NEW MEASUREMENT STANDARDS FOR 1990

On New Year's Day, new practical reference standards for the volt and the ohm will take effect worldwide. Both will be based on highly reproducible quantum effects rather than artifacts. The practical temperature scale will also change.

Barry N. Taylor

By international agreement, new practical reference standards for the volt and the ohm, based respectively on the Josephson effect and the quantum Hall effect, will be adopted worldwide on 1 January 1990. Until now, national standards laboratories have been using wire-wound resistors as practical reference standards for the ohm. Practical reference standards for the volt, on the other hand, have been based on the Josephson effect since the early 1970s. But four different such standards are in use in different countries, and their values all differ significantly from the volt as defined in the Système International d'Unités (SI), the internationally accepted system of measurement units.

These new practical reference standards will also affect the measurement of current and power worldwide, and in the US new standards will affect the measurement of capacitance and mass. On the same date, a new practical temperature scale will also go into effect worldwide.

The new practical volt and ohm standards reflect the 1988 Recommendations of the International Committee of Weights and Measures (CIPM) and its Consultative Committee on Electricity (CCE).[1,2] By "the volt" (V) one means specifically the unit of electromotive force and electric potential difference defined in the SI, which is the modern version of the MKS system, and by "the ohm" (Ω) one means the SI unit of resistance. A practical reference standard or "representation" of the volt or ohm is simply a practical unit of voltage or resistance.

Système International

To understand the need for such practical representations, consider that the three SI base mechanical units[3] are the meter (m), the kilogram (kg) and the second (s). The meter is now defined in terms of the speed of light in vacuum; the kilogram, the only SI unit still defined by a physical artifact, is the mass of the international prototype of the kilogram; and the second is defined in terms of the transition between the two hyperfine levels of the ground state of cesium-133.

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The SI unit of force, the newton, is *derived* from these three base mechanical units through Newton's second law; it is given by $N = m \cdot kg \cdot s^{-2}$. The joule, the SI unit of energy, follows from the definition of work: $J = N \cdot m = m^2 \cdot kg \cdot s^{-2}$. Finally, the SI unit of power, the watt, is defined as $W = J/s = m^2 \cdot kg \cdot s^{-3}$.

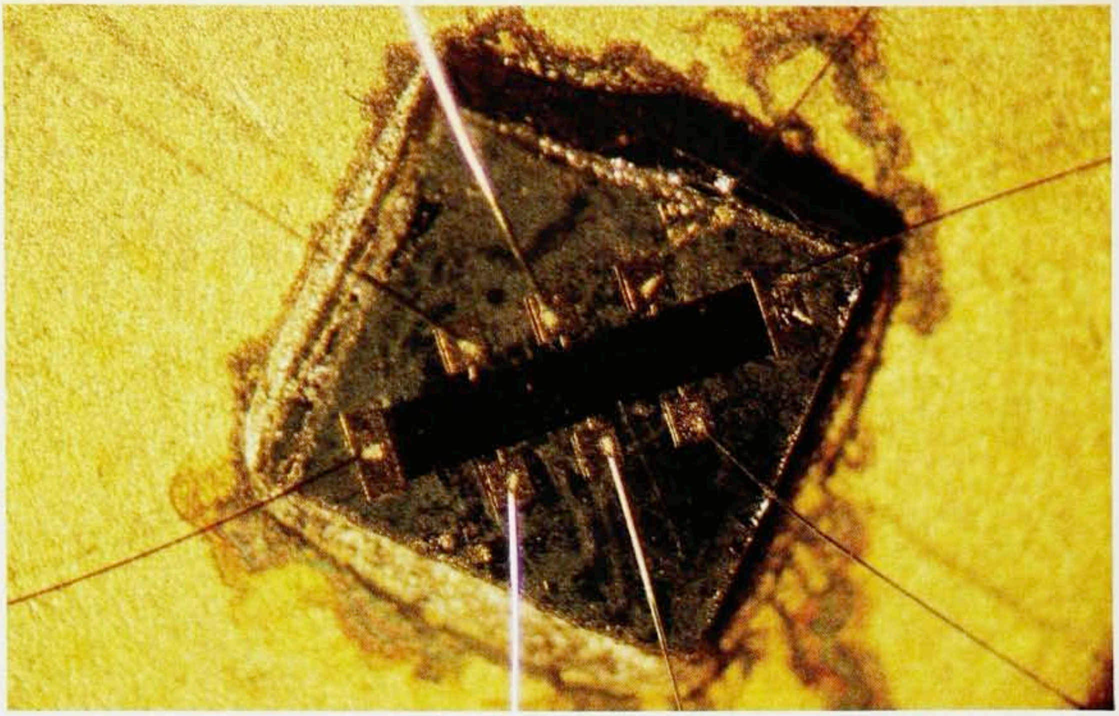
The SI base electric unit, the ampere (A), is defined as "that constant current which, if maintained in two straight parallel conductors of infinite length, of negligible circular cross section, and placed 1 meter apart in vacuum, would produce between these conductors a force equal to 2×10^{-7} newton per meter of length." This definition implies that μ_0, the permeability of the vacuum, is *exactly* $4\pi \times 10^{-7}\ N/A^2$.

The volt and ohm are then derived from the watt (and thus from the three base mechanical units) and the ampere, the base electric unit. Formally, $V = W/A = m^2 \cdot kg \cdot s^{-3} \cdot A^{-1}$ and $\Omega = V/A = W/A^2 = m^2 \cdot kg \cdot s^{-3} \cdot A^{-2}$.

Practical standards

Unfortunately, the complexity of the definitions of the volt and ohm precludes their ready experimental realization with high accuracy. This is a concern because of the severe demands of science, commerce and industry for worldwide uniformity and long-term reproducibility of voltage and resistance measurements. It has therefore become necessary to establish practical units of voltage and resistance, that is, *representations* of the volt and ohm that provide better long-term repeatability and constancy than the direct realizations of the SI units themselves.

The new 1990 volt and ohm representations based on the Josephson and quantum Hall effects are being introduced to improve the international uniformity of electrical measurements as well as their consistency with the SI. The wire-wound resistors that have been serving as practical representations of the ohm at the various national standards laboratories are subject to aging, and



Quantum-Hall-effect device. This is a GaAs–$Al_xGa_{1-x}As$ heterostructure whose interface, at low temperature and high magnetic field, confines a quantized two-dimensional electron gas. The dark central bar along which the two-dimensional current flows is 4 mm long. The Hall resistance of such devices, measured as a function of applied magnetic field, exhibits quantized plateaus that will serve as the worldwide practical standard of resistance beginning next January. **Figure 1**

their values differ from country to country. Furthermore, they differ significantly from the (SI) ohm. Basing the ohm representation on the quantum Hall effect will eliminate the problems of aging and differing artifacts, just as the Josephson effect has eliminated variations observed in national volt representations when they were based on electrochemical standard cells. The new Josephson volt representation that goes into effect worldwide next January will replace the various Josephson representations now in use.

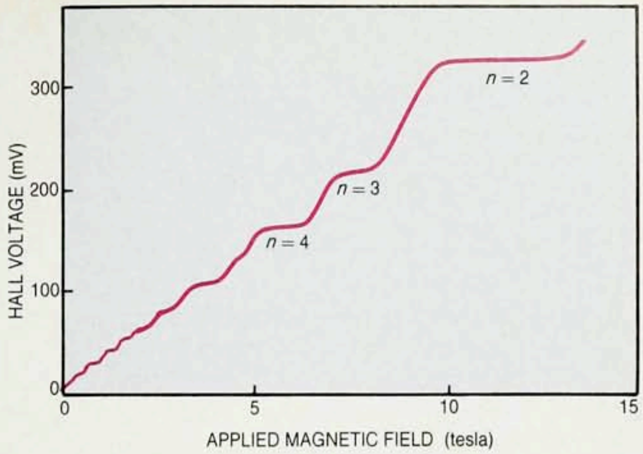
Quantum standards

The ac and dc Josephson effects are characteristic of weakly coupled superconductors. For example, two superconducting niobium films separated by an insulating layer 1 nm thick form a Josephson junction. When such a junction is irradiated with microwave radiation of frequency f, the curve of current vs voltage exhibits current steps at quantized Josephson voltages U_J. The voltage $U_J(n)$ of the nth step is nf/K_J, where n is an integer and K_J is now called the Josephson constant.

There is much experimental evidence indicating that K_J is independent of step number, frequency, superconductor material, temperature and other experimental variables to very high precision. That is to say, the Josephson constant appears to be a universal quantity. In fact, one experiment has shown[4] that K_J was the same for two Josephson devices made of different superconductors to within a relative difference of 2×10^{-16}. The experimental observations are consistent with the theory of the Josephson effects, which predicts that K_J is exactly equal to $2e/h$, where e is the elementary charge and h is the Planck constant.

The integral and fractional quantum Hall effects (see PHYSICS TODAY, January 1988, page 17) are characteristic of two-dimensional electron gases. Such a gas may be realized in a high-mobility GaAs–$Al_xGa_{1-x}As$ heterostructure of standard Hall-bar geometry when the applied magnetic field B is of order 10 T and the heterostructure is cooled to about 1 K. The electron gas confined at the interface is then fully quantized. Such a device is shown in figure 1. When a current I flows along the interface, one measures the Hall voltage drop U_H transverse to I in the plane of the current. The Hall resistance R_H is defined as the quotient U_H/I. For a fixed current I (typically 10–50 μA) through the heterostructure, the curve of Hall voltage vs B exhibits plateaus where U_H remains constant. In the limit of zero dissipation in the direction of current flow, the Hall resistance of the nth Hall plateau is quantized and given by $R_H(n) = R_K/n$, where n is an integer and R_K is called the von Klitzing constant, after Klaus von Klitzing, who discovered the quantum Hall effect in 1980. Figure 2 clearly shows quantum Hall plateaus starting with $n=2$. R_K is equal to the resistance of the $n=1$ plateau—about 25 813 ohms.

There is considerable experimental evidence that R_K is a universal quantity, provided that the quantum Hall device being measured meets certain criteria.[5] While the universality of R_K has not been demonstrated to the same level of precision as that of K_J, experimental investigations of the effect of plateau number, device material, device type, temperature and current show that R_K may be reproduced with a relative precision approaching a few parts in 10^9, if adequate precautions are taken. These experimental studies are consistent with the theory of the quantum Hall effect, which predicts that $R_K = h/e^2$. This quotient of fundamental constants can also be written as



Quantum Hall plateaus are evident in this plot of Hall voltage U_H vs applied magnetic field, measured by Marvin Cage and NIST colleagues on a device similar to that in figure 1. The data were taken at a temperature of 1.39 K, with the current I held fixed at 25.52 μA. The Hall resistance U_H/I shows plateaus at quantized values R_K/n, where $R_K \approx 25\,813\ \Omega$ appears to be a universal constant. **Figure 2**

$\mu_0 c/2\alpha$, where c, the speed of light in vacuum, is exactly 299 792 458 m/s and $\alpha \approx 1/137$ is the fine-structure constant.

Thus the Josephson and quantum Hall effects provide invariant "quantum standards" of voltage and resistance that can be used to establish highly reproducible and uniform representations of the volt and ohm worldwide through the international adoption of agreed "conventional" values of K_J and R_K. The conventional values of K_J and R_K adopted by the CIPM and CCE are $K_{J\text{-}90} = 483\,597.9$ GHz/V exactly and $R_{K\text{-}90} = 25\,812.807\ \Omega$ exactly, where the subscript 90 indicates that these values are to come into effect on 1 January 1990, and not before.

Consistency with SI

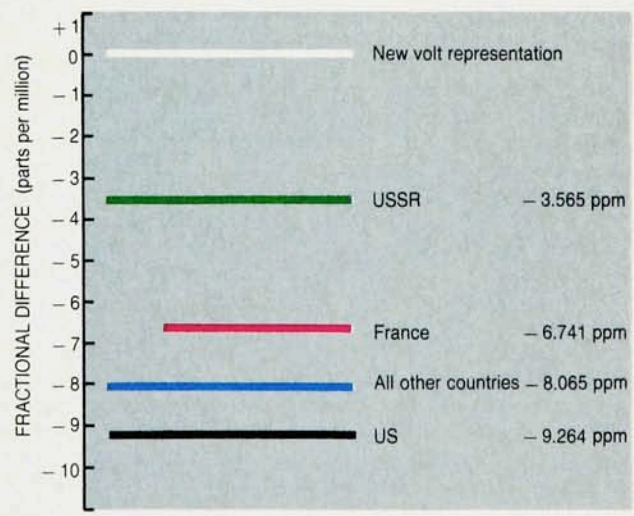
The agreement of these new practical representations of the volt and ohm with the SI has been ensured by deriving $K_{J\text{-}90}$ and $R_{K\text{-}90}$ from the best available direct measurements of K_J and R_K in SI units, as well as from relevant determinations of fundamental constants.[6] (Our cover shows an instrument built by Thomas Olsen and colleagues at the National Institute of Standards and Technology for the determination of K_J in SI units.) Indeed, the CIPM believes that an ideal representation of the volt based on the Josephson effect (assuming no experimental error) and $K_{J\text{-}90}$ will agree with the (SI) volt to within a conservatively assigned relative uncertainty of 0.4 parts per million (one standard deviation). Similarly, an ideal representation of the ohm based on the quantum Hall effect and $R_{K\text{-}90}$ should agree with the (SI) ohm to within 0.2 ppm.

It must be emphasized that these conventional values of the Josephson and von Klitzing constants are being adopted for the purposes of practical electrical metrology only. The CIPM and CCE are not "defining" the values of $2e/h$ and h/e^2 (or α), nor are they altering the definitions of the SI units. Indeed, as noted by the CCE,[1] the Josephson and quantum Hall effects and the values $K_{J\text{-}90}$ and $R_{K\text{-}90}$ cannot be used to define the volt and ohm in the present SI. To do so would require a change in the status of μ_0 from an exactly defined constant, which would nullify the definition of the ampere. It would also result in electric units that are incompatible with the definition of the (SI) kilogram and units derived from it.

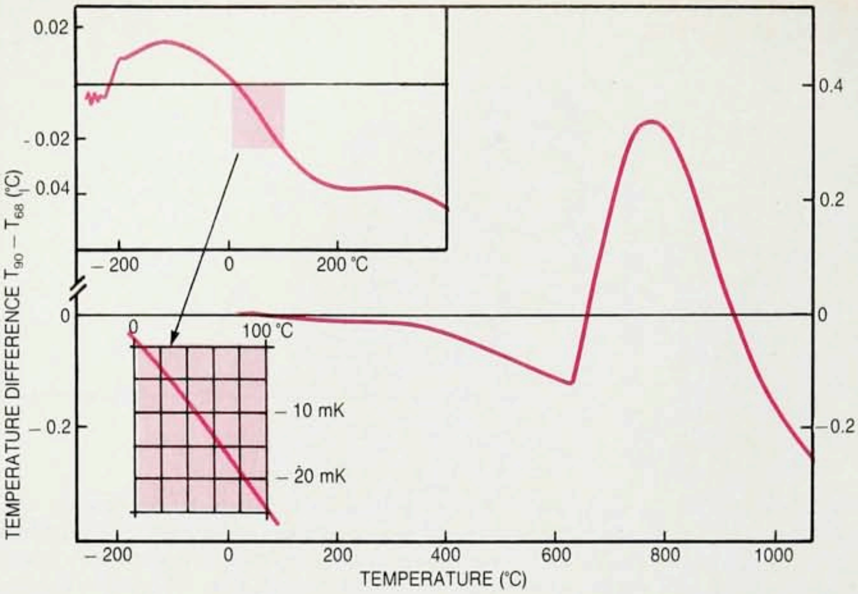
One should therefore not be disturbed that the compilation of recommended values of the fundamental constants beginning on page BG 8 of the *Buyers' Guide* (Part 2 of this issue of PHYSICS TODAY) lists values of $2e/h$ and h/e^2 slightly different from the CIPM/CCE conventional values of K_J and R_K to be used for the new volt and ohm standards. The values in the *Buyers' Guide* come from the 1986 CODATA (Committee on Data for Science and Technology) set of recommended values for the physical constants,[8] the most up-to-date, self-consistent set available; it is currently in use worldwide. The new conventional values of K_J and R_K, on the other hand, are based mainly on improved data that became available after the completion of the 1986 CODATA compilation. A new CODATA least-squares adjustment of the fundamental constants is scheduled to be finished in 1993. However, the CIPM/CCE conventional values of K_J and R_K for the new practical standards are not expected to be altered in the forseeable future.

In the new year

On New Year's Day, implementation of the new international volt and ohm representations in the US will result



The new practical representation of the volt, effective 1 January 1990, compared with the four existing national practical representations it will supersede. All these practical reference standards, new and old, are based on the Josephson effect, but the new representation uses a revised conventional value of the Josephson constant ($K_{J\text{-}90} = 483\,597.9$ GHz/V *exactly*) that provides better agreement with the (SI) volt than do the four values now in use in different countries. The US volt representation will increase by 9.264 ppm. **Figure 3**



Difference between the new 1990 International Temperature Scale (ITS-90) and the 1968 scale (IPTS-68) it supersedes. The plot at upper left shows the region below 400 °C with expanded vertical scale. The region from 0 to 100 °C is further expanded at lower left. ITS-90, which becomes effective next 1 January, improves the agreement of the practical scale with SI thermodynamic temperature. **Figure 4**

in increases of 9.264 ppm and 1.69 ppm, respectively, in the values of the national volt and ohm representations maintained at the National Institute of Standards and Technology (NIST, formerly the National Bureau of Standards). Because $A = V/\Omega$ and $W = V^2/\Omega$, the resulting increase in the values of the US representations of the ampere and the (electrical) watt will be about 7.57 ppm, and 16.84 ppm respectively. The changes in the electric unit representations of most other countries will be of comparable magnitude. See figure 3.

These changes are sufficiently large that thousands of electrical standards, measuring instruments and electronic systems throughout the world will have to be adjusted to bring them into conformity with the new representations. The change will affect, for example, standard cells and resistors, solid-state voltage references, high-precision digital voltmeters and multimeters, and programmable voltage sources.

In adjusting standards and instruments to bring them into conformity with the new representations, one should bear in mind that if a measurement unit increases in size by x parts per million, the value of a quantity measured in terms of this unit will *decrease* by x ppm. This means, for example, that the emf value assigned a standard cell in the US immediately prior to 1 January 1990 must be decreased by 9.264 ppm on New Year's Day. Similarly for a digital voltmeter, the reading obtained for an arbitrary but constant input voltage after the meter is adjusted to the new volt representation must be 9.264 ppm smaller than the reading prior to the adjustment. However, the situation is reversed for a programmable voltage source. In that case the adjustment should have the effect of increasing the positive voltage output of the source by 9.264 ppm.

Capacitance, mass and temperature

In the US the value of the national representation of the farad maintained at NIST, which is based on the mean capacitance of a group of fused silica reference capacitors periodically calibrated by a calculable cross capacitor, will be reduced on 1 January 1990 by about 0.14 ppm to bring it into better agreement with the (SI) farad.[7] Consequently the values assigned standard capacitors calibrated by NIST will need to be increased by this amount. Similarly, the value of the US representation of the kilogram disseminated by the NIST mass-calibration service will be increased by 0.17 ppm to bring it into better agreement with the (SI) kilogram. Therefore, on 1 January 1990 the values assigned mass standards calibrated by NIST should be correspondingly decreased.

In accordance with the 1988 Recommendation of the CIPM, the International Practical Temperature Scale of 1968 (IPTS-68) will be superseded on 1 January by the International Temperature Scale of 1990 (ITS-90). The new practical temperature scale is in much closer agreement with thermodynamic temperature, as defined in the SI, than is the IPTS-68, which has been found to deviate significantly from thermodynamic temperature in certain temperature regions. Figure 4 compares the old and new practical scales. Because nearly all temperature measurements are based on the IPTS-68, the introduction of the ITS-90 will have a significant effect on precision thermometry.

For further information regarding the changes in the US electric unit representations and a copy of NIST Technical Note 1263, *Guidelines for Implementing the New Representations of the Volt and Ohm Effective January* 1, 1990, write to the author, Barry N. Taylor, at the National Institute of Standards and Technology, Building 220, Room B258, Gaithersburg, Maryland 20899. For further information regarding the change in the US calibrations of mass standards, write to Richard S. Davis at NIST, Building 220, Room A117. Additional information regarding ITS-90 can be obtained from B. W. Mangum at NIST, Building 221, Room B128.

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