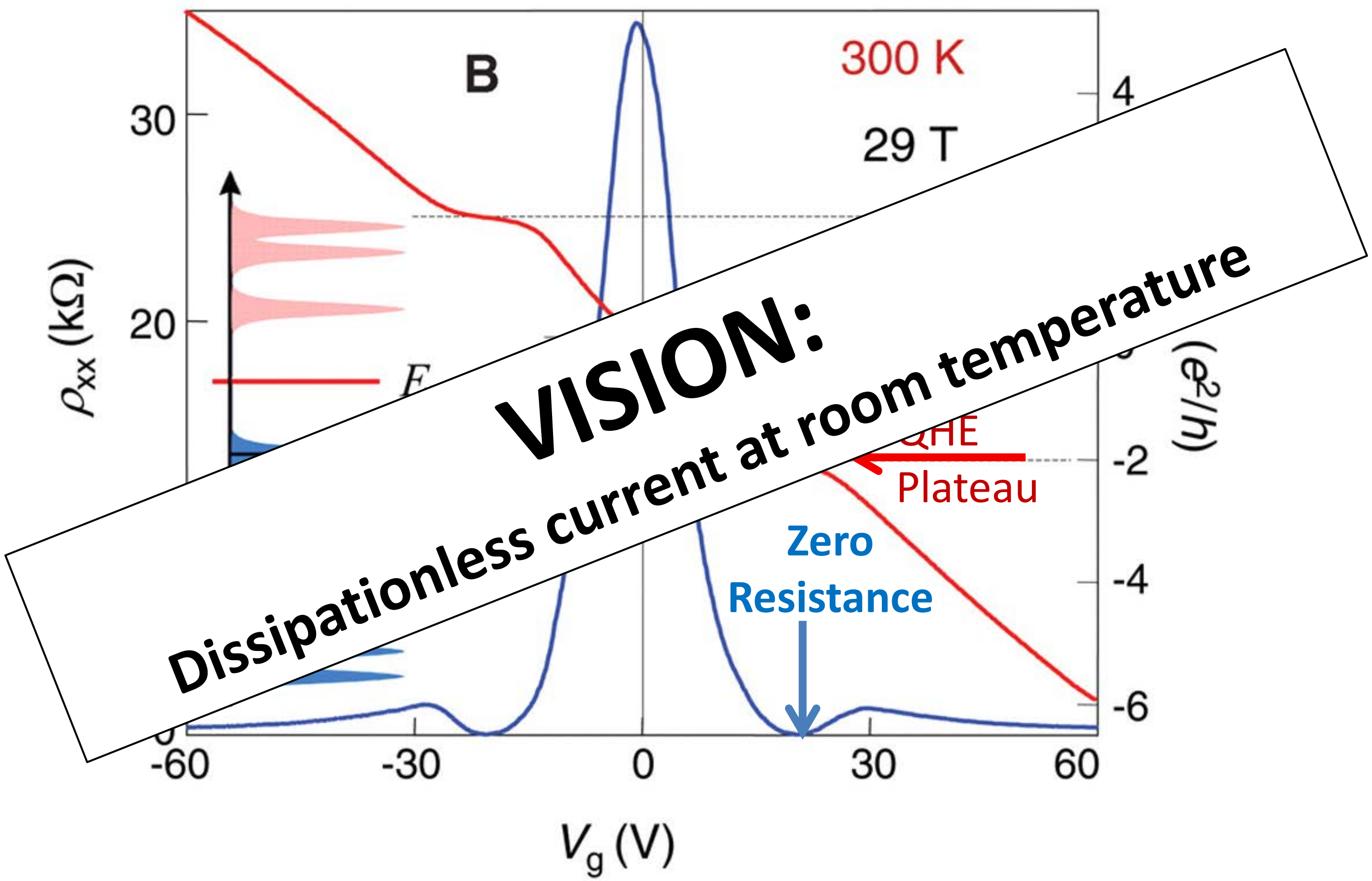
C Chang et al. Science 2013;340:167-170

The QAH Effect Measured at 30 mK.



C Chang et al. Science 2013;340:167-170

Room-temperature QHE in Graphene.



K S Novoselov et al. Science 2007;315:1379

Published by AAAS

Fundamental Constants

Quantity	Symbol	Numerical value	Unit
electron mass	m_e	$9.109\,382\,91(40) \times 10^{-31}$	kg
proton mass	m_p	$1.672\,621\,777(74) \times 10^{-27}$	kg
proton-electron mass ratio	m_p/m_e	$1836.152\,672\,45(75)$	
Avogadro constant	N_A, L	$6.022\,141\,29(27) \times 10^{23}$	mol^{-1}
Faraday constant $N_A e$	F	$96\,485.3365(21)$	$C\ mol^{-1}$
molar gas constant	R	$8.314\,4621(75)$	$J\ mol^{-1}\ K^{-1}$
Boltzmann constant R/N_A	k	$1.380\,6488(13) \times 10^{-23}$	$J\ K^{-1}$
Stefan-Boltzmann const. $\pi^2 k^4/60\hbar^3 c^2$	σ	$5.670\,373(21) \times 10^{-8}$	$W\ m^{-2}\ K^{-4}$
magnetic flux quantum $h/2e$	Φ_0	$2.067\,833\,758(46) \times 10^{-15}$	Wb
Josephson constant $2e/h$	K_J	$483\,597.870(11) \times 10^{9}$	$Hz\ V^{-1}$
von Klitzing constant h/e^2	R_K	$25\,812.807\,4434(84)$	Ω
electron volt (e/C) J	eV	$1.602\,176\,565(35) \times 10^{-19}$	J
(unified) atomic mass unit $\frac{1}{12}m(^{12}C)$	u	$1.660\,538\,921(73) \times 10^{-27}$	kg

A more extensive listing of constants is available in the references given above and on the NIST Physical Measurement Laboratory Web site: physics.nist.gov/constants.

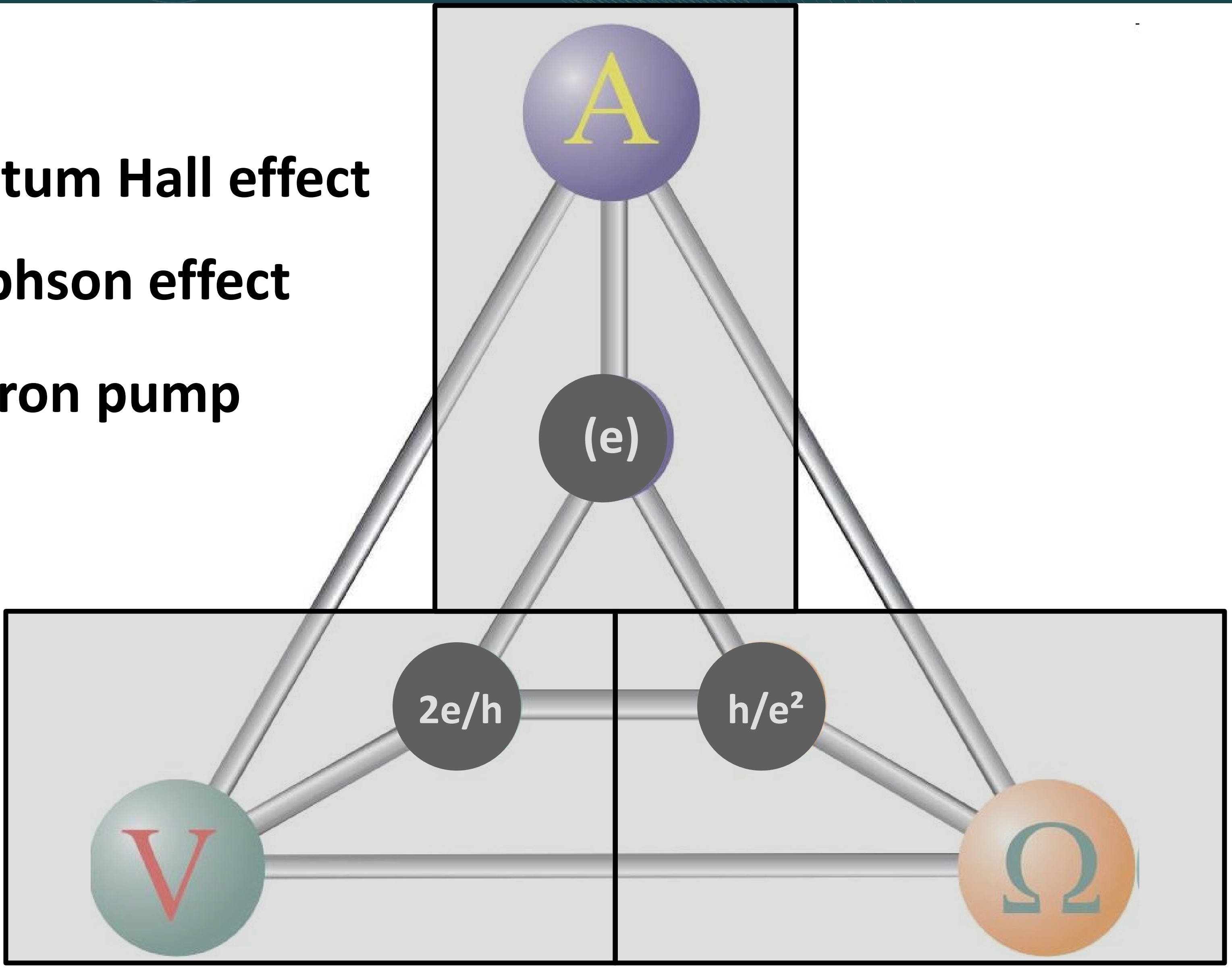
NIST
National Institute of Standards and Technology
U.S. Department of Commerce

Consistency Check by "Ohms Law"

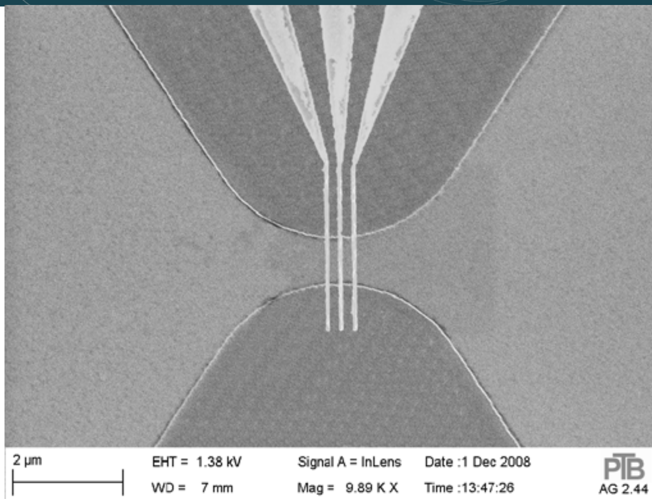
quantum Hall effect

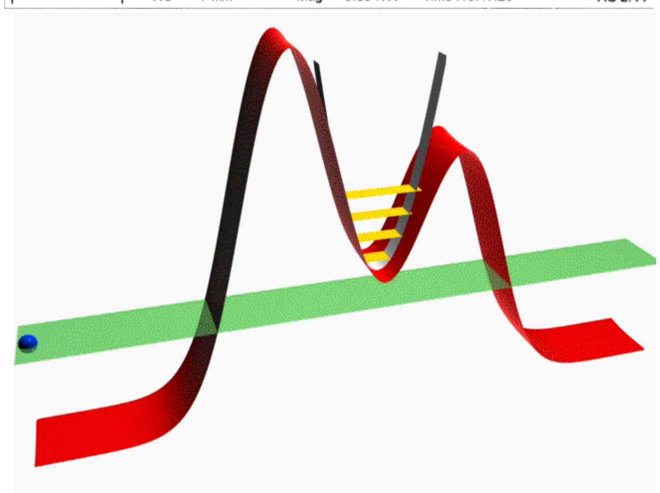
Josephson effect

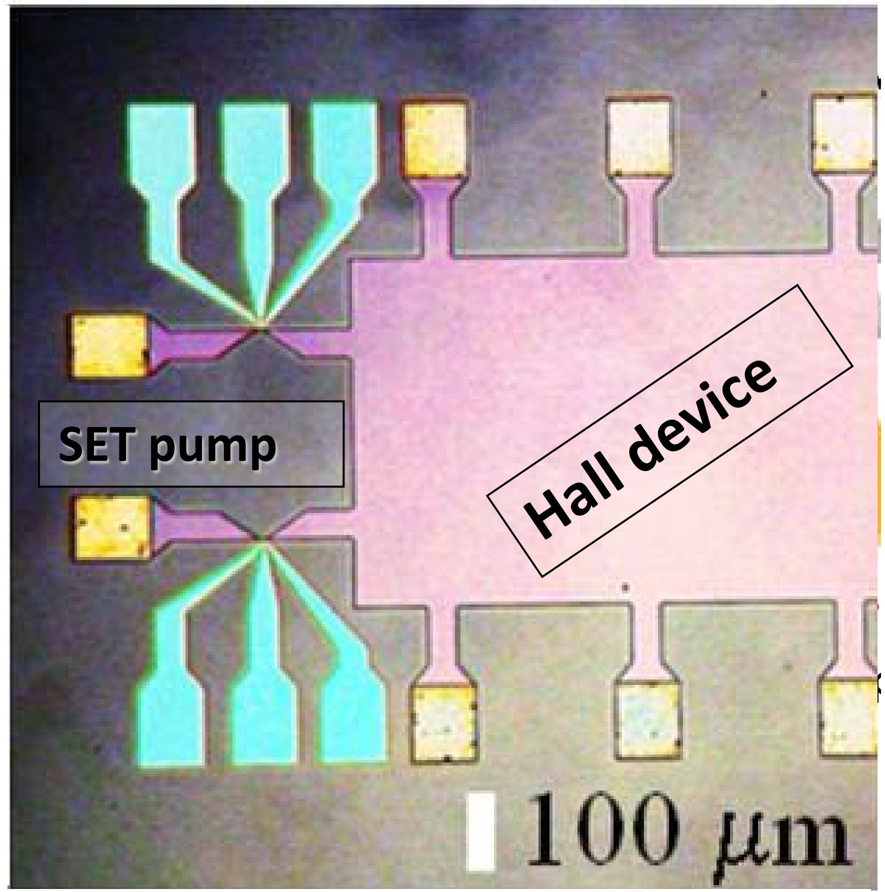
electron pump



Semiconductor Quantized Voltage Source





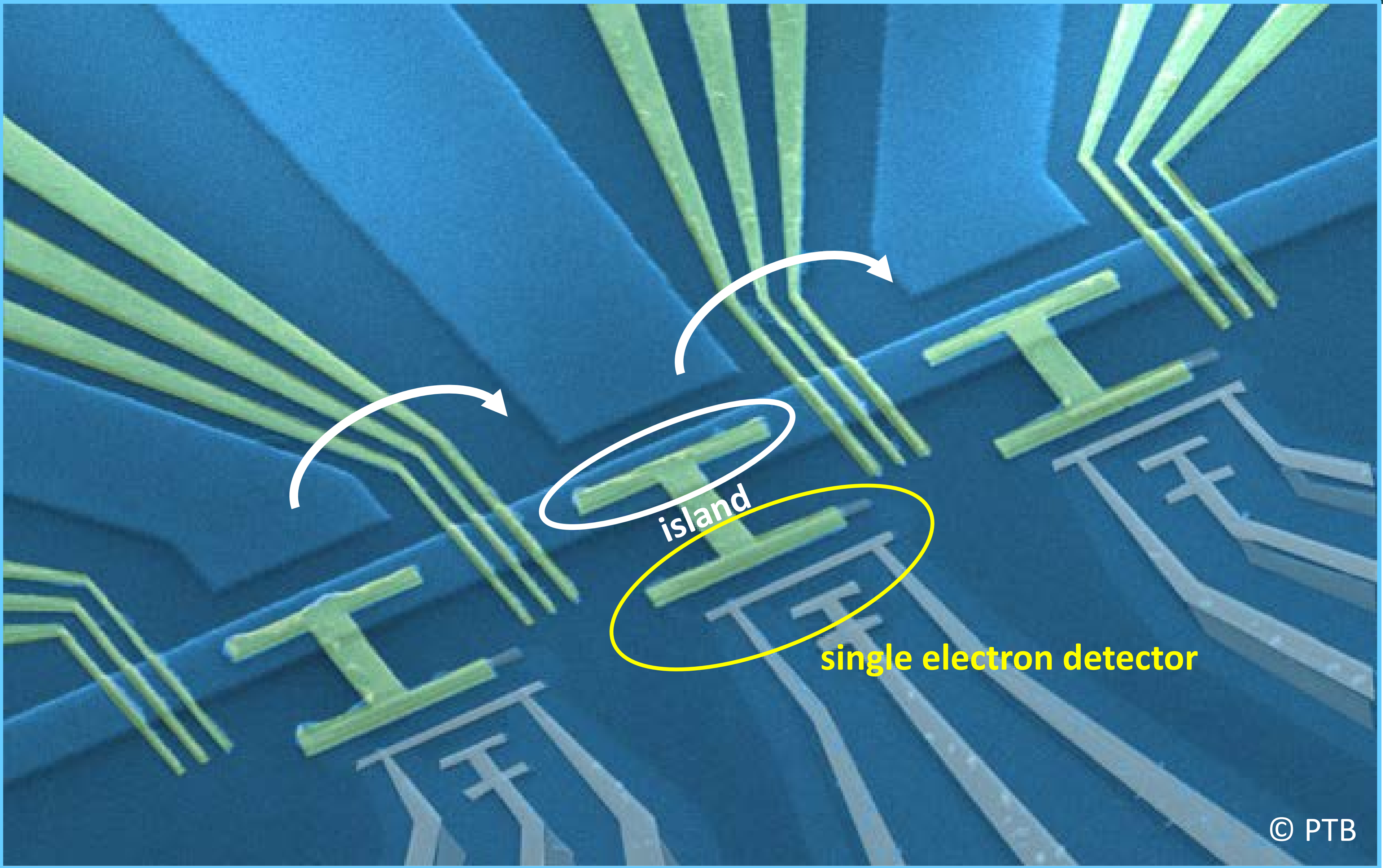


An "integrated quantized circuit" (IQC)

Frank Hohls et al.,Phys. Rev. Lett. 109, 056802

Metrological triangle confirmed up to uncertainty level of ≈1 ppm

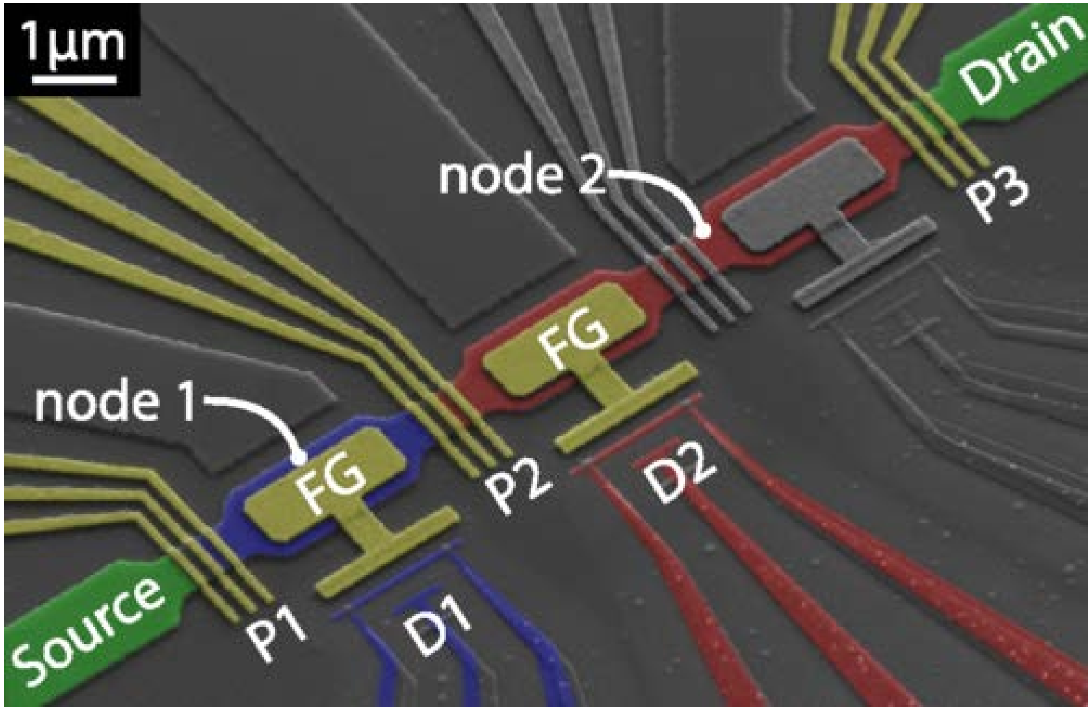
Error Correction (Electron Pumps in Series)

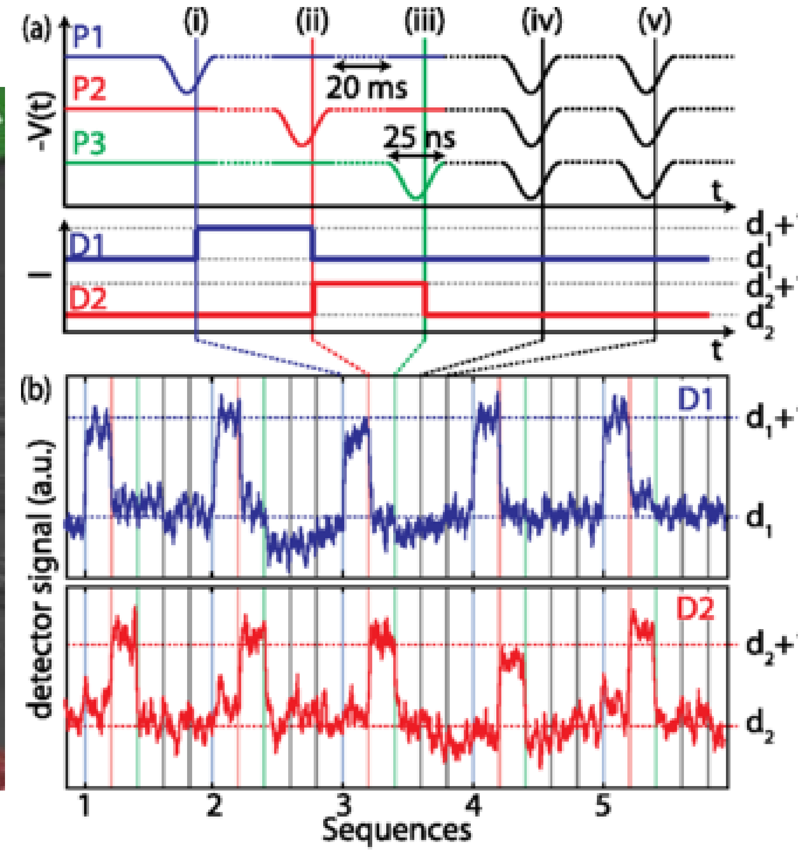


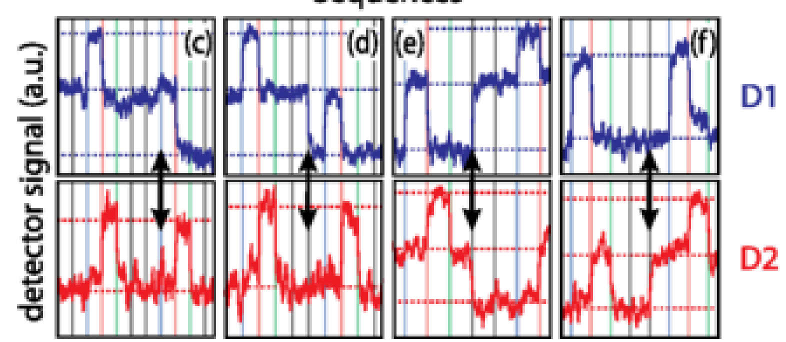
Self-Referenced Single-Electron Quantized Current Source

Lukas Fricke, Michael Wulf, Bernd Kaestner, Frank Hohls, Philipp Mirovsky, Brigitte Mackrodt, Ralf Dolata, Thomas Weimann, Klaus Pierz, Uwe Siegner, and Hans W. Schumacher

Phys. Rev. Lett. 112, 226803 (2014)







jumps in the detector signal ≙ 1 electron

For practical applications:

Josephson voltage and quantized Hall resistance are fixed by the fundamental constants *h* and *e*.

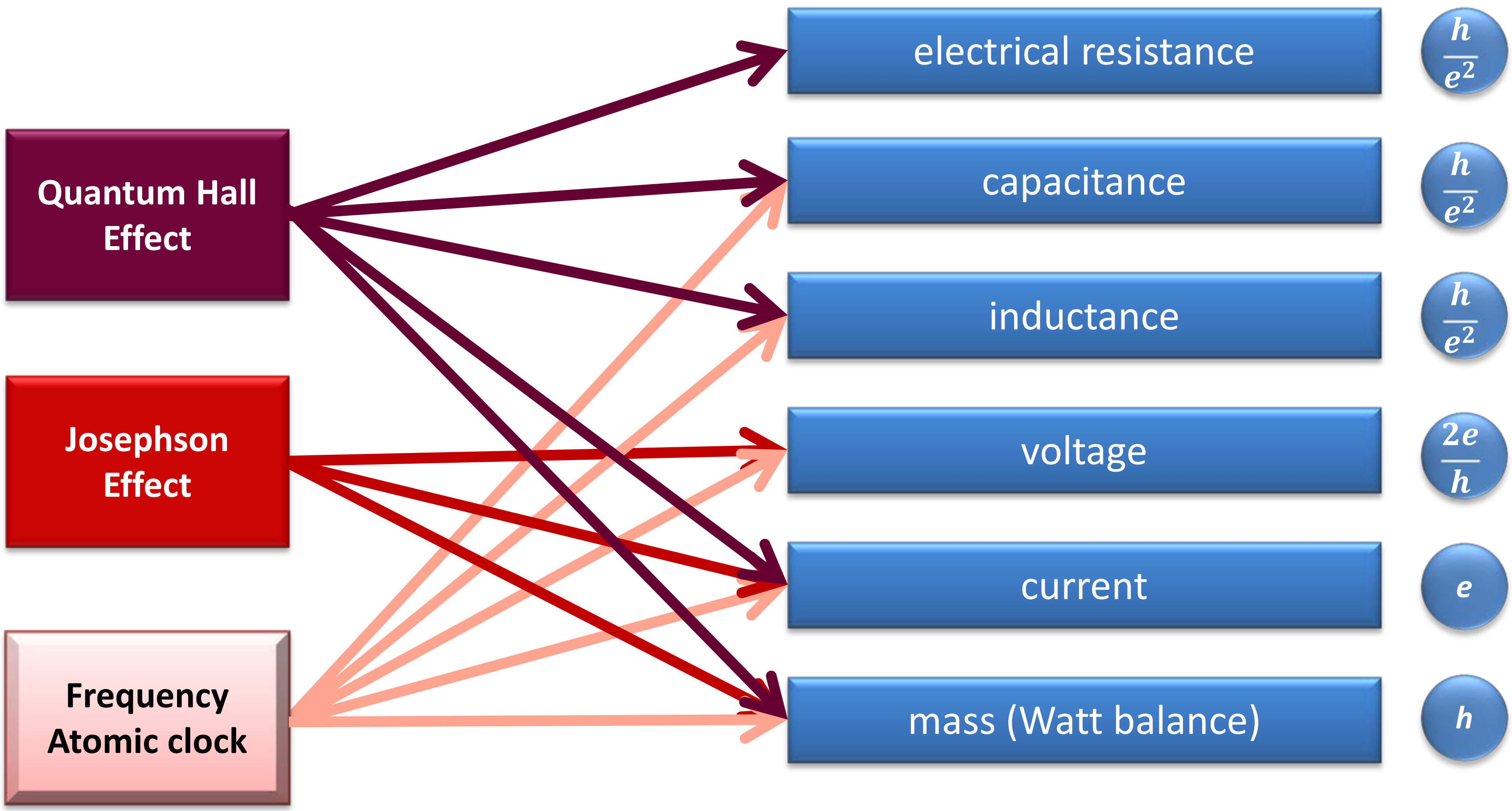
Josephson effect: Voltage $U \leftrightarrow e/h$

Quantum Hall effect: Resistance $R \leftrightarrow h/e^2$

All electrical quantities can be measured
(with high precision!)
in units of h and e

Electrical Quantum Standards Formed the Basis for the New SI

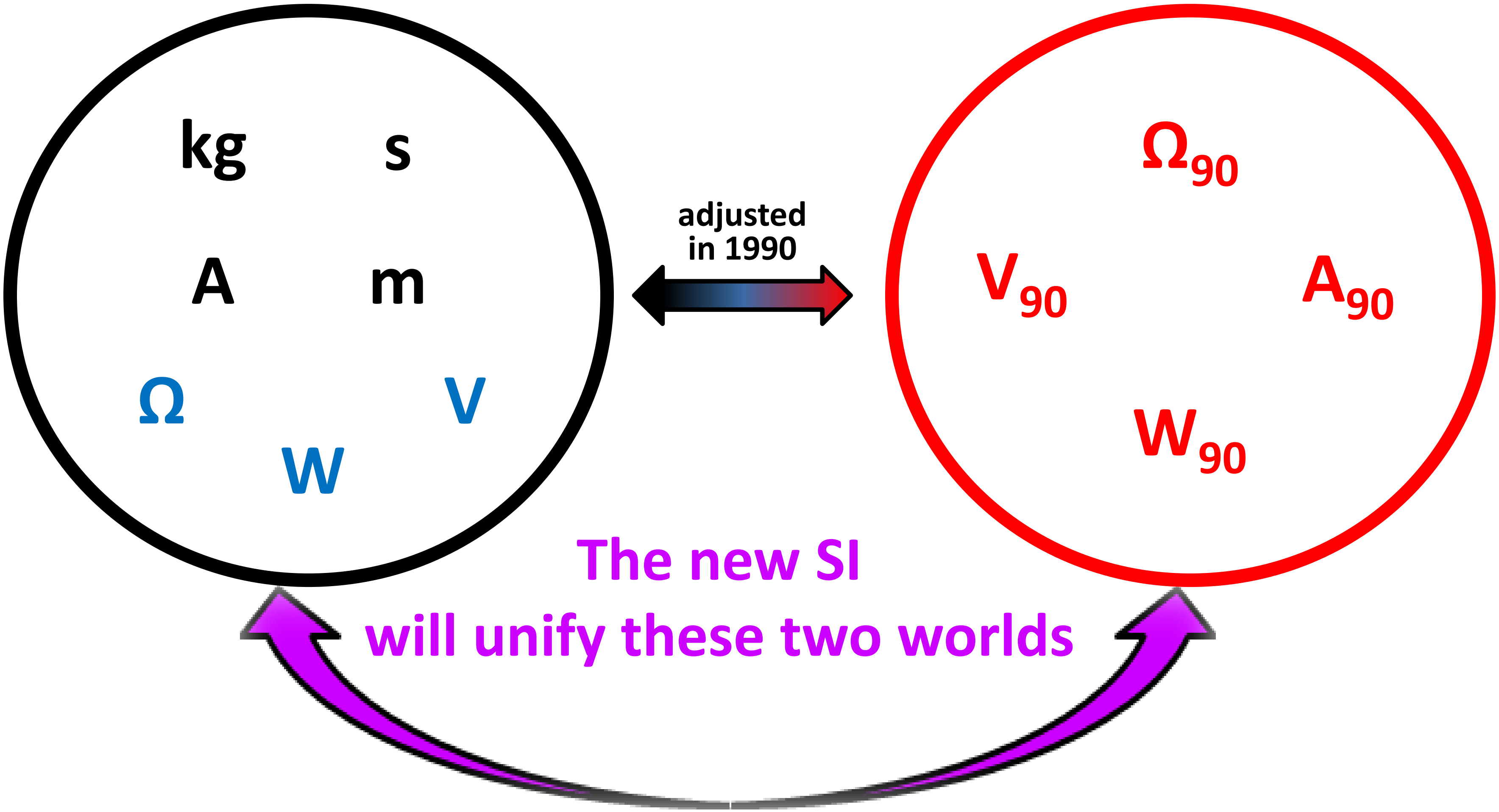
units based on fundamental constants *h* and *e* and on frequency (atomic clock)



Quantum-Units: A Parallel World in our SI System

SI Units
(base and derived)

Quantum Units
(conventional units outside the official SI units)



Metrologia 42 (2005) 431–441 doi:10.1088/0026-1394/42/5/014

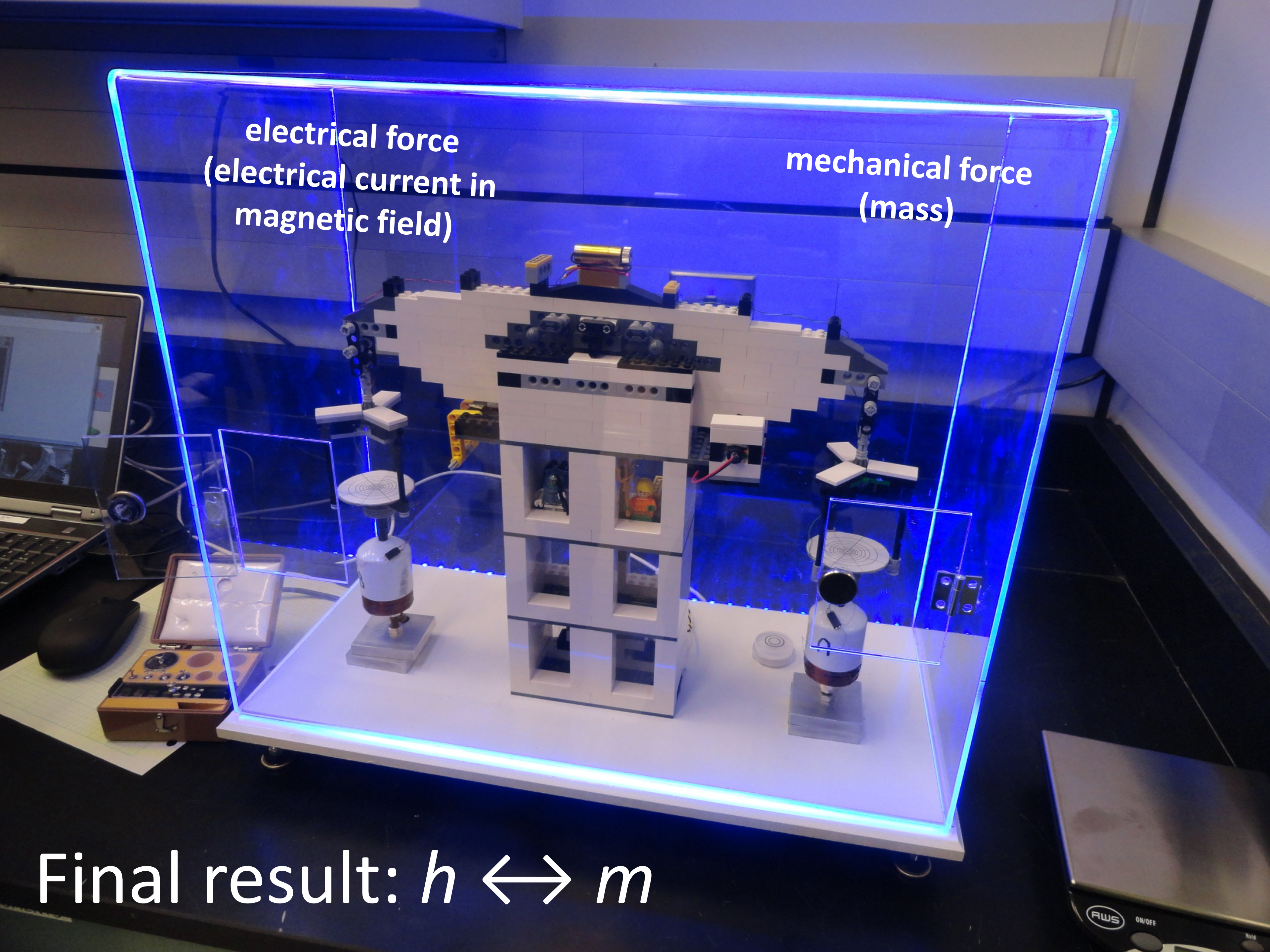
Towards an electronic kilogram: an improved measurement of the Planck constant and electron mass

Richard L Steiner, Edwin R Williams, David B Newell and Ruimin Liu

National Institute of Standards and Technology (NIST), 100 Bureau Dr Stop 8171, Gaithersburg, MD 20899-8171, USA

Abstract

The electronic kilogram project of NIST has improved the watt balance method to obtain a new determination of the Planck constant h by measuring the ratio of the SI unit of power W to the electrical realization unit W_{90}, based on the conventional values for the Josephson constant $K_{J\text{-}90}$ and von Klitzing constant $R_{K\text{-}90}$. The value $h = 6.626\,069\,01(34) \times 10^{-34}$ J s verifies the NIST result from 1998 with a lower combined relative standard uncertainty of 52 nW/W. A value for the electron mass $m_e = 9.109\,382\,14(47) \times 10^{-31}$ kg can also be obtained from this result.



Final result: $h \leftrightarrow m$

A LEGO Watt Balance:
An apparatus to demonstrate the definition of mass based on the new SI

L.S. Chao, S. Schlamminger, D.B. Newell, and J.R. Pratt
Physical Measurement Laboratory, National Institute of Standards and Technology, Gaithersburg, MD 20899

G. Sineriz, F. Seifert, A. Cao, and D. Haddad
Joint Quantum Institute, University of Maryland, College Park, MD 20742

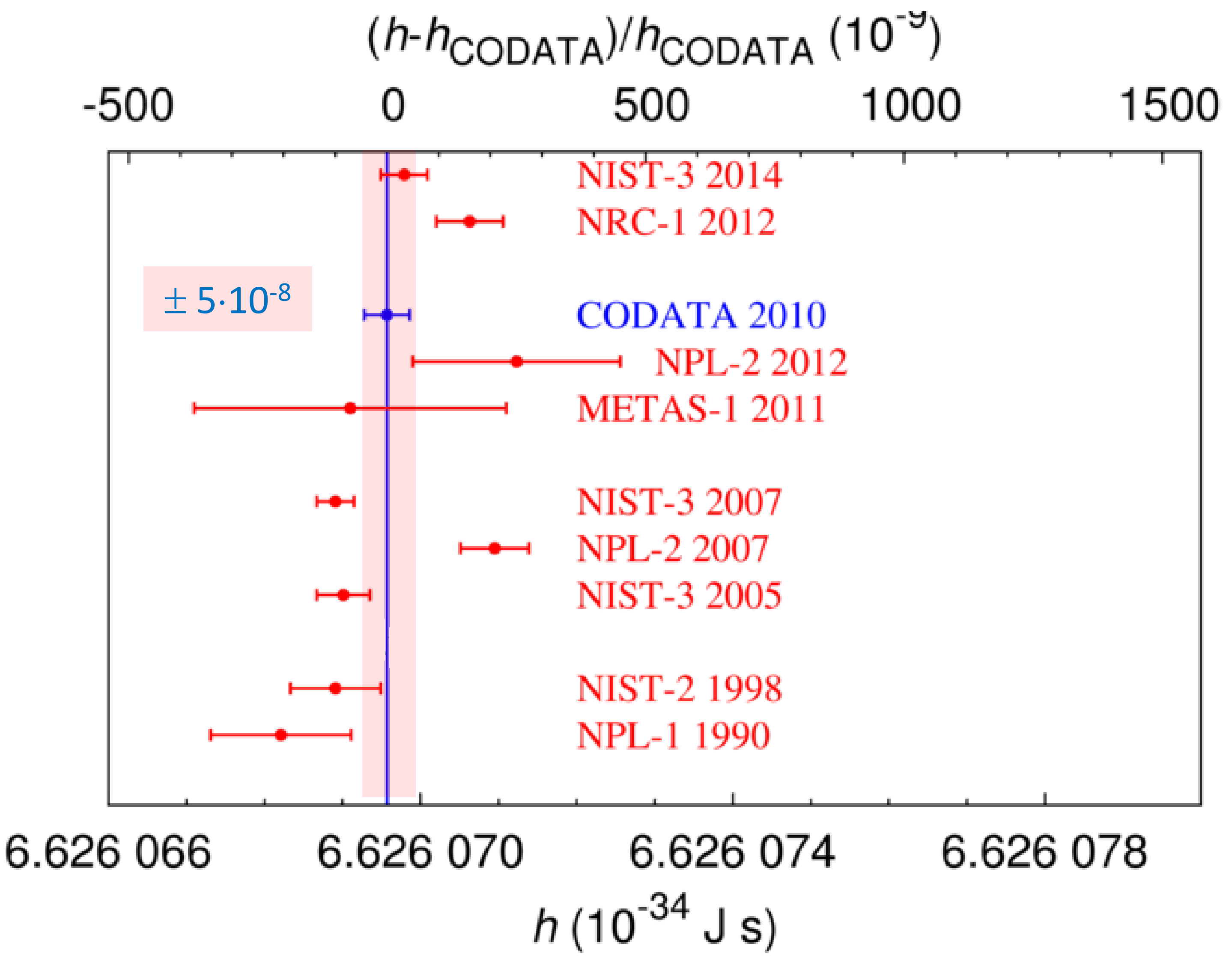
X. Zhang
Computational Instrumentation Lab, Massachusetts Institute of Technology, Cambridge, MA 02139
(Dated: December 15, 2014)

A global effort to redefine our International System of Units (SI) is underway and the change to the new system is expected to occur in 2018. Within the newly redefined SI, the present base units will still exist but be derived from fixed numerical values of seven reference constants. More specifically, the unit of mass, the kilogram, will be realized through a fixed value of the Planck constant h. For instance, a watt balance can be used to realize the kilogram unit of mass within a few parts in 10^8. Such a balance has been designed and constructed at the National Institute of Standards and Technology. For educational outreach and to demonstrate the principle, we have constructed a LEGO tabletop watt balance capable of measuring a gram size mass to 1 % relative uncertainty. This article presents the design, construction, and performance of the LEGO watt balance and its ability to determine h.

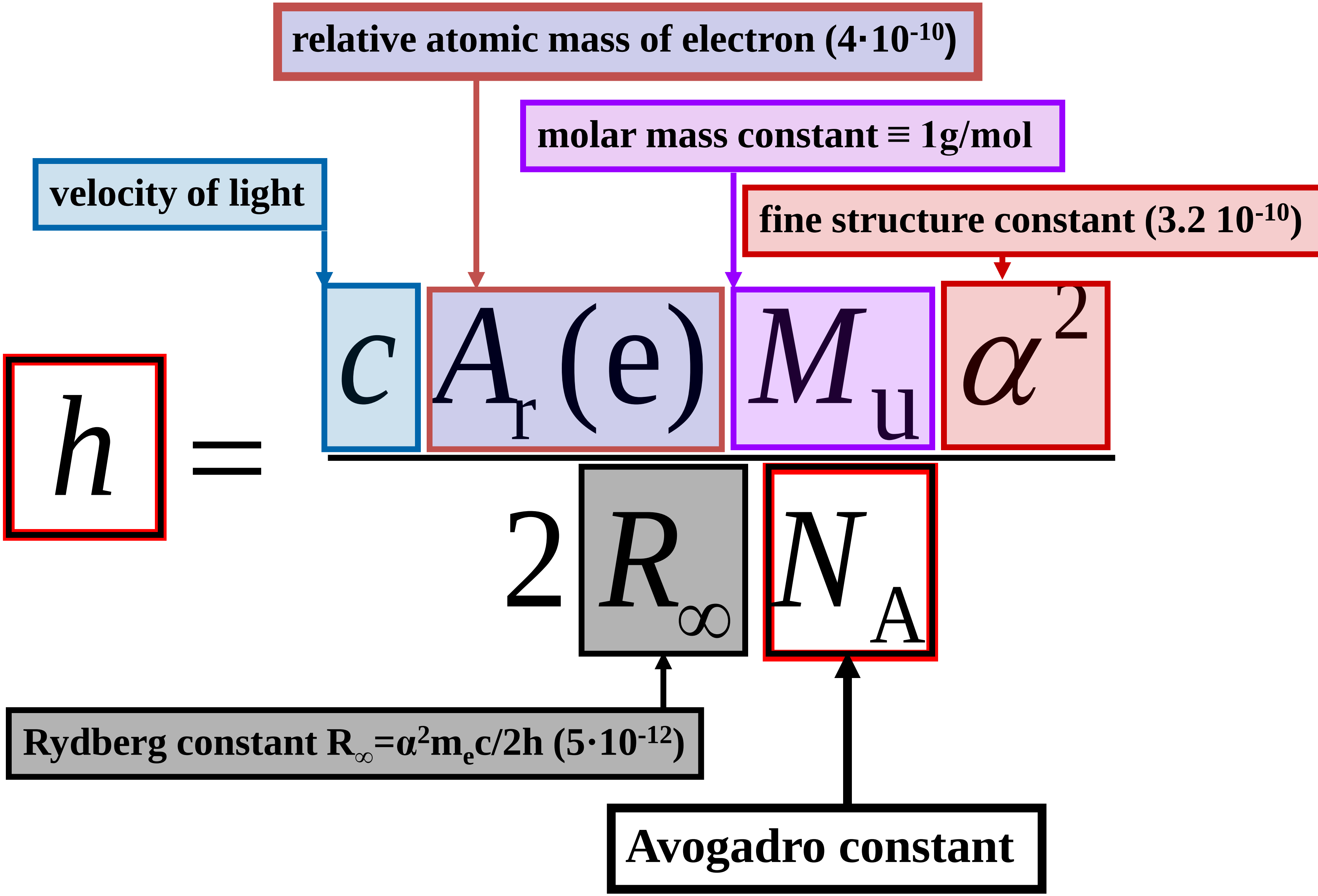
MASS m → PLANCK CONSTANT h

In the future (new SI):
PLANCK CONSTANT h → MASS m

Summary of Planck Constant Measurements



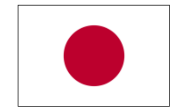
Watt balance data



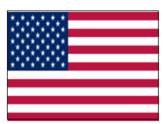
$h \cdot N_A$ = 3.9903126821(57) x 10^{-10} Js/mol, with relative uncertainty of 1.4×10^{-9}

IAC (International Avogadro Coordination)



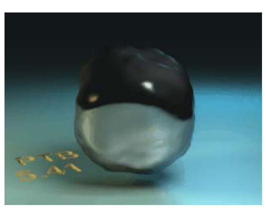
$$N_A = \frac{M_{Si} \cdot V_{sphere}}{\sqrt{8} \cdot d_{220}^3 \cdot m_{sphere}}$$

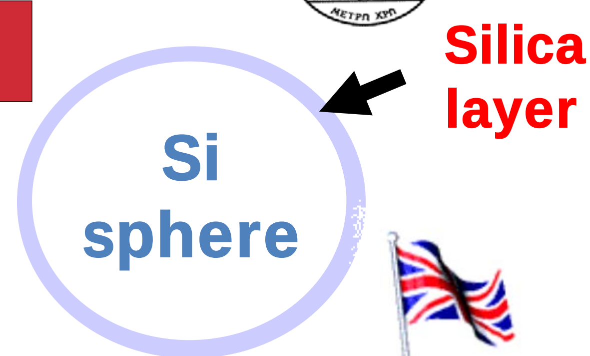



2003

^{28}Si for

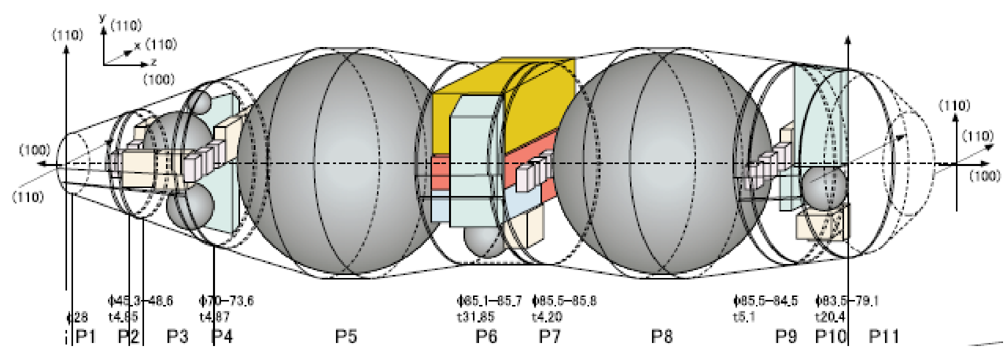
***M* improvement**





^{28}Si: 99,9957%

$$N_A = \frac{M_{Si} \cdot V_{Kugel}}{\sqrt{8} \cdot d_{220}^3 \cdot m_{Kugel}}$$

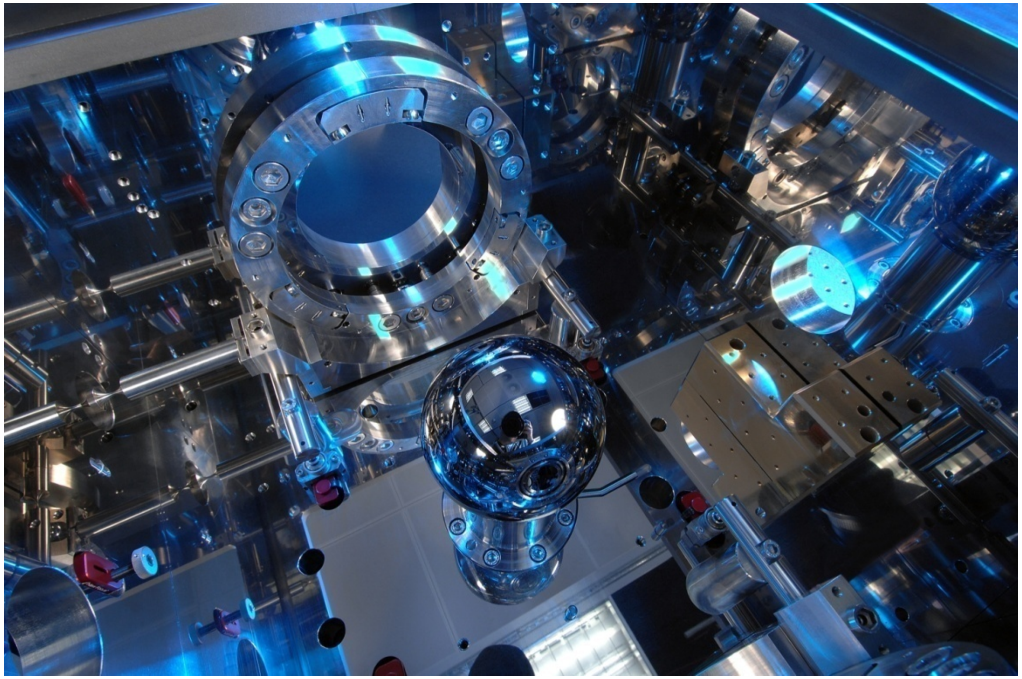


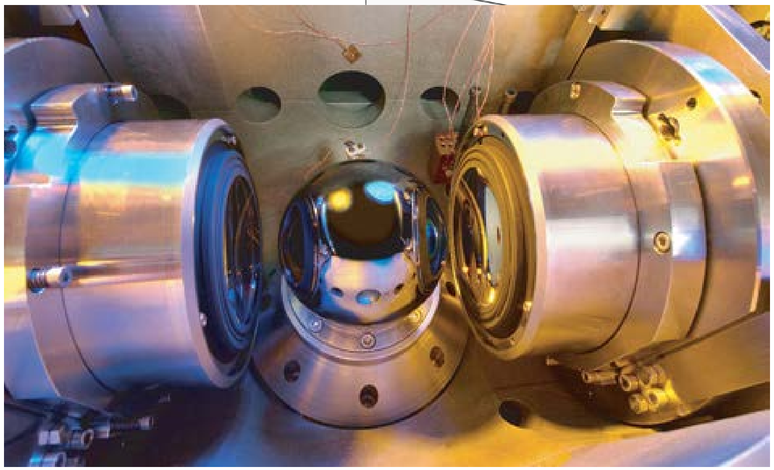
IAC

2007/2008

$$N_A = \frac{M_{Si} \cdot V_{Kugel}}{\sqrt{8} \cdot d_{220}^3 \cdot m_{Kugel}}$$

Volume: interferometer for spheres

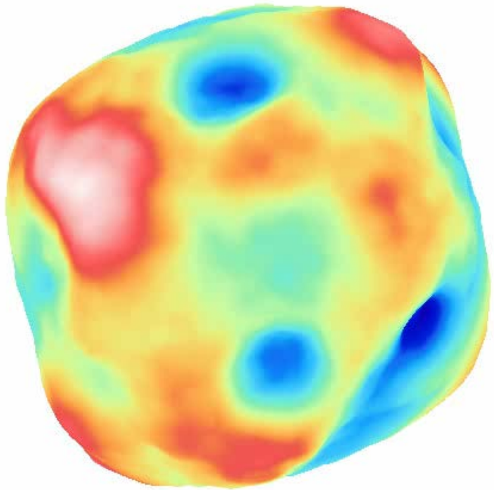




PTB‘s sphere interferometer with spherical symmetry

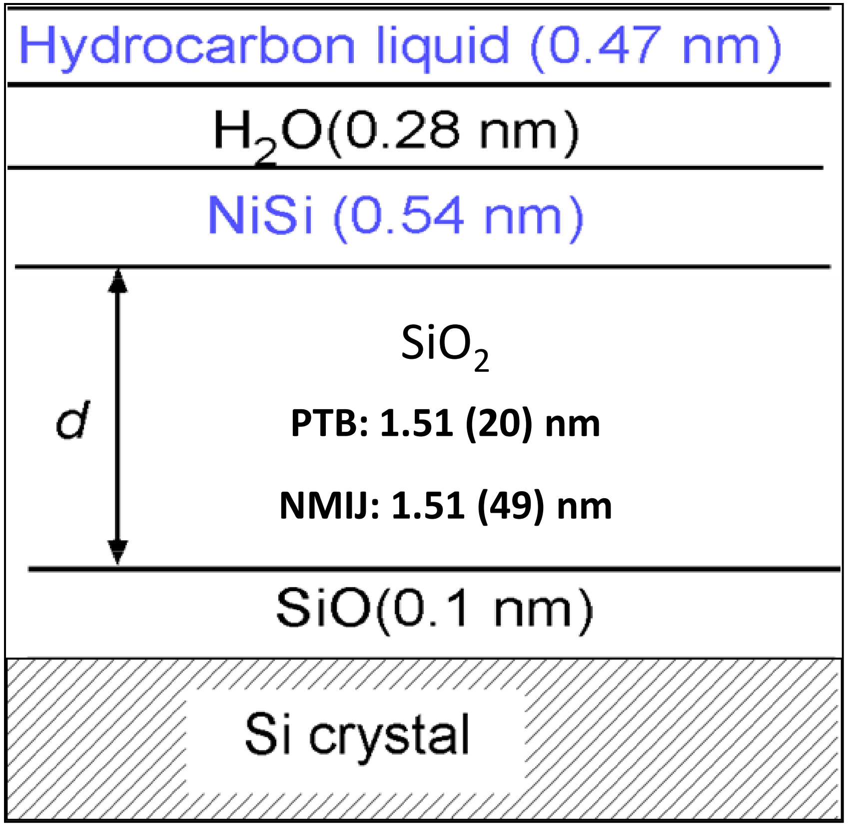
PTB‘s sphere interferometer enables complete topographies of spheres, $n_{diameter} \approx 600\ 000$.

The radius uncertainty is 0.8 nm



Radius topography of ^{28}Si-sphere S8. Peak to valley deviations from roundness amount to **99 nm**.

Surface layer characterization for sphere AVO28-8



d_{SL} (nm)
2.72(33)

m_{SL} (μg)
215(16)

Uncertainty budget

Quantity	Relative uncertainty 10^{-9}	Contribution %
Molar mass	8	7
Sphere mass	5	3
Surface	16	27
Sphere volume	22	51
Lattice parameter	10	10
Point defects	4	2

Avogadro project and Watt balances
allow high precision measurements of Planck Constant *h*

Watt balances has been built up in many countries and seems to be the best way to realize the unit of mass on the basis of a fixed value for the Planck constant

QUANTUM HALL EFFECT WILL PLAY AN IMPORTANT ROLE IN OUR NEW INTERNATIONAL SYSTEM OF UNITS


Gewichtiges Vorhaben: Das Kilogramm soll neu definiert werden, denn das Urkilogramm ist unpraktisch, und es verändert sich sogar. An der Physikalisch-Technischen Bundesanstalt in Braunschweig soll eine präzise vermessene, hochreine Siliziumkugel benutzt werden, um das Kilogramm auf eine Naturkonstante zu gründen: das Plancksche Wirkungsquantum. Peter Becker hat dieses Projekt 30 Jahre lang geleitet. Inzwischen ist er im Ruhestand. In der rechten Hand hält er eine Kopie des Urkilos, in der linken eine Siliziumkugel.
kilogram
prototype
silicon sphere
Avogadro project

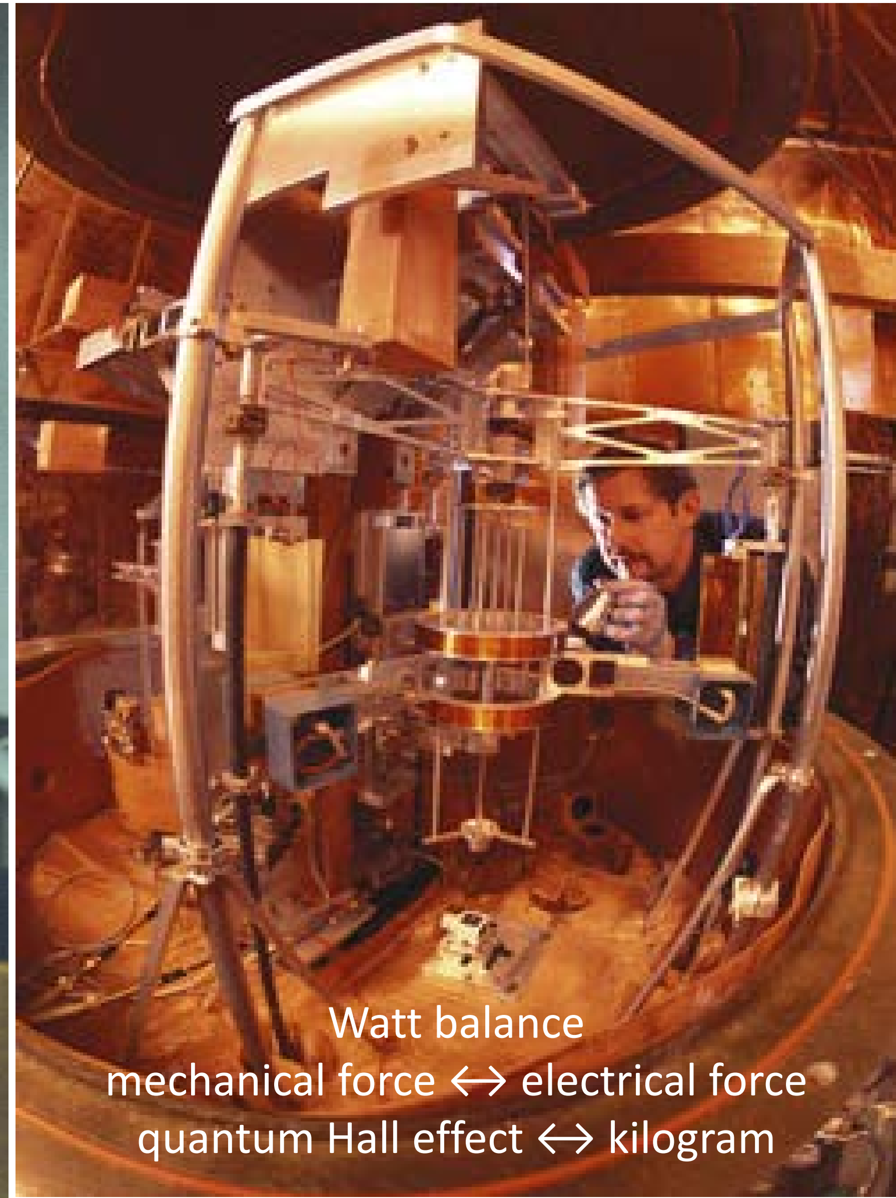
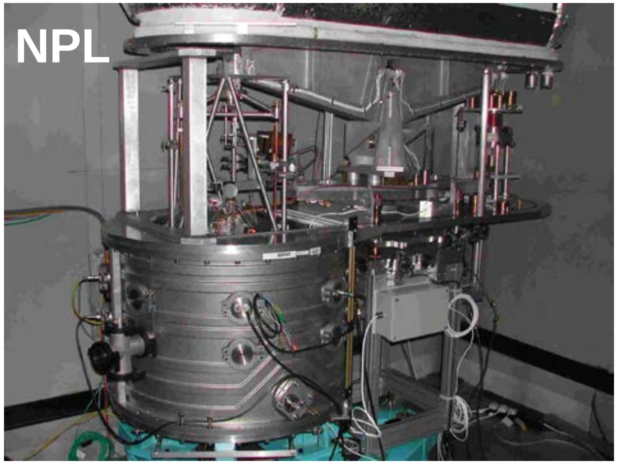
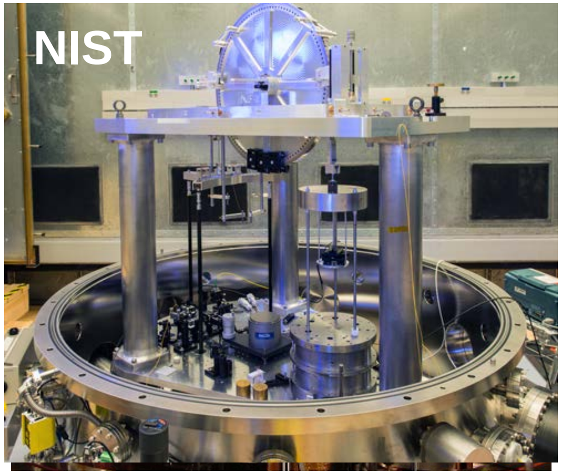
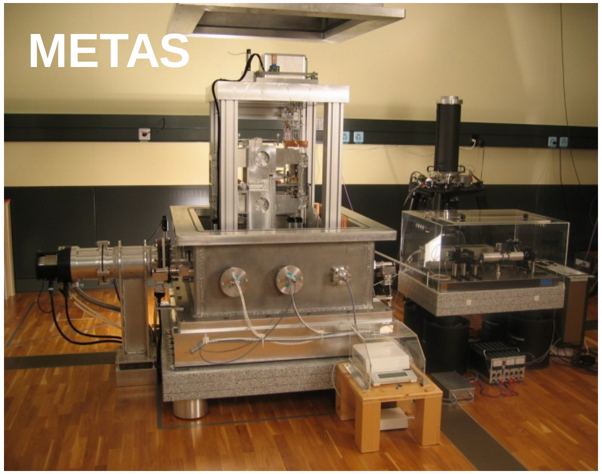
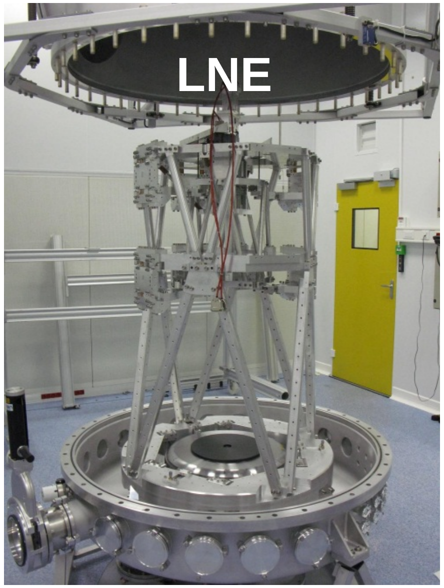

Watt balance
mechanical force ↔ electrical force
quantum Hall effect ↔ kilogram

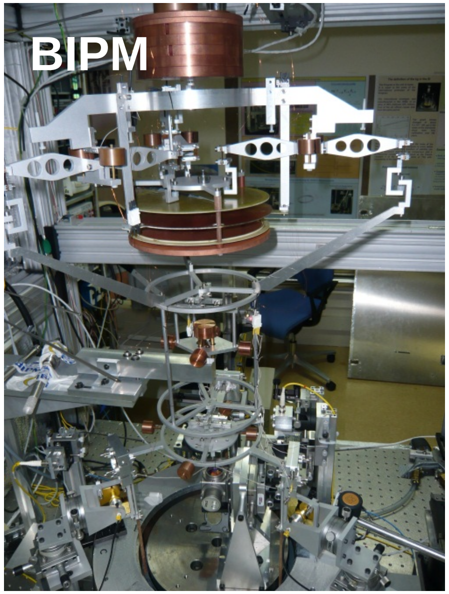
Photo Gallery of all Watt Balances

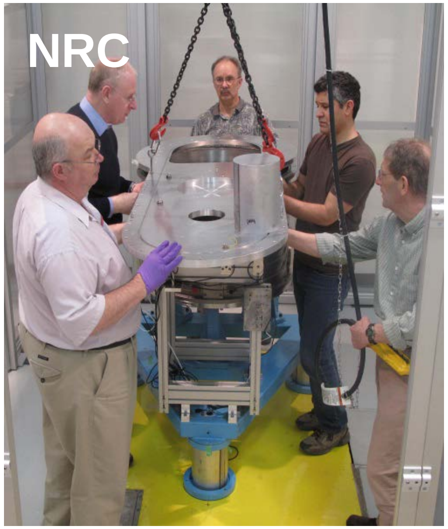








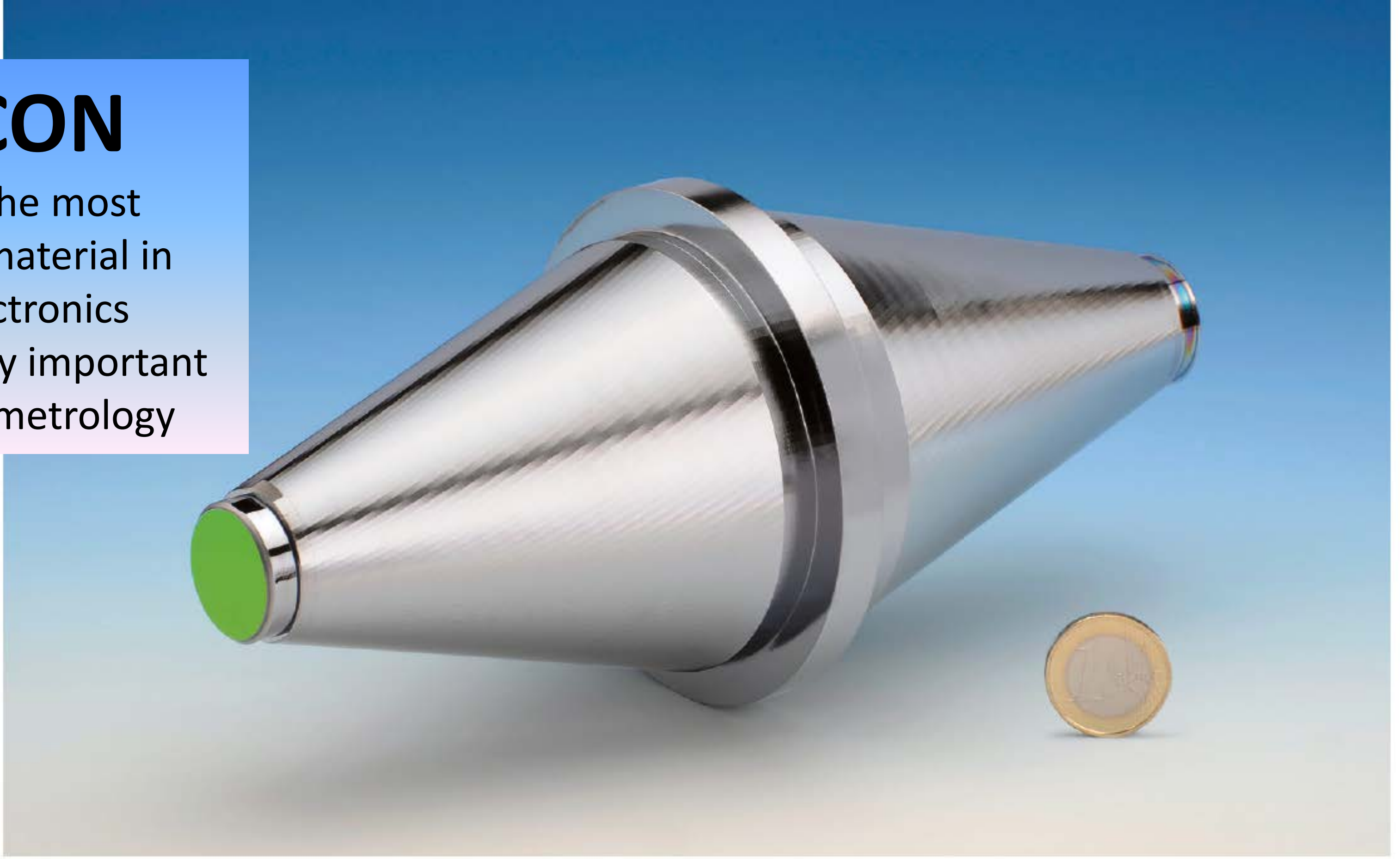




Basic research on a silicon MOSFET opened the possibility of a new system of units based on fundamental constants

SILICON

not only the most important material in microelectronics
but also a very important material in metrology



The size of the new silicon resonator compared to the size of a coin

The most stable laser in the world

Silicon resonator with length stability unachieved so far – for improved optical atomic clocks

Thank you for your attention!