



Physikalisch-Technische Bundesanstalt
National Metrology Institute

The new International System of Units (SI)



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The system of references we use to “measure the world” is well defined. For instance, we divide time into seconds, length into meters and mass into kilograms. The International System of Units (SI) has been approved by nearly 100 states and is thus a global success story. The SI is now being fundamentally revamped so that it will be able to face all scientific and technical challenges of the 21st century with ease. Fundamental constants such as the speed of light or the charge of an electron will now provide the optimal basis for the definition of the units.



The idea

The second and the meter have long attained a state that the other units can only be envious of: they are based on invariable physical properties. The second, for example, is based on a defined number of oscillations in the electron shell of the cesium atom, and the definition of the meter exploits the speed of light as a fundamental characteristic of nature. The decisive advantage of using fundamental constants as the basis for the definition of units is that they are exactly what their name suggests – constant. In contrast, if the meter is embodied as the original prototype of the meter (for instance, in the form of a platinum/iridium rod with an x-shaped cross section), it is basically impossible to achieve consistency. The slightest variation in temperature leads to a change in the length of this meter, and things become even worse if the prototype is damaged. For any prototype of the meter, changes on the order of micrometers are inevitable, even when it is handled with the greatest care. In our high-tech world, where the nanometer has long become commonplace, such changes have a significant impact and must therefore be prevented. The solution to this problem is to avoid using a material measure to define a unit, but to use a

fundamental constant instead. This change towards standard (!) fundamental constants still lies ahead for all the remaining units, but the roadmap for this change has already been defined. In the autumn of 2018 (if everything goes according to plan, which is very probable), the revised system of units will be signed and sealed by an international conference in Paris.

The experiments

In the system that comprises the units currently in use, the values of the fundamental constants are determined. This is how we have defined what a kilogram is, and we use this unit to determine the mass of a proton, of an electron or of other elementary particles. This leads to the remarkable situation that the values of the fundamental constants are in a permanent state of flux, since our measurement capabilities are reflected in these values. There is even a group of experts, the “CODATA Task Group on Fundamental Constants” in the United States, whose task it is to assess the values of fundamental constants measured in physics laboratories throughout the world and to bring them in line with one another. Every four years, the charge of an electron, to name one example, is assigned a new numerical value although – in reality – the charge itself has not changed at all. What has changed is merely our proficiency at the art of measuring and thus our knowledge of the world.



As early as 1900, Max Planck, by formulating his (radiation) law, already brought “constants” into play as well as the idea of “natural measurement units” that would be valid “for all times and all civilizations, even extraterrestrial and non-human ones”.

Photo (taken about 1901): Archives of the Max Planck Society, Berlin-Dahlem

Δv

The trouble with the kilogram

To put it bluntly, the kilogram is outdated. It still is what it was at the end of the 19th century – namely, the mass of a particular metallic cylinder stored in a safe at the International Bureau of Weights and Measures (BIPM) near Paris. Each kilogram weight in the world is based on this prototype of the kilogram. And this is not all: numerous other units, such as the mole or the ampere, depend on the kilogram. If there is a problem with the kilogram, there is thus automatically a problem with these other units as well. The problems with the definition of the kilogram arise because the kilogram is realized as a material measure, i.e. as an object – and macroscopic objects are bound to undergo changes. The prototype of the kilogram and the national copies each member state of the Metre Convention has received are no exceptions to this rule. Today, if the assertion is made that no one knows how heavy a kilogram is with microgram accuracy, this may contradict the definition, but describes the problem quite adequately. These circumstances prompted metrologists to solve this problem.

Two experiments that are based on different principles have been conceived to make the kilogram's future stable. In one approach, the force of gravity that acts on a weight is compensated for by an electromagnetic force. This approach exploits several electrical quantum effects, so that these experiments (the so-called “watt balance experiments”) provide a value of Planck's quantum of action h . Essential contributors to this experiment are located in Canada, the United States and England. An alternative method to this (which is preferred by PTB) links a macroscopic mass with the mass of an atom. Counting an extremely large number of atoms can only be achieved if the atoms are located in a structure with a strong order, namely in a monocrystalline structure. This experiment (which is called the “Avogadro experiment” because it directly yields the Avogadro constant as a result) is based on a crystal sphere made of isotopically pure silicon which, as the base material, was concentrated in ten thousands of centrifuges. Despite the scientific competition prevailing between these two experiments, they will eventually have to find common ground. Only if the results from both experiments are in agreement with each other will they pave the way for the new kilogram.

The event

Every four years, the metrological community comes together on the occasion of a “global family meeting”. The member states and the associate states of the Metre Convention (an intergovernmental treaty that goes back to 1875) delegate political and scientific representatives to the General Conference on Weights and Measures (CGPM) in Paris in order to define the metrological path that is to be taken in the years thereafter. Here, changes to the International System of Units must not only be scientifically well-founded, but it must also be possible to achieve consensus about their implementation in science at the political level. After all, the units we want to use for measurements are not only elements of a small scientific community, but an essential tool for all commercial and scientific



By revising the system of units, the tables will be turned: in the new system, it will be possible to express any velocity as a function of the speed of light, or each electric charge as a function of the elementary charge of an electron. This means that, in the new system, the units are no longer set in stone but are calculated on the basis of the specified fundamental constants. However, it would be preferable, for example, for 37 °C to remain the body temperature of a healthy human being or for us not to have to worry about the new definition of the kilogram while we are standing on our bathroom scale. For this reason (i.e., to ensure a smooth transition from the old system to the new system), metrology laboratories are trying to measure the constants in question one last time with the best possible accuracy. These experiments are being conducted in the form of a cooperative competition between the national metrology institutes. And eventually, besides the already defined “clock frequency” in the cesium atom and the speed of light, the following constants will also be assigned fixed values: Planck's quantum of action (or Planck's constant) h , the Avogadro constant N_A , the Boltzmann constant k_B and the elementary charge e .



activities. Any change to the system of units has immediate consequences on the “measuring economy” in all of its technological areas and also for each citizen – as a consumer, as a customer or as a patient – whose everyday life is always a “measured life”. Decisions concerning the system of measurement, such as those made at the General Conference, are therefore not made *en passant* but have been prepared and reflected upon for a long time in advance. This is particularly true of the coming General Conference in November 2018, which has the adoption of the fundamental revision of the SI on its agenda. The prerequisites and requirements for a new SI have already been formulated at several previous General Conferences and have therefore set target marks for metrological laboratories. According to the indicators, the metrology institutes will attain the objectives set (especially sufficiently small measurement uncertainties). It is planned for the new SI to officially come into force on 20 May 2019, a very symbolic date – World Metrology Day, the Metre Convention’s anniversary.

The new SI at school

The question “What is a kilogram?” asked by a teacher is an easy catch for all schoolchildren who have taken a look at their books, even only a furtive one. All the correct answer requires are the terms “prototype of the kilogram”, “very old” and “Paris” – these say everything. According to the new definition, the same question – provided a teacher would ask it at all – would only prompt physics aces to put their hands up. From the point of view of most schoolchildren, this is obviously a shame, but that’s how it is: the new SI is considerably more abstract and intellectually demanding than the current system. First, every schoolchild would have to grasp the basics of the general meaning of fundamental constants and to question this very notion: What are fundamental constants? Where did they come from in the first place? Why are they the way they are? Then, the selected fundamental constants must be understood more in depth. This probably still works quite well with the speed of light, but what about a constant with the dimension of an action (h)? The actual problem with understanding the new system is that the selected constants are not a literal realization of the base units. If this were the case, each unit would be attributed “its own constant”. This, however, would presuppose that this constant had the exact same dimension as the unit in question. The previous definition of the meter, for instance, which was based on a wavelength of light as an elementary length, was an example of such a “simple attribution”. In contrast, the new SI requires higher intellectual transfer capacities. Nearly all quantities used in mechanics (which are formed on the basis of the units of time, length and mass) are realized via the three constants of a frequency, a velocity and an action. What is essentially done here is a representation of the world by means of a new coordinate system. The challenge consists

in finding one’s bearings in this new system – a challenge not only for each schoolchild, but also for the didactic approaches of each teacher.

The new SI in science

The new system of units represents a milestone in the history of science and will – in the foreseeable future, after the new definitions take effect – also represent a milestone in the history of technology. At the same time, the new system, due to its universal validity, represents considerably more than this: it is a milestone in the history of civilization itself. From the Middle Ages until well into the 18th and 19th centuries, the units were decreed by the sovereign of a country, and used regionally for the most part. With the French Revolution at the close of the 18th century came the abandonment of feet, ells and miles, lines, fathoms and rods in favor of a measure wrested from the planet Earth – the meter was born, and with it came the kilogram. The Metre Convention (in 1875) and its Member States put these units into use throughout the world. Today, our life on this planet is characterized by a single, uniform measuring system; this applies, without exception, to science and, to a large extent, to everyday life. And in 2018, the step will then be taken that reaches beyond our little planet. By being based on fundamental constants, the definitions of the units become, in principle, universal. For science, this is a tremendous progress, alone from a systematic point of view. “Systematic” refers to the scope of application of the SI and at the same time represents its inner logics. In the new SI, the differentiation into base units and derived units, for example, is no longer needed. All units are instead “derived” from fundamental constants; against this background, they are all equivalent.



The new SI in technology

For the scientific community, progress takes effect as soon as the new definitions have been adopted. In the technical area, progress will show in the long run. What is even more important: no technological barriers of any kind will be inherent in the new system of units. If, in the current system, the mass of the prototype of the kilogram varies within a certain order of magnitude, then the best achievable accuracy is limited by exactly this factor. In contrast, the new SI is not subject to variations, since the fundamental constants have been attributed binding fixed values. Thus, the definition of the kilogram will be independent of any possible mass drifts of any material measure. All electrical units (including the ampere) will be included in the system via quantum realizations (via the Josephson and the quantum Hall effects or “simply” by counting electrons per units of time). Last but not least, the mole will now also be defined via a fixed number of particles (the Avogadro constant) of a specified substance. Thus, the following applies to the new SI: if you can measure more precisely, then the units can be realized with greater accuracy as well, without changing the definition they are based on. In a high-tech world where length subdivision does not end with nanometers and time subdivision does not end with femtoseconds, this technical openness towards the new SI is a huge bonus for all future progress in terms of precision. And this openness applies to the whole scale of the unit concerned, since the fundamental constants do not emphasize any particular section of a scale. This differs somewhat from the present situation, where the kilogram favors the 1 kg graduation mark on the mass scale, or the triple point of water correspondingly favors the 0.01 °C graduation mark on the temperature scale.

The new SI in public life

For the general public, the good news about the SI is that life will continue as usual. Measurements performed after the adoption of the new definitions will not be any different than those carried out the day before. The changes in the system of the SI will go unnoticed in everyday life. The scale at the supermarket and the pump at the gas station will work in exactly the same way after the new definitions have come into force. Whether it is the complete blood count at a medical laboratory or the large-scale coordinate measuring machine in industry – neither will provide different values with the new definitions. And the electricity bill will not change either – at least not due to the new SI. One of the most important requirements for the revision of the system of units is for it to take place smoothly and without causing any service interruption. Far from being a highly esthetic theoretical structure (even though metrologists are very enthusiastic about the systematic nature of the new system), the SI is more of a system that was designed to work in practice and is supposed to make our technical daily routine manageable, even in a globalized world. The really good news about the new SI for the public at large is therefore that there is massive global consensus that the kilogram, the kelvin and their cohorts are now standing on solid ground. And the other good news for all export-dependent countries is that nothing can now keep them from having brisk commercial exchanges with all Martians and others.

 μ
 K_{cd}

The candela

 $\Delta\nu$
 K

The kelvin

Images:

The new SI is much more abstract. In this system, each unit is obtained via fundamental constants that, by means of multiplication, are coupled with each other. In most cases, several fundamental constants are indeed necessary in order to realize a unit. The meter, for instance, needs two constants; the kilogram needs three.

Annex: The units and “their” constants

In the new SI, seven fundamental constants will be assigned fixed values. These numerical values originate from the CODATA least squares adjustments in the summer of 2017.

- Frequency of the **hyperfine structure transition** of the ground state in the cesium 133 atom
 $\Delta\nu = 9\,192\,631\,770\,\text{s}^{-1}$
- **The speed of light** in vacuum
 $c = 299\,792\,458\,\text{m s}^{-1}$
- **Planck’s constant**
 $h = 6.626\,070\,15 \cdot 10^{-34}\,\text{J s}$ ($\text{J s} = \text{kg m}^2 \text{s}^{-1}$)
- **The elementary charge**
 $e = 1.602\,176\,634 \cdot 10^{-19}\,\text{C}$ ($\text{C} = \text{A s}$)
- **The Boltzmann constant**
 $k = 1.380\,649 \cdot 10^{-23}\,\text{J K}^{-1}$ ($\text{J K}^{-1} = \text{kg m}^2 \text{s}^{-2} \text{K}^{-1}$)
- **The Avogadro constant**
 $N_A = 6.022\,140\,76 \cdot 10^{23}\,\text{mol}^{-1}$
- The **photometric spectral luminous efficacy** K_{cd} of monochromatic radiation of frequency $540 \cdot 10^{12}\,\text{Hz}$ is exactly 683 lumen per watt.

The second (s)

$$1\,\text{s} = 9\,192\,631\,770/\Delta\nu$$

The meter (m)

$$1\,\text{m} = (c/299\,792\,458)\,\text{s} = 30.663\,318\dots\,c/\Delta\nu$$

The kilogram (kg)

$$1\,\text{kg} = (6.626\,070\,15 \cdot 10^{-34})\,\text{m}^{-2}\,\text{s} = 1.475\,521\dots \cdot 10^{40}\,h\,\Delta\nu/c^2$$

The ampere (A)

$$1\,\text{A} = e/(1.602\,176\,634 \cdot 10^{-19})\,\text{s}^{-1} = 6.789\,686\dots \cdot 10^8\,\Delta\nu\,e$$

The kelvin (K)

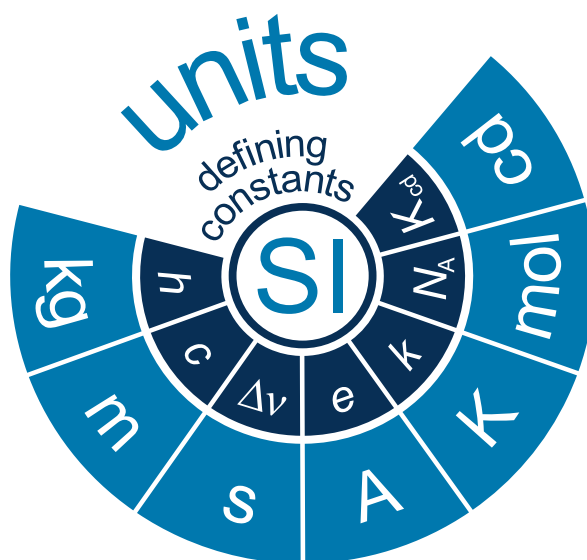
$$1\,\text{K} = (1.380\,649 \cdot 10^{-23}/k)\,\text{kg m}^2 \text{s}^{-2} = 2.266\,665\dots\,\Delta\nu\,h/k$$

The mole (mol)

$$1\,\text{mol} = 6.022\,140\,76 \cdot 10^{23}/N_A$$

The candela (cd)

$$1\,\text{cd} = (K_{\text{cd}}/683)\,\text{kg m}^2 \text{s}^{-3} \text{sr}^{-1} = 2.614\,830\dots \cdot 10^{10}\,(\Delta\nu)^2\,h\,K_{\text{cd}}$$



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Cover photo (Earth): NASA