Evolution of “Système International”: Quantum Based Standards and the Past/Future of Electrical Measurements

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...The Congress shall have Power To...

...and fix the Standard of Weights and Measures;
The Origin of the Metric System
Now known as International System of Units (SI)

• Adopted by Intl. committee on December 10, 1799
• Came into common use in 19th century
  – In U.S., Metric Act of 1866 permitted its use, preempts state laws that forbade its use
• Standards kept in the Archives of France
• Basic principles:
  – Decimalization
  – Based on nature (not monarchs)
  – Open access
• Until 20th Century the “Metric System” was only weights (kilogram) and measures (meter)
  – Also areas and volumes, derived from length
Alternative Title
Are fundamental constants really constant?
Treaty of the Meter (1875)

1870: Paris conference to consider constructing new primary metric system standards
  – Originals from 1799 were aging and worn

1872: 2nd conference decides that new meters and new kilograms should be constructed to conform with the standards in the French Archives
  – Committee appointed to carry out this decision

1873: Committee agrees upon improved materials and designs for standards

1875: French Government calls diplomatic conference to consider how to validate the new meters and kilograms
  – One shot operation?
  – Framework for permanent maintenance?

1878: Ratified by the U.S. Senate – U.S. original signatory!
International Bureau of Weights and Measures

Bureau international des poids et mesures

[Intl. Committee for Weights and Measures]
Comité international des poids et mesures

[CGPM]
Consists of delegates from Member States and meets every four years

[Consultative Committees]
Joint Committees

[Diplomatic Treaty]
Governments of BIPM’s Member States

[Diplomatic Body]
General Conference on Weights and Measures
Conférence générale des poids et mesures

[Intl. Committee for Weights and Measures]
Consists of 18 individuals elected by the CGPM, charged with the supervision of the BIPM and of its activities, meets biannually

[Technical Body]

[International Bureau of Weights and Measures]
Bureau international des poids et mesures

Intergovernmental organization with headquarters located in Sèvres, France with Laboratories and ~ 70 permanent staff
The Columbian Exhibition (1893)
Birthplace of International Electrical Standards

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

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

• In 1921 the Treaty of the Meter is Amended to add:
  – Coordinating the measures of electrical units
  – Establishing and keeping standards of electrical units, and their “test copies”
  – Duty to determine the physical constants
  – Coordinating “similar determinations affecting other institutions”

• Ratified by the U.S. Senate in 1923

• In 1954 the CGPM decides to adopt 6 base units (meter, kilogram, second, ampere, Kelvin, and candela) giving rise to the modern SI

• In 1960 adopts the name “Système International d’Unités”

• In 1971 the CGPM adds the 7th SI base unit the mole
Toward Redefining the SI

With the creation of the SI, the process to revise and improve the units in a way that benefits the system as a whole and makes them based on nature truly begins.

In 1967 the second is defined as 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 $^{133}\text{Cs}$ atom.

In 1983 the meter was redefined as the length of the path travelled by light in vacuum during a time interval of 1/299,792,458 of a second.

Where are we and what remains to be done?

Are our “current” electrical units part of the SI?
Standards for Electrical Units Since 1990

The “volt” realized by Josephson Junction devices, with $K_{J-90} = 483,597.9 \text{ GHz/V}$

$K_J = 2e/h$

The “ohm” realized by Quantum Hall Effect devices, with $R_{K-90} = 25,812.807 \Omega$

$$R_H = \frac{h}{ie^2} = \frac{1}{ie_0ca}$$

$T = 278 \text{ mK}$

$I = 0.255 \text{ mA}$

These two quantum standards, the Josephson effect (1962, Nobel Prize 1973) and the quantum Hall effect (von Klitzing 1980, Nobel Prize 1985) are so robust that in 1987 the CGPM established conventional electrical units! (Graphene QHR underway)
Are Fundamental Constants really constant?

Barney & Clyde
BY GENE WEINGARTEN, DAN WEINGARTEN AND DAVID CLARK

Why haven’t we changed the definition of a kilogram? We haven’t?

The official definition is still the mass of the International Prototype of the kilogram, an actual lump of stuff that’s stored somewhere.

Why that’s so... Exactly! What if someone snuck in and shaved off a piece?

But now is more accurately defined via oscillations of the cesium atom. Correct. Very good.

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The Two Biggest Headaches in SI Today

1) The artifact kilogram

In 2013, in preparation for the redefinition of the kilogram, the BIPM conducted an “extraordinary” comparison of its working standards with the IPK. During the 25 years since the 3rd periodic verification the unit of mass as maintained by the BIPM through its working standards was found to be 0.035 mg too high relative to the IPK.

1) The electrical units…
The Planned 2018 Redefinition: Quantum SI

• Redefine the:
  – kilogram
  – ampere
  – kelvin
  – mole

• By determining through best experiment the values of, then fixing the values of:
  – Planck constant
  – Elementary electric charge (of electron)
  – Boltzmann constant
  – Avogadro constant

• Bases the SI on fundamentals of nature, consistent with the original aims of the *Treaty of the Meter*!

• Since Planck’s constant $h$ and electric charge $e$ will become fixed, electrical units as practiced will be in the new SI!
Why change the SI if it’s not broken?

• It is broken – In 1948 electrical units were added to the SI but since 1990 conventional electrical units based on the Josephson constant \( K_J = 2e/h \) and von Klitzing constant \( R_K = h/e^2 \) has been used – Note nobody realizes the Ampere directly (NIST came close once)

• Mass is unstable

• It would improve science

• It’s consistent with the original goals of the metric system

• Advantages:
  • Reduced uncertainties of many fundamental constants.
  • Improved usage of the SI in some scientific measurements.
  • Reduced uncertainties of electrical quantities and the practical realizations become part of the SI.
  • Invariance in time and space.
  • The SI becomes more accessible at the highest level of accuracy.

• But with increased uncertainty in mass related quantities.
What does this mean for Electrical Units?

<table>
<thead>
<tr>
<th>Formula for SI Unit</th>
<th>Relative Change</th>
</tr>
</thead>
<tbody>
<tr>
<td>( V = V_{90} [1 - (100 \times 10^{-9})] )</td>
<td>-100 ppb</td>
</tr>
<tr>
<td>( \Omega = \Omega_{90} [1 - (17 \times 10^{-9})] )</td>
<td>-17 ppb</td>
</tr>
<tr>
<td>( A = A_{90} [1 - (83 \times 10^{-9})] )</td>
<td>-83 ppb</td>
</tr>
<tr>
<td>( C = C_{90} [1 - (83 \times 10^{-9})] )</td>
<td>-83 ppb</td>
</tr>
<tr>
<td>( W = W_{90} [1 - (183 \times 10^{-9})] )</td>
<td>-183 ppb</td>
</tr>
<tr>
<td>( F = F_{90} [1 + (17 \times 10^{-9})] )</td>
<td>17 ppb</td>
</tr>
<tr>
<td>( H = H_{90} [1 - (17 \times 10^{-9})] )</td>
<td>-17 ppb</td>
</tr>
</tbody>
</table>

**Note:** For non-quantum standards such as the Calculable Capacitor (F) no shift occurs since it is directly traceable to the current SI through length & time.

## Comparing the Current and New SI

<table>
<thead>
<tr>
<th>Current SI</th>
<th>New “Quantum” SI</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Base quantity</strong></td>
<td><strong>Base unit</strong></td>
</tr>
<tr>
<td>Time</td>
<td>second (s)</td>
</tr>
<tr>
<td>Length</td>
<td>meter (m)</td>
</tr>
<tr>
<td>Mass</td>
<td>kilogram (kg)</td>
</tr>
<tr>
<td>Electrical Current</td>
<td>ampere (A)</td>
</tr>
<tr>
<td>Therm. Temperature</td>
<td>kelvin (K)</td>
</tr>
<tr>
<td>Amount of Substance</td>
<td>mole (mol)</td>
</tr>
<tr>
<td>Luminous intensity</td>
<td>candela (cd)</td>
</tr>
</tbody>
</table>

Quantum Measurement Division (QMD)

- QMD is at the center of the redefinition of the "Quantum SI"
  - Mohr, Taylor, and E. Williams instrumental in basic idea
  - CODATA (Committee on Data for Science and Technology) recommended values will be basis for fixing the constants

- QMD realizes electrical, mass, and force units
  - NIST Reorganization created a unique opportunity for the mise-en-pratique for mass!
  - Quantum based measurements provides foundation for advances in all units including beyond the standard quantum limit

Redefinition of the kilogram, ampere, kelvin and mole: a proposed approach to implementing CIPM recommendation 1 (CI-2005)

Ian M Mills¹, Peter J Mohr², Terry J Quinn³, Barry N Taylor² and Edwin R Williams²
The two constants \([h,k]\)... which occur in the equation for radiative entropy offer the possibility of establishing a system of units for length, mass, time, and temperature which are independent of specific bodies or materials and which necessarily maintain their meaning for all time and for all civilizations*, even those which are extraterrestrial and non-human.

-- Max Planck, 1900

*Planck uses language similar to that used by the Marquis de Condorcet when he transferred the original French length and mass standards to the Archives de la Republique in 1799. More on the new SI can be found in Dave Newell’s Physics Today article, July, 2014.
PML is Responsible for the International System of Units (SI)

How it is...
- Scientifically based
- Defined by consensus (Treaty of the Meter)
- Realized in practice
- Disseminated for routine uses
- Disseminated for new and novel uses
- Maintained and Improved

SI underpins all measurements, whether expressed in metric units, traditional British units, or other units

Watt Balance Basics

- Weighing or Force mode: An unknown weight $mg$ is balanced by an electromagnetic force on a horizontal coil of wire-length $L$ in a radial magnetic field of flux density $B$ when a current $I$ flows through the coil

$$mg = BLI$$

- Calibration or Velocity mode: The magnet’s strength $BL$ is measured by moving the coil at a velocity $v$ while recording the voltage $V$ across the coil terminals

$$BL = \frac{V}{v}$$

- The two modes can compare mechanical and electrical power, hence the name, watt balance

$$mgv = VI$$
Quantum Watt
AC Josephson Voltage Standard (ACJVS)

- intrinsically accurate, quantum voltage standard
- JJs act as perfect quantizers, converting arbitrary input pulses to output voltage pulses with quantum-accurate \( V-t \) area: 
  \[
  \int_{\text{pulse}} V(t) dt = \frac{h}{2e} \approx 2.07 \text{ mV-\text{ps}}
  \]
- 30 Gb/s data rate \( \Rightarrow \) picosecond pulse timing

\[ V_n = \frac{h}{2e} n f \]

\* precision control over amplitude and phase of arbitrary waveforms via pulse pattern and timing
AC Josephson Voltage Standard (ACJVS)

6,400 Josephson junctions per array connect arrays in series for increased voltage:
- rms output up to 250 mV for $n=1$ step
- rms output up to 500 mV for $n=2$ step

12,800 Josephson junctions per array
- rms output up to 1 V for $n=1$ step
- requires 4 separate bias channels
- 2 V, 4-array chip presently in development
View into the Future

• SI Redefinition will likely occur in 2018!
• Electrical Metrology
  – Will be brought back into the SI and *conventional units will be abrogated*
  – Current QHR systems are not robust
  – Graphene based QHR will be available soon
  – Numerous efforts for Single Electron Transistors (SETs) is underway (Si, GaAS, …)
  – Integration of two quantum standards (QHR, SETs, JVS) on a single device would revolutionize electrical instrumentation – through on chip application of Ohm’s law to create self-calibrating instruments