Back to Basics:

The International System of Units (SI) and NIST's Role as the National Measurement Institute

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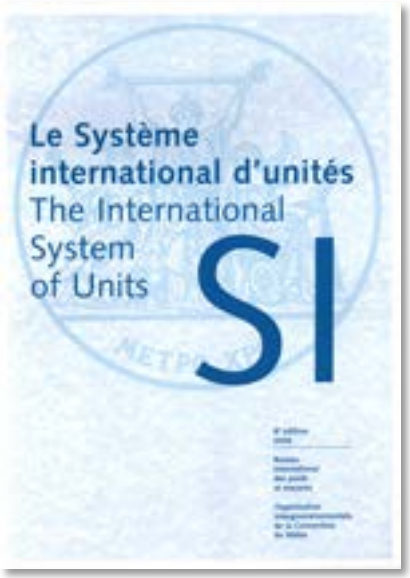
Bottom Line Up-Front:

The International System of Units (abbreviated SI from the French: Système international d'unités) is the modern version of "The Metric System,"

…but it's only partially like the original "Metric System."

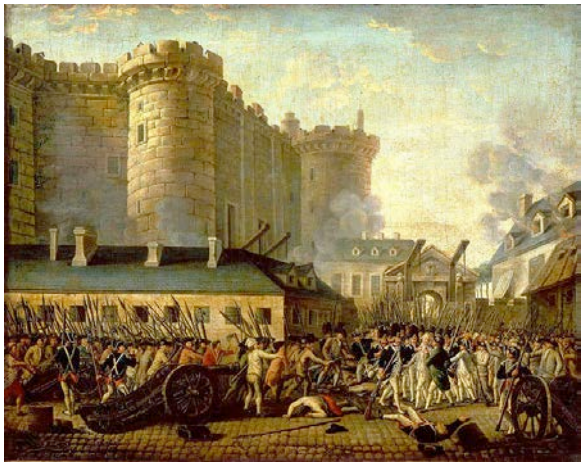
How did the "Metric System" start? And how did it evolve?



SI, as defined by the General Conference on Weights and Measures (CGPM)

The Metric System was Born in the Spirit of The French Revolution in the 1790s

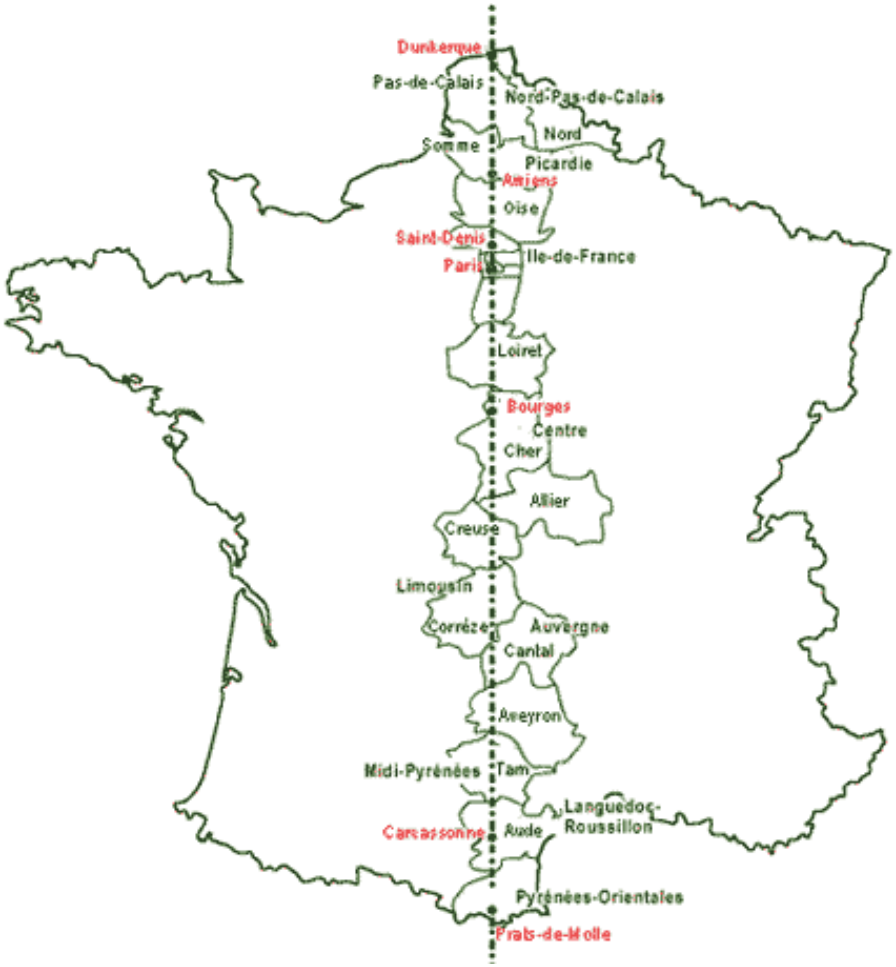
- Measurement systems based on monarchy and aristocracy to be replaced by one based on equality and natural law
  - Meter: 1/10,000,000 of Earth's meridian (North Pole to Equator)
  - Kilogram: weight of 1/1000 cubic meter of pure water
- Nationalistic systems to be replaced by internationally accepted one



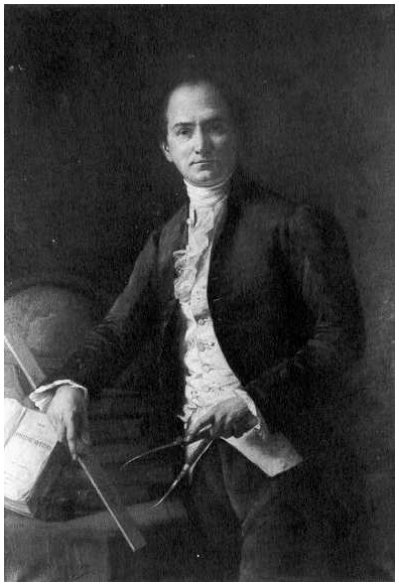
Storming of the Bastille
July 14, 1789

Both of these principles remain in the heart and soul of SI today.

Definition vs. Realization
Survey of the Earth, 1792–1799



Survey of the Meridian, Dunkirk to Barcelona



Jean-Baptiste Delambre
(1749–1822)

Pierre Méchain
(1744–1804)

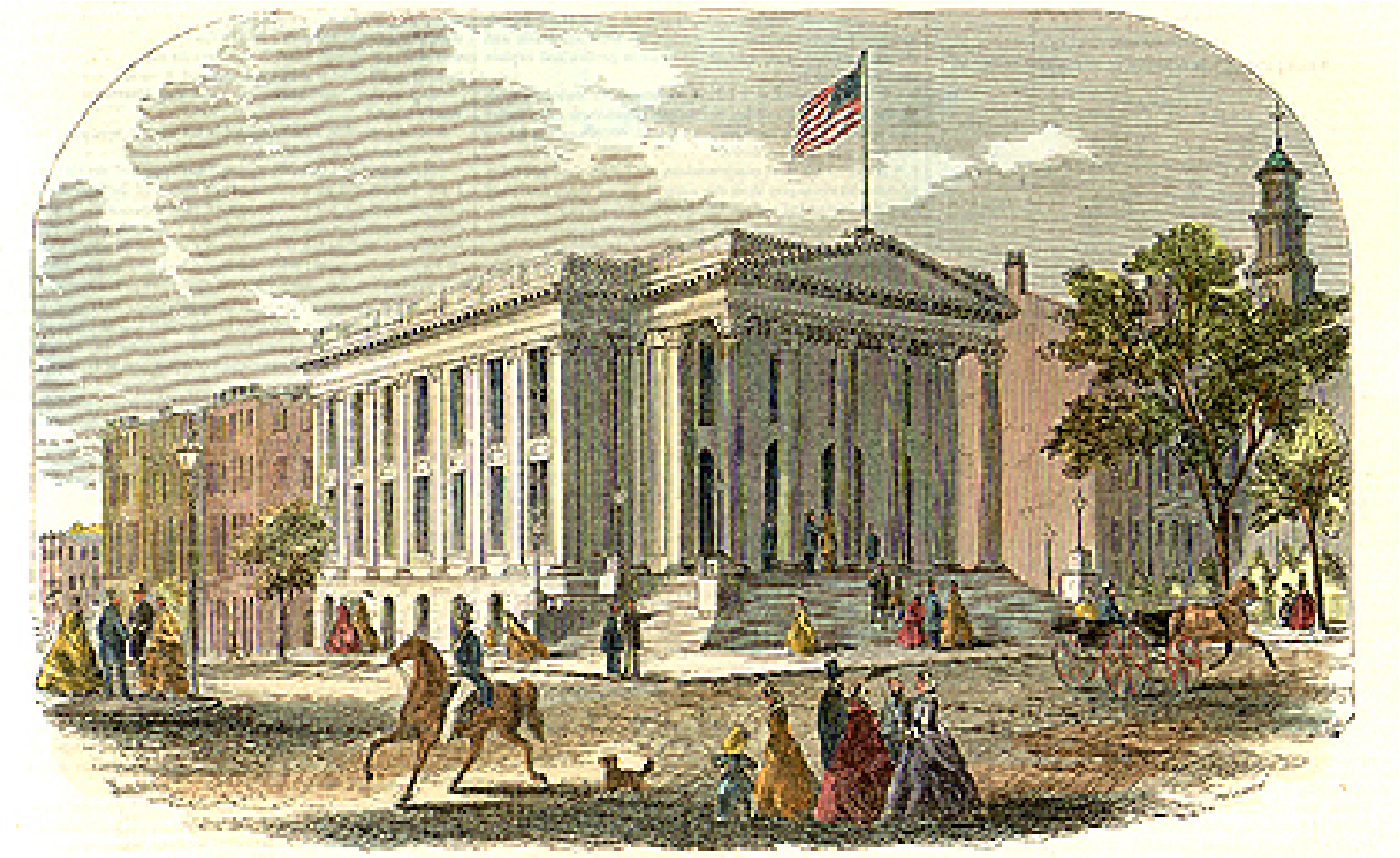
The More Things Change, The More They Stay the Same…

1) Define the unit of measurement, idealistically
2) Realize it experimentally
   (Usually requiring many years)
3) Memorialize the result on an artifact

The U.S. copy of the Committee Meter was acquired by Ferdinand Rudolph Hassler, the first Superintendent of the Survey of the Coast, from Johann Trallès, the Swiss delegate to the 1798 Paris Conference.

It is on display in the Museum in the NIST Library, dated 1799.

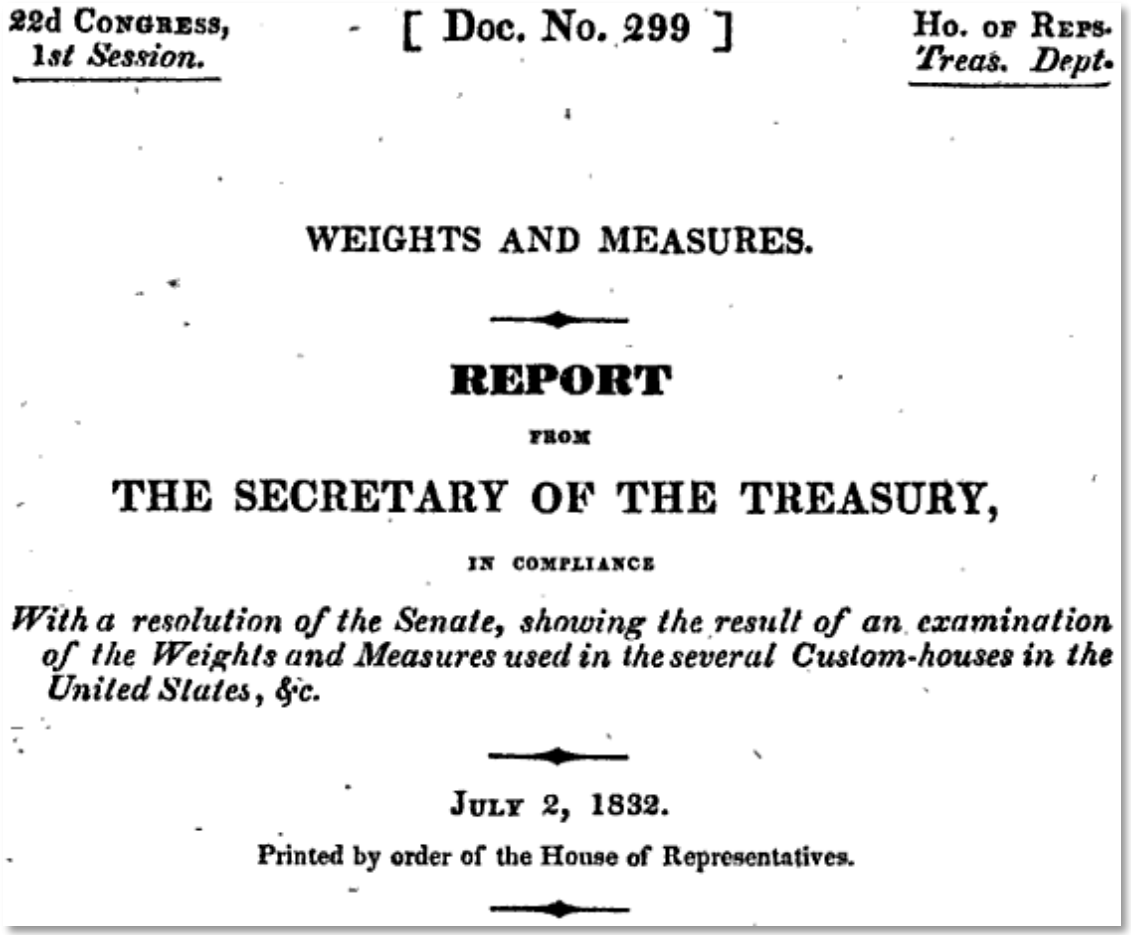
Funding the Federal Government
First Half of the 19th Century



The Custom House in Cincinnati, hand-colored wood engraving, ca 1850–1860.

Prior to the Income Tax (1861), the Federal Government was funded by duties levied at ports. (Original on display opposite 101/A123.)

Weights and Measures in the 1830s



22d CONGRESS, 1st Session. [Doc. No. 299] Ho. OF REPS. Treas. Dept.

WEIGHTS AND MEASURES.

REPORT

FROM

THE SECRETARY OF THE TREASURY,

IN COMPLIANCE

With a resolution of the Senate, showing the result of an examination of the Weights and Measures used in the several Custom-houses in the United States, &c.

JULY 2, 1832.

Printed by order of the House of Representatives.

Concerned about the accuracy of the weights and measures used in the custom houses, the Senate asked the Secretary of the Treasury to look into it.

Weights and Measures in the 1830s
Oops!...

This examination has been made with great care and ability; and the report presents fully both the results, and the means employed in obtaining them. It will be seen that great discrepancies exist between the weights and measures used in the different custom-houses—some being too small, and others too large; but, that the mean corresponds nearly with the standards as fixed by the English laws, previously to, and at the epoch of the declaration of American independence.

The existence of these discrepancies is not surprising considering the manner in which the weights and measures have been obtained in the custom houses. It is, nevertheless, a serious evil, inasmuch as it produces inequalities in the duties levied at the different ports; and thus contravenes the spirit of the constitution, which declares that all duties, imposts, and excises, shall be uniform throughout the United States. It is believed, however, that this department has full authority to correct the evil, by causing uniform and accurate weights and measures, and authentic standards, to be supplied to all the custom-houses. With this view, proceedings were instituted by my predecessor, with the President's approbation, and are now in progress, for effecting that object, by fabricating at the United States' Arsenal in this city, under the immediate personal superintendence of Mr. Hassler, the necessary standards, as well as weights and measures, which

The results were not good, and deemed to be "a serious evil."
The report precipitated the formation of the Office of Weights and Measures.

Metric Act of 1866

Congressman John A. Kasson of Iowa, Chairman of the House Committee on Coinage, Weights, and Measures (1863–1867), Drafted the Metric Act of 1866

- Made it permissible, but not required, to use Metric System in the U.S.
- Defined:
  - Meter = 39.37 inch
  - Kilogram = 2.2046 lbs
- Separately, Congress ordered copies of Metric standards to be made and sent to the states

Metric System (Version 2.0)
Treaty of the Meter (1875)

Standard Meter prototypes

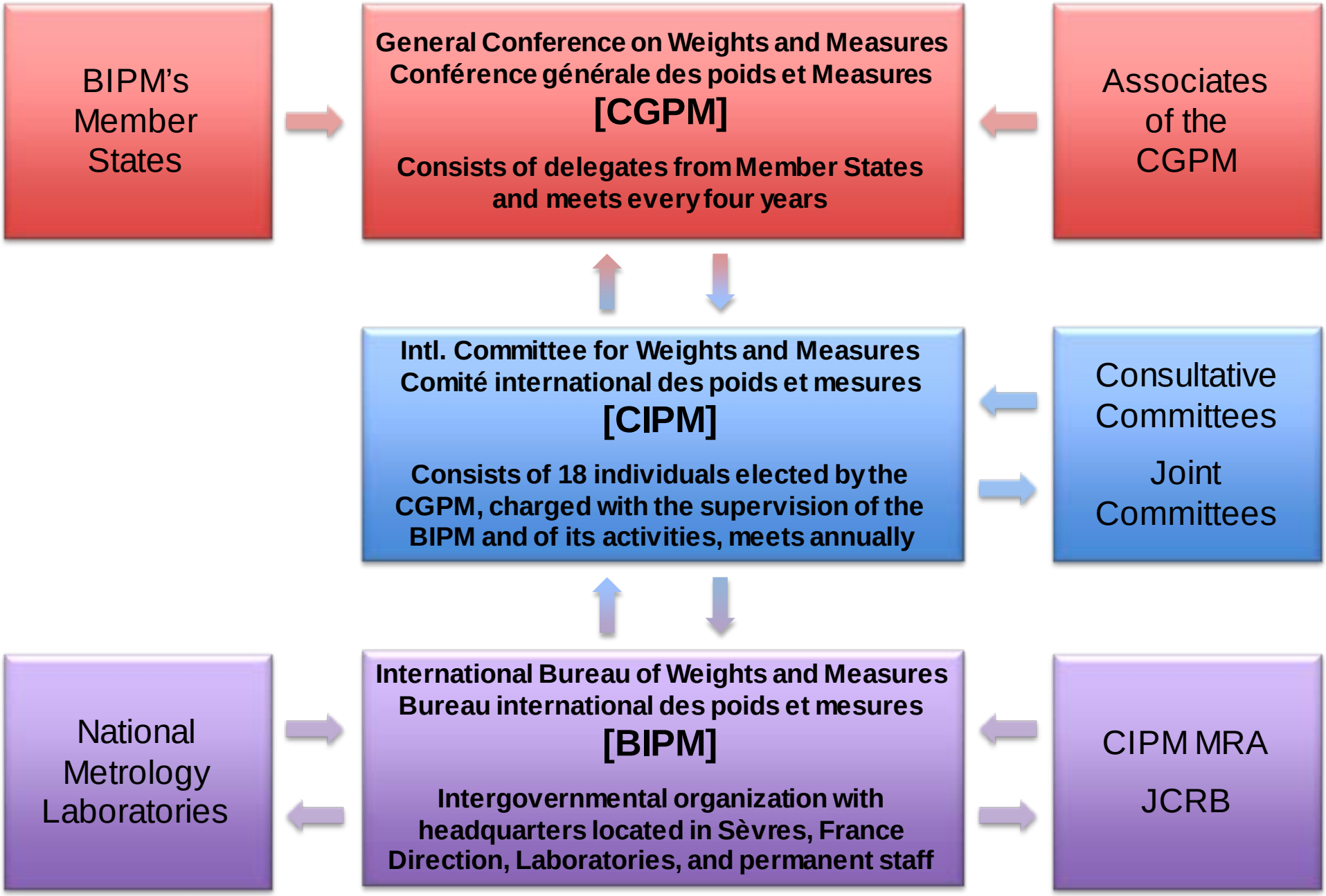
Shown: National Prototype Meter No. 27, received by the U.S. in 1890

Standard Kilogram prototypes

Shown: International Prototype of the Kilogram, kept at BIPM

Treaty of the Meter (1875)
Governance Structure

- General Conference for Weights and Measures (CGPM)
  - Diplomatic body
  - Duty to discuss and initiate improvements to metric system
  - One nation, one vote
- International Committee on Weights and Measures (CIPM)
  - Technical body
  - Duty to acquire, fit-up, and supervise the Bureau
- International Bureau of Weights and Measures (BIPM)
  - Permanent laboratory
  - Comparisons, verifications, custody of standards
- Ratified by U.S. Senate in 1878


BIPM's Member States
General Conference on Weights and Measures
Conférence générale des poids et Measures
[CGPM]
Consists of delegates from Member States and meets every four years
Associates of the CGPM
Intl. Committee for Weights and Measures
Comité international des poids et mesures
[CIPM]
Consists of 18 individuals elected by the CGPM, charged with the supervision of the BIPM and of its activities, meets annually
Consultative Committees
Joint Committees
National Metrology Laboratories
International Bureau of Weights and Measures
Bureau international des poids et mesures
[BIPM]
Intergovernmental organization with headquarters located in Sèvres, France
Direction, Laboratories, and permanent staff
CIPM MRA
JCRB

State of the Metric System
Late 19th Century

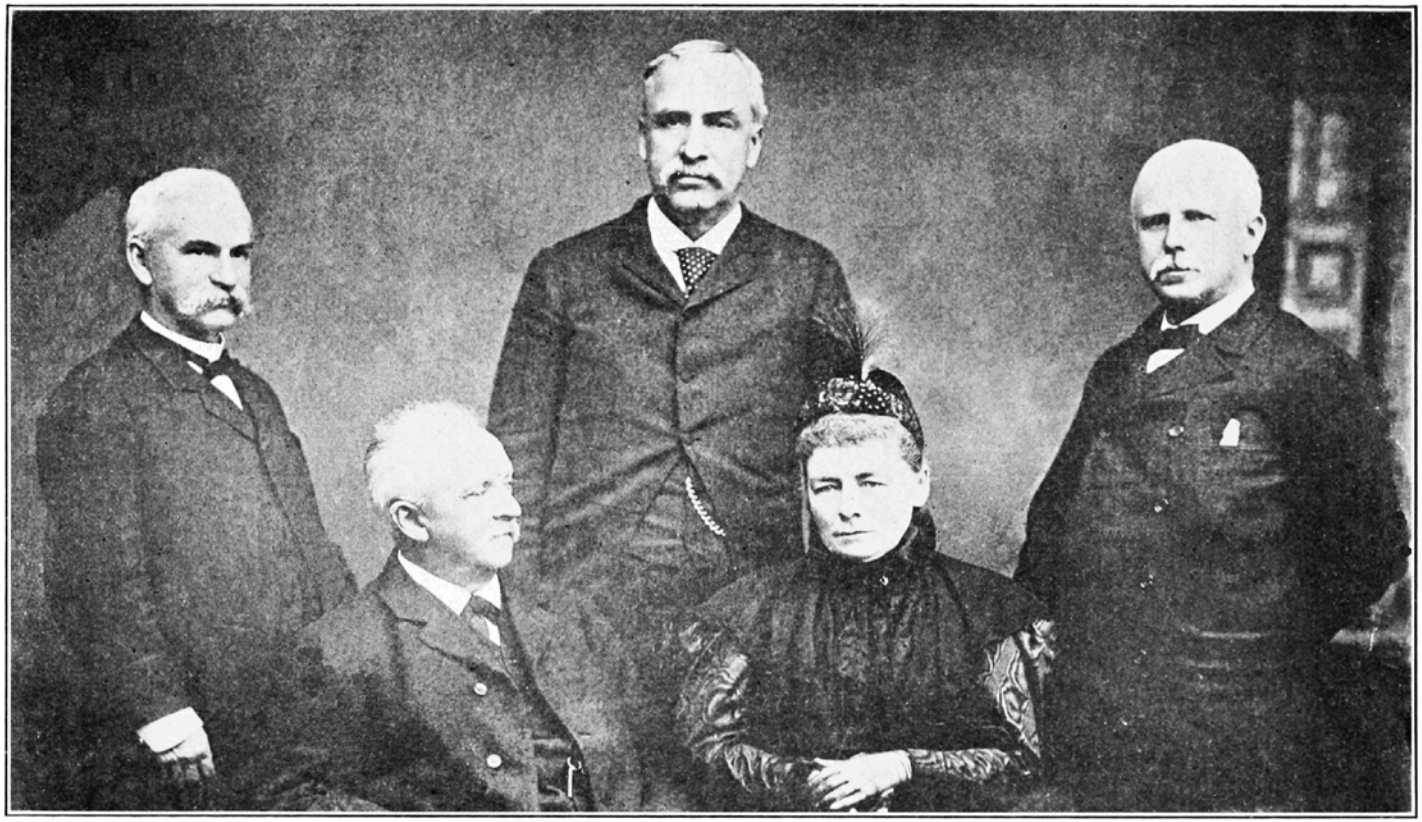
- The "Metric System" was *only* weights (kilogram) and measures (meter)
  - Also areas and volumes, derived from length
- Ambiguous whether "weight" of kilogram was a measure of "mass" or "force"
  - Kilogram decided to be a unit of "mass" at the 3rd meeting of the CGPM (1901)

The Columbian Exhibition (1893)

Court of Honor and Grand Basin of the
1893 World's Columbian Exposition (Chicago, Illinois)

Here, in 1893, the International Electrical Congress established the first international standards for the measurement of electrical quantities (ampere, ohm, volt, …)

Thomas C. Mendenhall, Superintendent Coast and Geodetic Survey (1889–1894)



Thomas Mendenhall, standing, far right; Hermann von Helmholtz and his wife, Anna, seated. Stopping off in Washington en route home from Chicago, 1893.

Mendenhall expanded the scope of the Office of Weights and Measures to include scientific standards, drafted the electrical standards adopted in Chicago.

The Mendenhall Order (1893)

- The Metric Act of 1866 not withstanding, henceforth:
  - Foot = $\frac{1200}{3937}$ Meter
  - Pound = $\frac{1}{2.20462}$ Kilogram

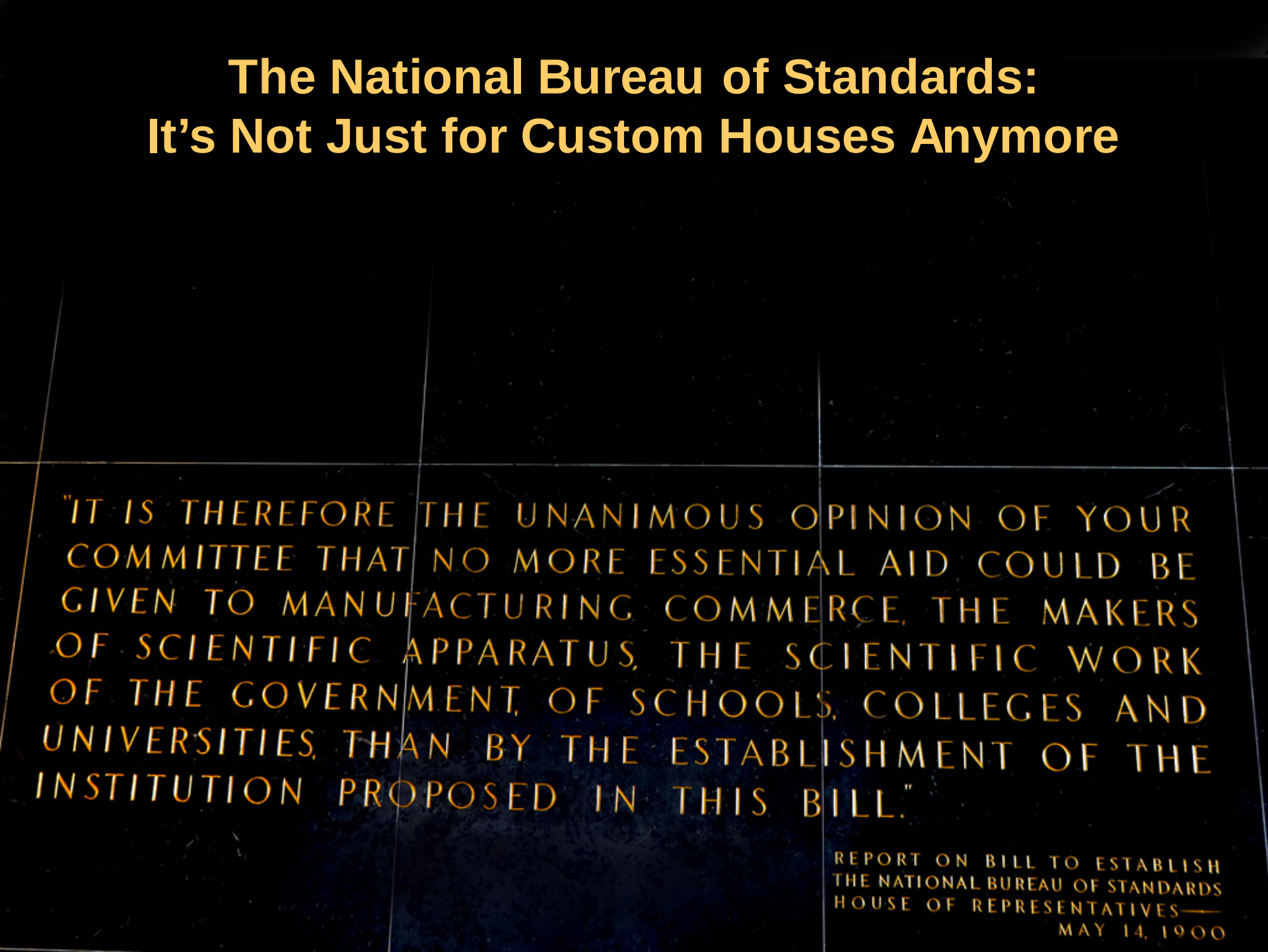
(Revised to $\frac{1}{2.20462234}$ Kilogram in 1894)

The Metric standards of the BIPM became primary in the U.S.

Henry Smith Pritchett, Superintendent Coast and Geodetic Survey (1897–1900)

In 1897, astronomer and mathematician Henry S. Pritchett succeeded the retired Civil War General William Duffield as the ninth Superintendent of the Coast and Geodetic Survey. Pritchett spun out the Office of Weights and Measures to create the National Bureau of Standards.

The National Bureau of Standards: It's Not Just for Custom Houses Anymore



Treaty of the Meter
1921 Amendments

- Added coordinating the measures of electrical units
- Added establishing and keeping standards of electrical units, and their “test copies”
- Added duty to determine the physical constants
- Added coordinating “similar determinations affecting other institutions”
- Ratified by the U.S. Senate in 1923

Definition of the Ampere

1927: 7th CGPM creates the Consultative Committee for Electricity (CCE, name changed to Consultative Committee for Electricity and Magnetism in 1997)

1939: CCE recommends adoption of a four-dimensional system based on the meter, kilogram, second, and ampere

1946: CIPM approves

1948: 9th CGPM decides:

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 2×10^{-7} newton per meter of length.

Definition of the Candela

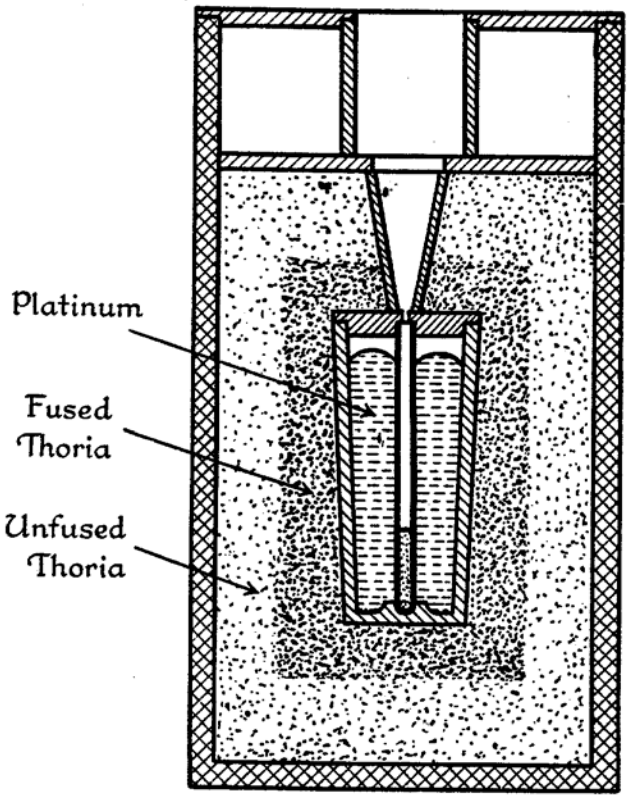


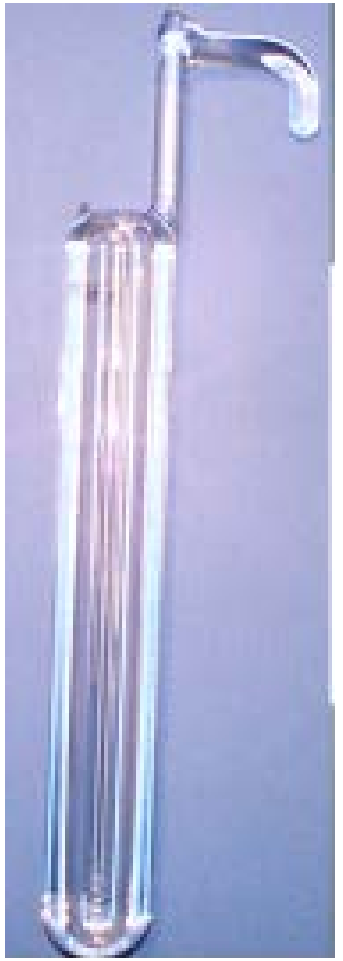
FIG. 99. The Primary Standard of Light.

"The candela is the luminous intensity, in the perpendicular direction, of a surface of 1/600 000 square meter of a black body (full radiator) at the temperature of freezing platinum under a pressure of 101325 newton per square meter."

In 1948, the CGPM also adopted the first international standard for the brightness of light (stated here as amended in 1967). [The candela definition was changed in 1979.]

Definition of the Kelvin

1954: The kelvin, unit of thermodynamic temperature, is the fraction 1/273.16 of the thermodynamic temperature of the triple point of water
(10th CGPM, Resolution 3)
(13th CGPM, Resolution 4, renamed)



A triple-point cell

In 1954, the CGPM added a unit of measurement for temperature to the metric system.

The Beginning of the System of Units

1954: 10th CGPM, Resolution 6: practical system of units

In accordance with the wish expressed by the 9th Conférence Générale des Poids et Mesures (CGPM) in its Resolution 6 concerning the establishment of a practical system of units of measurement for international use, the 10th CGPM

decides to adopt as base units of the system, the following units:

length	meter
mass	kilogram
time	second
electric current	ampere
thermodynamic temperature	degree Kelvin (renamed “kelvin” in 1967)
luminous intensity	candela

A comprehensive system of measurement units was now complete.

The Système International d'Unités (SI)

1960: 11th CGPM adopts the name "Système International d'Unités" for the compilation of its work, the compete, modernized Metric System

- Units of measurement and rules for usage

1971: 14th CGPM adds the "mole" to SI as the seventh base unit, as the amount of substance

- The International Union of Pure and Applied Physics (IUPAP) and the International Union of Pure and Applied Chemistry (IUPAC) did not agree until 1960 to base the mole on ^{12}C, rather than ^{16}O.

The Système International d'Unités (SI)

- Creation of the SI *began* the process to revise and improve the units in a way that benefited the system as a whole
- Since 1960, rapid improvement of unit definitions and realizations
- Examples:
  - Changes to definition of the "second"
  - Changes to definition of the "meter"

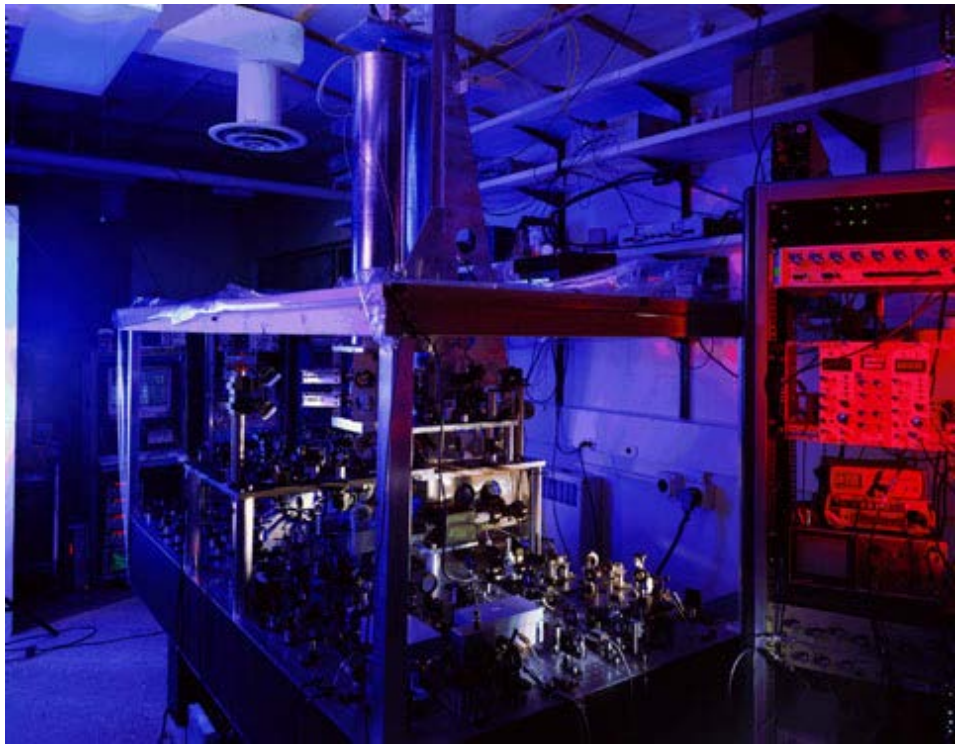
Definition of the Second

The second was defined originally as 1/86,400 of the "mean solar day." The exact definition was left to astronomers.

1960: 11th CGPM adopted definition given by the International Astronomical Union, which was based on the tropical year

Definition of the Second

1967: *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* ^{133}Cs *atom.*



NIST-F2, today's primary atomic frequency standard

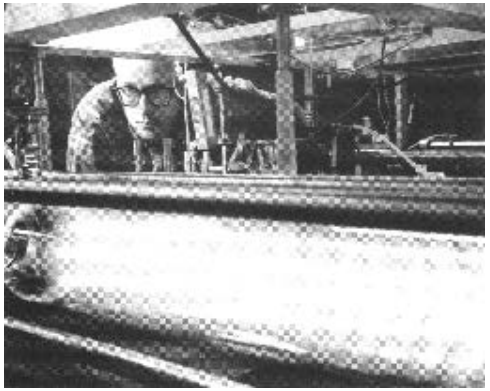
Definition of the Meter

1889: International Prototype Meter

1960: Based on wavelength of ^{86}Kr radiation

1983: *The meter is the length of the path travelled by light in vacuum during a time interval of* 1/299,792,458 *of a second.*
(17th CGPM, Resolution 1)

The Speed of Light



Start with a methane-stabilized HeNe Laser

Determine its wavelength using the Kr standard

3.392231376(12) µm

Determine its frequency using the Cs standard

88.376181627(50) THz

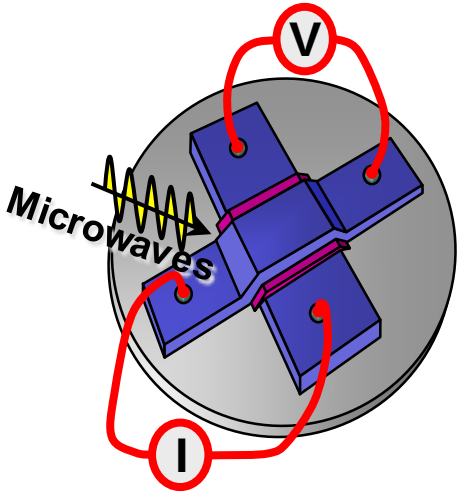
Multiply to get the Speed of Light!

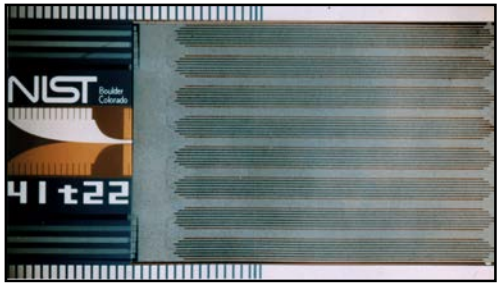
299,792,456(1.1) m/s

Similar Redefinitions on Tap

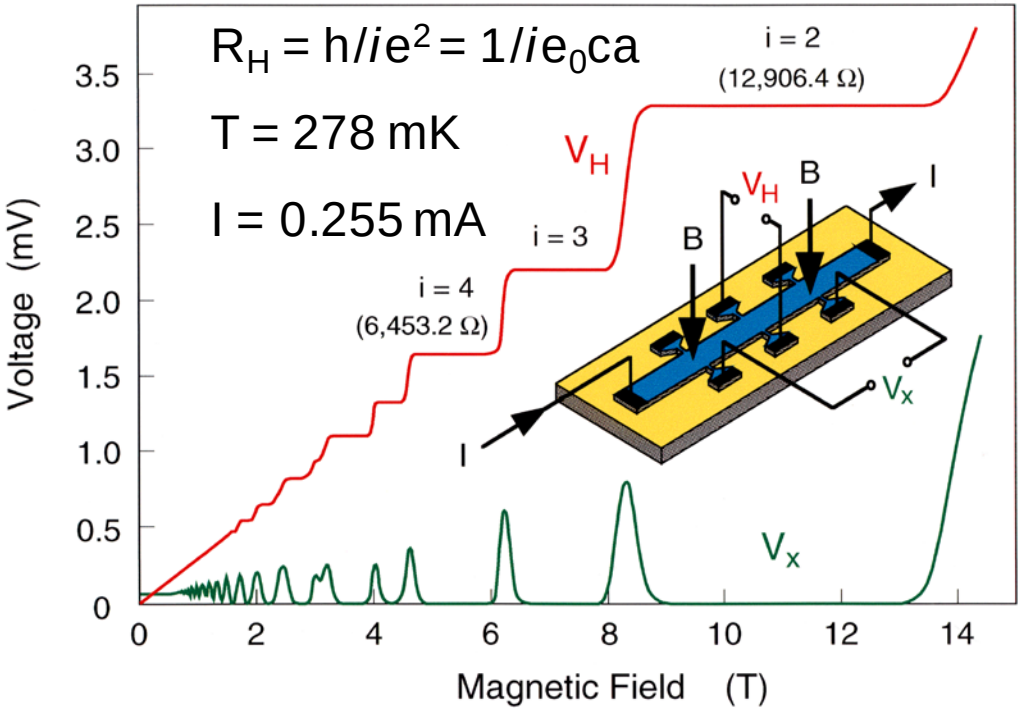
- Similarly, the CIPM is currently considering possible redefinitions of:
  - kilogram
  - ampere
  - kelvin
  - mole
- Determined through best experiment, then fixing, the values of:
  - Planck constant
  - Elementary electric charge (of electron)
  - Boltzmann constant
  - Avogadro constant
- May be considered by 25th CGPM, in 2014

Reference Standards for Electrical Units Since 1990





The "volt" realized by Josephson Junction devices, with K_{J-90} = 483,597.9 GHz/V

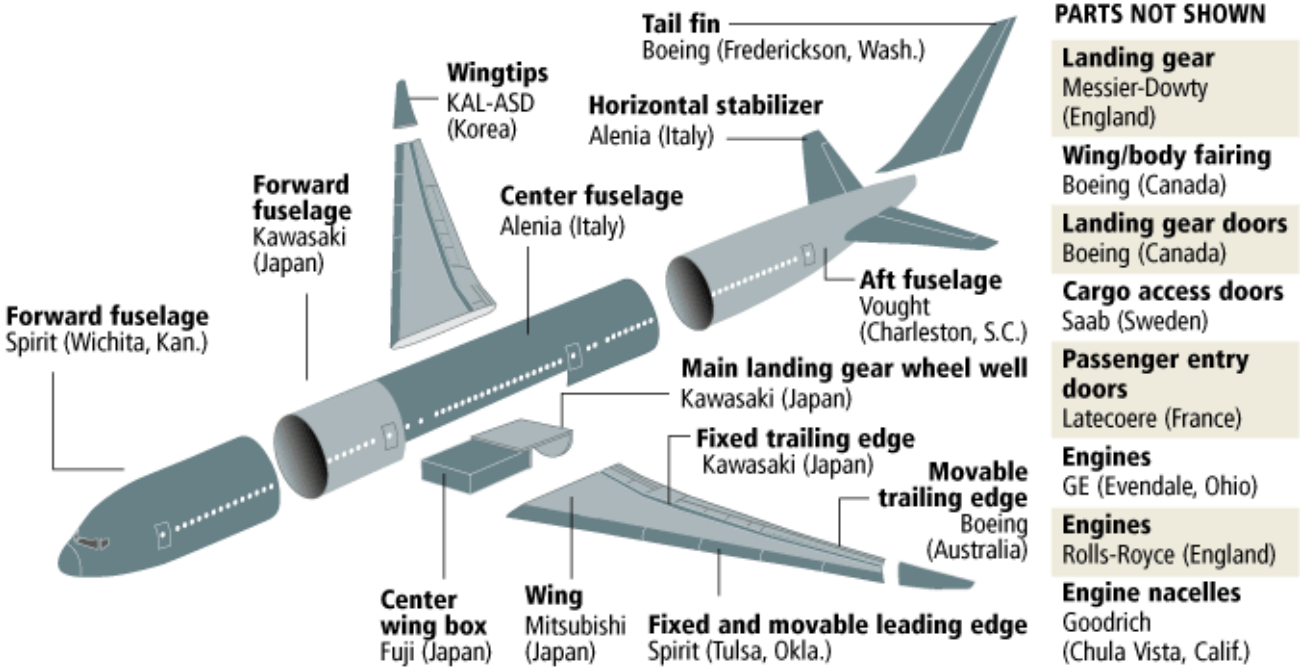


The "ohm" realized by Quantum Hall Effect devices, with R_{K-90} = 25,812.807 Ω

The Système International d'Unités (SI)

- SI cited in U.S. law:
  - 1974, Education Amendments (repealed 1981)
  - 1975, Metric Conversion Act
  - 2007, COMPETES Act formally amended Metric Act of 1866, and made SI the "Metric System" in the U.S.
- These laws qualify that the SI is, "as interpreted or modified for the U.S. by the Secretary of Commerce"
  - Power delegated to the Director of NIST
- NIST realizes the SI units from their definitions for use in the United States

Ensuring Equivalent Measurements Across the Globe



- Major subassemblies of the Boeing 787 Dreamliner are produced by a distributed network of suppliers
- Airplanes require maintenance wherever their port of call
- "Stovepiped" national measurement systems are not compatible with 21st century requirements

The Mutual Recognition Arrangement of the CIPM

- Establishes the degree of equivalence of national measurement standards maintained by NMIs
- Provides for the mutual recognition of calibration and measurement certificates issued by NMIs
- Provides governments and other parties with a secure technical foundation for wider agreements related to international trade, commerce, and regulatory affairs
- Requires key comparisons of national standards
- BIPM maintains database of statements of the measurement capabilities of each NMI
- **Solidifies the ties between nations, and makes SI a more truly international system**

For Further Information

1) Arthur H. Frazier, "United States Standards of Weights and Measures, Their Creation and Creators," Smithsonian Institution Press (1978) http://www.sil.si.edu/smithsoniancontributions/HistoryTechnology/pdf_hi/SSHT-0040.pdf

2) "The Coast Survey 1807–1867," and "Science on the Edge: The Story of the Coast and Geodetic Survey from 1867–1970," Essays by John Cloud, Historian, NOAA Central Library, at http://www.lib.noaa.gov/noaainfo/heritage/coastandgeodeticsurvey/index.html

3) Rexmond C. Cochrane, "Measures for Progress, A History of the National Bureau of Standards," (1966) http://nistdigitalarchives.contentdm.oclc.org/cdm/compoundobject/collection/p15421coll1/id/5779

4) L.A. Fischer, "History of standard weights and measures of United States," Bulletin of the Bureau of Standards, Vol. 1, 365–381 (1905) Scientific Paper 17 (S17) http://nistdigitalarchives.contentdm.oclc.org/cdm/compoundobject/collection/p16009coll11/id/5956/rec/9

5) Henry S. Pritchett, "The Story of the Establishment of the National Bureau of Standards," Science Vol. XV, No. 373 281–284 (February 21, 1902) http://www.sciencemag.org/content/15/373/281.full.pdf

6) Website of the BIPM http://www.bipm.org/en/home/

7) Website of Physical Measurement Laboratory http://physics.nist.gov/cuu/Units/index.html

8) Website of the U.S. Metric Association http://www.metric.org/

9) "The Meter: A Measurement for All People and All Times, Practical Implementation of the Universal Standard," http://www.planetseed.com/node/16531

Credits

1) Title Slide: Photograph of David Wineland, © Geoffrey Wheeler, 2003; Dawn Cross, NIST, 2011; Charles Gibson, © Robert Rathe, 2002; Sae Woo Nam, © Geoffrey Wheeler, 2003.
2) Cover art of SI publication, http://www.bipm.org/en/si/si_brochure/general.html, © BIPM, 2006
3) Storming of the Bastille, oil on canvas, anonymous artist, date unknown, from the museum collection at the Palace of Versailles http://en.chateauversailles.fr/,http://en.wikipedia.org/wiki/File:Anonymous_-_Prise_de_la_Bastille.jpg
4) Survey of the Meridian, from http://www.planetseed.com/node/16531 © Ministère de l'Économie, des Finances et de l'Industrie, France; Jean-Baptiste Delambre, painting by Henri Coroenne, 1879, based on the bust stored at l'Observatoire de Paris http://patrimoine.obspm.fr/Peintures/Portraits/Portraits.html, © Observatoire de Paris; Pierre Méchain, painting by Hurle, 1882, © Observatoire de Paris, http://en.wikipedia.org/wiki/File:Pierre_mechain.jpg
5) Hassler copy of the Committee Meter, NIST Museum Collection http://museum.nist.gov/object.asp?ObjID=12
6) Custom House in Cincinnati, NIST Museum Collection http://museum.nist.gov/object.asp?ObjID=14
7) Weights and Measures Report of 1832, http://books.google.com/books?id=rlY7AAAAcAAJ&printsec=frontcover#v=onepage&q&f=false
9) John A. Kasson, photograph by Mathew Brady, 1865, http://en.wikipedia.org/wiki/File:JAKasson.jpg; (similar image at http://www.old-picture.com/mathew-brady-studio/Honorable-Kasson-Adam-John.htm)

Credits (Continued)

10) Meter bar, from the NIST Museum Collection, http://museum.nist.gov/object.asp?ObjID=37; International Prototype of the Kilogram, http://www.bipm.org/en/scientific/mass/prototype.html

11) The Treaty of the Meter is published in The Statutes at Large of the United States of America, Vol. 20, pp. 709–724 (1879).

12) Organizational chart, after http://www.bipm.org/utils/en/pdf/structure.pdf

14) The Columbian Exhibition, photographer unknown, from http://en.wikipedia.org/wiki/World's_Columbian_Exposition

15) Mendenhall and Helmholtz, photograph by Dr. S. J. Meltzer, from http://commons.wikimedia.org/wiki/File:PSM_V85_D521_Group_photograph_of_herman_helmholtz_and_academic_friends.png, originally from The Popular Science Monthly **85**, p. 517 (Nov. 1914) http://archive.org/stream/popularsciencemo85newy#page/517/mode/1up

16) The Mendenhall Order is reprinted as Appendix 3 of NIST SP 447, Louis E. Barbrow and Lewis V. Judson, "Weights and Measures Standards of the United States, A brief history" http://www.nist.gov/pml/pubs/sp447/index.cfm

17) Henry Smith Pritchett, photography courtesy of the MIT Museum, http://libraries.mit.edu/archives/exhibits/pritchett-reif/index.html

18) Inscription in NIST Administration Building lobby, photography and post production by Curt Suplee (NIST), 2012

19) The 1921 Amendments to the Treaty of the Meter are published in The Statutes at Large of the United States of America, Vol. 43 (Part 2), pp. 1686–1694 (1925).

Credits (Continued)

20) See http://physics.nist.gov/cuu/Units/ampere.html and NIST Publication SP 330 http://physics.nist.gov/Pubs/SP330/sp330.pdf, p. 16 and Sec. 2.1.1.4.

21) See http://physics.nist.gov/cuu/Units/candela.html and NIST Publication SP 330 http://physics.nist.gov/Pubs/SP330/sp330.pdf, Sec. 2.1.1.7. Origin of picture unknown.

22) See http://physics.nist.gov/cuu/Units/kelvin.html and NIST Publication SP 330 http://physics.nist.gov/Pubs/SP330/sp330.pdf, Sec. 2.1.1.5. Photograph: NIST.

26) See http://physics.nist.gov/cuu/Units/second.html and NIST Publication SP 330 http://physics.nist.gov/Pubs/SP330/sp330.pdf, Sec. 2.1.1.3.

27) NIST-F2 frequency standard, photograph © Geoffrey Wheeler

28) International Prototype Meter, photograph from http://www.nist.gov/pml/wmd/metric/length.cfm

29) Photograph of Ken Evenson and the speed-of-light experiment from http://www.100.nist.gov/ph_energy.htm.
See also http://nvlpubs.nist.gov/nistpubs/sp958-lide/191-193.pdf.
See also http://prl.aps.org/abstract/PRL/v29/i19/p1346_1.

30) See http://www.nist.gov/pml/newsletter/siredef.cfm.
See http://www.bipm.org/utils/common/pdf/si_brochure_draft_ch2.pdf.
See http://iopscience.iop.org/0026-1394/43/3/006/.

31) Photograph of Josephson Junction device: NIST. Origin of other slide figures: unknown.

33) Illustration from http://bintang.site11.com/Boeing_787/Boeing787_files/Assembly.html

34) See http://www.bipm.org/en/cipm-mra/objectives.html

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Standards and Technology
U.S. Department of Commerce