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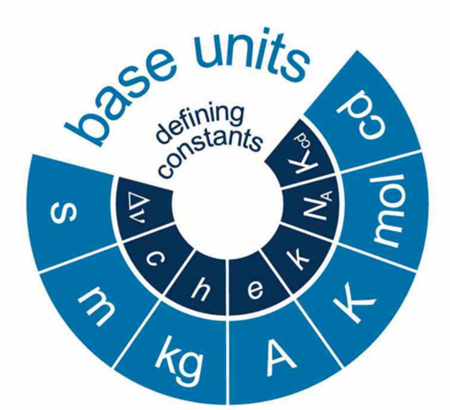
A new foundation for all measures

Fundamental constants are to define the units in the International System of Units in the future



In the new International System of Units (SI), seven fundamental constants are determined as defining reference values. (Diagram: PTB)

The second and the metre have already surged ahead. The kilogram, the ampere and the other physical base units are now trying to catch up. This is one way of describing what is currently happening in the world of metrology, in the world of measuring. The International System of Units is facing a redefinition of its foundations: fundamental constants are to serve as the defining reference values for all seven base units and for all derived units in the future. Delicate, unstable objects such as the International Prototype of the Kilogram or completely impractical definitions like the one used for the electric current will then be a thing of the past. The experimental preparations for these new definitions are running at full speed all over the world – and especially at the Physikalisch-Technische Bundesanstalt (PTB). At the next General Conference on Weights and Measures in 2018, it is expected that this new era will be officially heralded. The scientific and high-technology communities will benefit from this. Consumers will not notice the changes in their everyday measurements.

How long is a second, how far is a metre and how heavy is a kilogram? Everyone knows – at least roughly. But in a high-tech world things want to be measured a little more precisely than "roughly". And so the metrologists of this world have always tried to put the basis of their actions on a firm footing and to define the physical units as well as possible. If all the definitions were already as advanced as those of the units of time and length, the second and the metre, then the metrological world would be completely fine. Looking at the measurement of time, atomic clocks have set the benchmark for almost 50 years – the second can be derived from the energy structure of a caesium atom. And for the measurement of length, the International Prototype Metre bar has belonged to the past for decades and has made space for more modern definitions. Today, the metre is that distance which light travels in a certain fraction of a second. With the speed of light as an invariable fundamental constant, this definition is perfect. Unlike the prototype metre bar, it cannot be bent, lengthened, shortened or changed in any other way.

Metrologists would like the same principle to apply to all the other base units, especially to the kilogram and the mole, the ampere and the kelvin. The definitions of these four show much room for

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improvement: the International Prototype of the Kilogram and its national copies suffer from fluctuations in mass and unexplained drifts. The kelvin temperature scale is based on water – and the defining fixed point of this scale (the so-called triple point) is sensitively dependent on the exact isotopic composition of the water used. The ampere is defined by means of an idealized experimental set-up of two infinitely thin conductors of infinite length and their force on each other – an anachronism above all compared to the units for electric potential difference and electric resistance, which are based on quantum effects.

This situation affecting some of the base units has tormented metrologists for years and is thus, at the same time, an enormous incentive to look for solutions. Just like for the second and the metre, fundamental constants might change everything for the better. As soon as a connection between a base unit and a fundamental constant is found, the old definition can be shelved, as long as (and this is where the actual crux of the issue lies) precisely this fundamental constant is known with sufficiently good accuracy, i.e. can be measured with precisely this accuracy. In the laboratories of the National Metrology Institutes (NMIs), experiments on measuring these selected fundamental constants are therefore currently being undertaken. And meanwhile the results are so promising that the International Committee for Weights and Measures passed clear resolutions for a new system of units at its last General Conference in November 2014: in all likelihood the new definitions will come into force at the next General Conference in 2018 and thus be binding for all 55 Member States and 41 Associates of the Metre Convention.

The remaining time until the next General Conference will now be used in all large NMIs for preparing the redefinitions experimentally. At PTB all the base units are hot research areas: PTB's results of measuring the fundamental constants for the new kilogram (Planck constant), the new mole (Avogadro constant) and the new kelvin (Boltzmann constant) as well as the realization of the new ampere (elementary charge per second) are key results for the redefinitions.
jes/ptb

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Further information is available from:

- J. Stenger, J. H. Ullrich, "Für alle Zeiten … und Culturen", Physik Journal 13 (2014) No. 11
- Resolutions of the 25th CGPM (General Conference on Weights and Measures): http://www.bipm.org/en/cgpm-2014/

Annex:
Fundamental constants for refining the base units in the International System of Units (SI = Système international d'unités)

The planned redefinitions in the SI will join each base unit with a "defining constant" and determine the numerical values for these seven selected constants. A clear one-to-one correspondence exists for the second and the mole. For the other base units, more than one specified constant is needed. For the metre for instance, apart from the speed of light, the caesium reference frequency is also needed. What is important in the framework of the redefinition is that with the determination of the seven constants, all the derived units are automatically defined. Hence the coulomb (as ampere times second) is directly a multiple of the constant "elementary charge".

Physical quantity	Base unit	Defining fundamental constant
Time	**Second**	**$\Delta\nu(^{133}Cs)_{hfs}$ (hyperfine splitting transition)** The ground state hyperfine splitting frequency of the caesium 133 atom $\Delta\nu(^{133}Cs)_{hfs}$ is exactly 9 192 631 770 hertz, Hz.
Length	**Metre**	**c (speed of light)** The speed of light in vacuum c is exactly 299 792 458 metre per second, m s^{-1}
Mass	**Kilogram**	**h (Planck constant)** The Planck constant h is exactly 6.626 069 57 × 10^{-34} joule second, J s.
Electric current	**Ampere**	**e (elementary charge)** The elementary charge e is exactly 1.602 176 565 × 10^{-19} coulomb, C.
Temperature	**Kelvin**	**k_B (Boltzmann constant)** The Boltzmann constant k_B is exactly 1.380 648 8 × 10^{-23} joule per kelvin, J K^{-1}.
Amount of substance	**Mole**	**N_A (Avogadro constant)** The Avogadro constant N_A is exactly 6.022 141 29 × 10^{23} reciprocal mole, mol^{-1}.
Luminous intensity	**Candela**	**K_{CD} (photometric spectral luminous efficacy)** The photometric spectral luminous efficacy K_{CD} of monochromatic radiation of frequency 540 × 10^{12} Hz is exactly 683 lumen per watt, lm W^{-1}.

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The Physikalisch-Technische Bundesanstalt, Germany's national metrology institute, is a scientific and technical higher federal authority falling under the competence of the Federal Ministry for Economic Affairs and Energy.

Physikalisch-Technische Bundesanstalt (PTB)

At PTB in Berlin and Braunschweig, time comes from atomic clocks, lengths are measured far into the nano-world, scientists do research on fundamental questions concerning the physical units, and the employees in the laboratories calibrate measuring instruments, meeting the most demanding requirements. Therefore, the Physikalisch-Technische Bundesanstalt is among the top names in metrology worldwide. As Germany's national metrology institute, PTB is Germany's highest authority when it comes to correct and reliable measurements. It is the supreme technical authority of the Federal Ministry for Economic Affairs and Energy (BMWi) and employs a total of approx. 1900 staff members at its two sites (Braunschweig and Berlin).