Essay: Quantum Hall Effect and the New International System of Units

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On 20 May 2019 the International System of Units will switch over to a new, globally accepted set of definitions based on constants of nature. The quantum Hall effect, discovered 39 years ago, plays an essential role in this development and will now contribute to a new definition of the kilogram. Ironically, the title of publication in *Physical Review Letters* that introduced the quantum Hall effect is, in hindsight, inaccurate in view of the revised units [K. von Klitzing, G. Dorda, and M. Pepper, New Method for High-Accuracy Determination of the Fine-Structure Constant Based on Quantized Hall Resistance, Phys. Rev. Lett. **45**, 494 (1980)].

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Each year, on 20 May, World Metrology Day is celebrated to mark the establishment in 1875 of an internationally accepted set of units via a treaty signed by 17 nations. Last November, delegates from 59 nations met in Versailles and agreed to a transition to a new version of the International System of Units (the SI system) on 20 May 2019. While length and time have been measured in the current system of units with constants of nature—the velocity of light and a special transition frequency of the cesium atom, respectively—the 2019 protocol will introduce fixed values of constants of nature for all legal measurements. The Planck constant h, the elementary charge e, the Boltzmann constant k, and the Avogadro constant N_A will form the basis for a measurement system "for all times, for all people," relating its units to the most stable quantities in the Universe.

Effective 20 May 2019, the International System of Units is the system of units in which [1]

Defining constant	Symbol	Numerical value	Unit
Unperturbed ground-state hyperfine transition frequency of ^{133}Cs	$\Delta\nu_{\mathrm{Cs}}$	9 192 631 770	Hz
Speed of light in vacuum	c	299 792 458	m/s
Planck constant	h	$6.626\,070\,15 \times 10^{-34}$	J s
Elementary charge	e	$1.602\,176\,634 \times 10^{-19}$	C
Boltzmann constant	k	$1.380\,649 \times 10^{-23}$	J/K
Avogadro constant	N_A	$6.022\,140\,76 \times 10^{23}$	mol^{-1}
Luminous efficacy of monochromatic radiation of frequency 540×10^{12} Hz	K_{cd}	683	lm/W

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In 1900 Max Planck developed the vision of using fundamental constants for the definition of measurement units "that necessarily retain their significance for all cultures, even unearthly and nonhuman ones" [2]. However, the famous Planck units for length, time, mass, and temperature are not practical for high-precision realizations of units and practical applications.

The discovery of the quantum Hall effect, reported in *Physical Review Letters* in 1980 [3], played a crucial role in redefining units in terms of constants of nature. The unexpected observation that the Hall resistance in two-dimensional systems shows precise quantized steps with a fundamental resistance value of $h/e^2 \approx 25.8\ \mathrm{k}\Omega$ opened the way to direct determination of fundamental constants and the realization of an electrical resistor that is independent of the microscopic details of a device. Envisioned as a metrological application of this discovery, the initial version of the manuscript submitted to PRL on 30 May 1980 had the title "Realization of a Resistance Standard Based on Fundamental Constants." Such an application was inspired by the use of the ac Josephson effect as a voltage standard based on the fundamental constant $2e/h$, now known as the Josephson constant. Some years earlier, in 1973, the National Bureau of Standards of the U.S. had announced a new definition of a fixed value for the Josephson constant for the U.S. legal volt, which is more stable and reproducible than the earlier definition that had been based on an electrochemical cell [4].

The quantum Hall effect could similarly be used as a resistance standard more stable than any wire resistor. Indeed, a conventional value for the von Klitzing constant h/e^2 was subsequently introduced in 1990 [5], improving the uniformity of resistance calibrations by more than two orders of magnitude. However, the initial focus of the quantized Hall resistance, today arguably the most important application of this quantum phenomenon, did not survive the peer review process. One of the referees correctly pointed out that not a fundamental resistor but just an accurate determination of h/e^2 is more interesting, since calibrated resistors in SI ohms are available via the ac resistance of a calculable capacitor [6]. It turns out that h/e^2 is identical (apart from a numerically fixed proportional constant $\mu_0 c/2$) to the inverse fine-structure constant α. In any case, our manuscript was eventually published with the more attractive title "New Method for High-Accuracy Determination of the Fine-Structure Constant Based on Quantized Hall Resistance." However, with the coming adoption of the new SI system in May, this title in hindsight will no longer be accurate as the quantized Hall resistance has a fixed value and the accuracy of the fine-structure constant is not determined by h/e^2 but by the value μ_0 of the permeability of the vacuum, which has to be determined experimentally.

The new International System of Units will integrate the quantum standards for the volt and the ohm, realized with the Josephson and quantum Hall effects, respectively, and adjusted to the SI system in 1990 into a harmonized measurement system based on constants of nature. The consequence of this unification is that in May the basis for voltage calibrations will change by 0.107 ppm and that for resistance calibrations by 0.018 ppm. While initially this change would be of significance only for major metrology institutes working at the highest levels of precision, any continuing discrepancy between conventional units and SI units would have a creeping negative impact on industrial applications and measurements. That said, the main reasoning behind the decision to revise the International System of Units was that the definition of the unit of mass is based on what is after all an artifact—a platinum-iridium alloy cylinder stored in a Paris suburb. The new definition based on fundamental constants will be inherently more stable and accurate.

It is telling that basic research on a silicon field-effect transistor eventually led to the discovery of the quantum Hall effect, which in turn revolutionized not only electrical metrology but has now contributed to a new definition of the kilogram based on a fixed value of the Planck constant by comparing mechanical power with electrical power [7].

In this essay I focused on the impact of the quantum Hall effect specifically on metrology. However, for future PRL publications, aspects such as topology, the fractional quantum Hall effect, and new interaction phenomena will be more important, not to mention that a microscopic picture of the quantum Hall effect for real devices with electrical contacts and finite current flow is still missing.

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[1] Adopted 16 November 2018 resolution of the General Conference on Weights and Measures (CGPM), https://www.bipm.org/utils/en/pdf/CGPM/Draft-Resolution-A-EN.pdf.

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