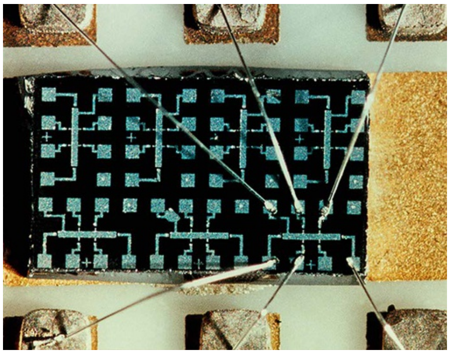
Metrology in 2019

Klaus von Klitzing tells the story of the quantum Hall effect's impact on metrology.

An unexpected discovery in the wee hours of 5 February 1980 marked the birth of the quantum Hall effect (QHE)[1]. The observation of very distinct plateaus in the Hall voltage of a 2D electron gas in a silicon-based field-effect transistor (pictured) initiated a new field of research with many different branches[2]. Its most practical consequence is its impact on metrology and the introduction of a new International System of Units (SI), expected to take effect in 2019 on World Metrology Day, 20 May.

The discovery of the QHE led to a new type of electrical resistor based on the von Klitzing constant $R_K = h/e^2$, a combination of the Planck constant h and the elementary charge e, approximately equal to 25,813 Ω. Today, it has been established that this resistor is universal for all 2D electron systems in strong magnetic fields with an uncertainty of less than one part in 10^{10}. It is more stable and more reproducible than any wire resistor. Consequently, in 1990, all metrology institutes throughout the world accepted a fixed value of 25,812.807 Ω as the quantized Hall resistance, meaning that worldwide uniformity exists at the level of one part in 10^{10}. The downside of this agreement is the fact that the 'quantum ohm' was fixed outside the official SI, so research activities to determine an SI ohm lost their appeal. Nevertheless, an SI ohm is necessary to determine the fundamental constant R_K quantitatively, which, except for a constant factor without uncertainty, is identical to arguably the most famous fundamental physical constant, the inverse fine-structure constant $\alpha^{-1} \approx 137$. The most accurate way to produce an SI ohm is via the calculable Thompson–Lampard capacitor[3], for which one must perform challenging impedance measurements of a capacitor. When the QHE was discovered, the SI ohm was more precisely known than the fine-structure constant, which is why the first QHE publication was entitled "New method for high-accuracy determination of the fine-structure constant based on quantized Hall resistance"[4]. However, this title will be wrong when the new SI features a fixed value for the von Klitzing constant[5]. When that happens, the manuscript's original title, "Realization of a resistance standard based on natural constants", rejected at the time by *Physical Review Letters*, will turn out to be more appropriate.



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Similar to the QHE, the Josephson effect also allows a connection to be made between an electrical unit and fundamental constants. Like the application of the QHE, the Josephson constant $2e/h$ is used all over the world for voltage calibrations so that all electrical units can be related to the fundamental constants h and e and realized with high stability and reproducibility.

The present situation of electrical quantum units is comparable to that of the international electrical units introduced in 1893. At that time, international electrical standards were defined based on the most stable and reproducible realizations of electrical units — a mercury wire for resistance and an electrochemical cell for voltage. These definitions were disconnected from idealized absolute units based on the centimetre–gram–second system. In the same way, the electrical quantum units used today are outside the official SI units.

An incorporation of the electrical quantum units into a new SI system with fixed values for h and e is envisaged for 2018. These fundamental constants will then replace the present definitions of the SI base units kilogram and ampere. Another interesting application of the electrical quantum units is to establish an electronic kilogram via the Kibble balance[6], which allows a direct connection to be made between the Planck constant and the kilogram. Note that fixed values for h and e in the new SI system will not lead to a fixed value for the fine-structure constant because the vacuum permeability $\mu_0 = 4\pi \times 10^{-7}$ V s A^{-1} m^{-1} is incorporated in the fine-structure constant and therefore only has a fixed value (via the definition of the ampere) in our present SI system.

Our measurement system started on a local level, where the size of a local leader's foot or hand or the weight of grains determined standards of length and mass. This was followed by a global system, where the Earth's properties played an important role in establishing an internationally accepted system of measures. Prototypes for the metre and the kilogram were meant to guarantee the stability of these units, but the kilogram in particular turned out to be unstable with time. Finally, with the introduction of a new SI system based on fixed values for constants of nature, Max Planck's vision will become reality: with the help of fundamental constants we have the possibility of establishing units that necessarily retain their significance for all cultures, even unearthly and nonhuman ones. The quantum Hall effect triggered this realization. ❐

KLAUS VON KLITZING is at the
Max Planck Institute for Solid State
Research, Heisenbergstrasse 1, D-70569
Stuttgart, Germany.
e-mail: k.klitzing@fkf.mpg.de

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m e Å s u R E_h F Ω °R μ_0 ε_0 α σ V R e