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NEW INTERNATIONAL SYSTEM OF UNITS, SI*

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On November 16$^{\text{th}}$, 2018, during the 26$^{\text{th}}$ meeting of the General Conference on Weights and Measures (CGPM) in Versailles, the new International System of Units, SI, was approved. In the new system, all seven units of measurement are defined by universal constants making the system independent of the properties of materials, as well as the place and time of the individual units realization. The four basic units — kilogram, ampere, kelvin and mole — were re-defined in terms of the following physical constants: the Planck constant h, the elementary charge e, the Boltzmann constant k and the Avogadro constant N_{A}, respectively. In the present paper, a brief history of system of units is presented, and information on the activity of scientists and the International Bureau of Weights and Measures that led to the re-definition of the system is provided.

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1. Introduction

The International System of Units having been in force since 1960, with several subsequent changes, defined seven basic units — metre, kilogram, second, ampere, kelvin, mole and candela — which are the units of physical quantities: length, mass, time, electric current, thermodynamic temperature, amount of substance, and luminous intensity, respectively [1, 2]. Three of them — metre (through c), ampere (with μ_0) and candela (as K_{cd}) — have been defined by fundamental or conventional constants. Three more definitions: of second (by $\Delta\nu_{\mathrm{Cs}}$), kelvin (by T_{WTP}) and mole (through $m\,^{12}\mathrm{C}$), were based on material and atomic properties, and the last one was the definition of kilogram based on an artefact (M_{IPK}). Only the 3 definitions based on fundamental constants guaranted invariation of the units. Other 4 units, defined by properties of matter, or by means of an artefact — like the kilogram — could change, and such changes were observed indeed [3].

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For example, the temperature of the triple point of water $T_{\rm WTP}$ strongly depends on an isotopic composition of water used as the standard [4, 5]. International comparisons of the kilogram (secondary) standards (the artefacts used by several National Metrology Institutes and the (primary) $M_{\rm IPK}$ stored in a BIPM safe) carried out between 1889 and 1989 showed changes in mass of the oldest national prototypes of kilogram with respect to the mass of the international prototype $M_{\rm IPK}$ equal of about $50\,\mu$g/100 years [3]. These findings influenced CIPM's decision of recommending to undertake research in order to change the definition of kilogram. It was considered that the unit of mass can be defined by the Planck constant h or the Avogardo constant $N_{\rm A}$ [6]. Shortly after this resolution, CIPM proposed to define all basic SI units in terms of the fundamental physical constants in order to eliminate any artefact or material dependencies and ensure the long-term stability of the units. In 2005, CIPM formulated the Recommendation No. 1 [7, 8] which postulated to define four units in terms of appropriate fundamental constants as follows:

— **kilogram** in terms of the Planck constant $\boldsymbol{h}$,

— **ampere** in terms of the elementary charge $\boldsymbol{e}$,

— **kelvin** in terms of the Boltzmann constant $\boldsymbol{k}$,

— **mole** in terms of the Avogadro constant $\boldsymbol{N_{\rm A}}$.

The primary criterion of the changes assumes that *essential condition of relevant experiments results must be met:*

— *at least two / three independent experiments should yield consistent values of the constants with suitable small uncertainty,*

— *at least one of these results should have the required uncertainty accepted for the new definition of units.*

Thereafter, the largest metrology institutions in cooperation with scientific institutes around the word, under the auspices of the International Committee of Weights and Measures (CIPM), begun intensive research to elaborate a new universal, often called *quantum* system of units. The required uncertainty of the experiments published by CODATA [9, 10] and accepted by BIPM for the new definition of the units was achieved only after 12 years of the research, in 2017! On November 16$^{\rm th}$, 2018, in Versailles the General Conference on Weights and Measures (CGPM), at its 26$^{\rm th}$ meeting, adopted the Resolution on the revision on the International System of Units, SI [11]. The System officially came into force on May 20$^{\rm th}$, 2019 when the World Metrology Day was celebrated.

2. Brief history of the system of units

The significant development — on a global scale — of science, technology and industry, as well as trade in the nineteenth century required the development of measurement principles and unification of the system of units of measurement. Already around 1832, C.F. Gauss proposed a three-dimensional coherent unit system — centimeter, gram, second — in which basic mechanical quantities — length, mass and time — were expressed. The system was known as the CGS system. The discovery and development of electricity and magnetism caused the need to extend this system by an additional, fourth unit, appropriate for electrical quantities as ampere or ohm. The first step on this way was done by G. Giorgi in 1901. Earlier, on May 20$^{\rm th}$, 1875, representatives of seventeen nations signed the Metre Convention [12], the basic international agreement on units of measurement. Then the International Bureau of Weights and Measures (French: Bureau international des poids et mesures, BIPM), an intergovernmental organization under the authority of the General Conference on Weights and Measures (French: Conférence générale des poids et mesures, CGPM) and the supervision of the International Committee for Weights and Measures (French: Comité international des poids et mesures, CIPM) were created. The four-dimensional system proposed by Giorgi, based on metre, kilogram, second, and ampere, was approved by CIPM as MKSA system in 1946. In 1954, at the 10$^{\rm th}$ meeting of CGPM, another two units — kelvin and candela — were added to the system, kelvin being the unit of thermodynamic temperature, candela — luminous intensity. In 1960, the 11$^{\rm th}$ CGPM gave the name of the system — the International System of Units, with abbreviation SI (from French: Système International (d'unités)). This system, with a few changes — among them, in 1971, a new unit, mole, was added — was in force until May 20$^{\rm th}$, 2019. The whole system defined 7 units: meter, kilogram, second, ampere, kelvin, mole, and candela [13].

3. New approach

When in 2005 CIPM recommended undertaking research leading to redefinition of measurement systems [5], it assumed that all seven SI units would be defined in terms of fundamental constants that describe the natural world:

— **second** in terms of frequency of the transition in ^{133}Cs atom $\boldsymbol{\Delta\nu_{\rm Cs}}$,

— **metre** in terms of the speed of light in vacuum $\boldsymbol{c}$,

— **kilogram** in terms of the Planck constant $\boldsymbol{h}$,

— **ampere** in terms of the elementary charge $\boldsymbol{e}$,

— **kelvin** in terms of the Boltzmann constant $\boldsymbol{k}$,

— **mole** in terms of the Avogadro constant $\boldsymbol{N_{\mathrm{A}}}$,

— **candela** in terms of the luminous efficacy of radiation $\boldsymbol{K_{\mathrm{cd}}}$.

The definitions will specify the exact numerical value of each constant when its value is expressed in the corresponding SI unit.

The research lasting several years focused on achieving the required accuracy of the individual constant measurements. It has been assumed that the measurement accuracy of the constant has to be such that the unit defined in terms of it is determined with an uncertainty comparable to that previously achieved. In 2017, CODATA (Committee on Data for Science and Technology) published the results that met this condition [9, 10].

The CODATA* 2017 values of the $\boldsymbol{h, e, k}$ and $\boldsymbol{N_{\mathrm{A}}}$ constants with relative standard uncertainty $\boldsymbol{u}$ are:

— the Planck constant $\boldsymbol{h} = 6.626\,070\,150\,(69) \times 10^{-34}\,\mathrm{J\,s}$ with $u = 1.0 \times 10^{-8}$,

— the elementary charge $\boldsymbol{e} = 1.602\,176\,634\,(83) \times 10^{-19}\,\mathrm{C}$ with $u = 5.2 \times 10^{-9}$,

— the Boltzmann constant $\boldsymbol{k} = 1.380\,649\,03(51) \times 10^{-23}\,\mathrm{J\,K^{-1}}$ with $u = 3.7 \times 10^{-7}$,

— the Avogadro constant $\boldsymbol{N_{\mathrm{A}}} = 6.022\,140\,758\,(62) \times 10^{23}\,\mathrm{mol^{-1}}$ with $u = 1.0 \times 10^{-8}$.

Based on these results, numerical values of the seven constants were used for definition of the new SI. The values of the defining constants have no uncertainty.

4. The SI new definitions

The International System of Units, the SI, is the system of units in which:

— the unperturbed ground state hyperfine transition frequency of the caesium 133 atom $\boldsymbol{\Delta\nu_{\mathrm{Cs}}}$ is 9 192 631 770 Hz,

— the speed of light in vacuum $\boldsymbol{c}$ is 299 792 458 $\mathrm{m\,s^{-1}}$,

— the Planck constant $\boldsymbol{h}$ is $6.626\,070\,15 \times 10^{-34}$ J s,

— the elementary charge $\boldsymbol{e}$ is $1.602\,176\,634 \times 10^{-19}$ C,

— the Boltzmann constant $\boldsymbol{k}$ is $1.380\,649\times10^{-23}$ J K^{-1},

— the Avogadro constant $\boldsymbol{N_A}$ is $6.022\,140\,76\times10^{23}$ mol^{-1},

— the luminous efficacy of monochromatic radiation of frequency 540×10^{12} Hz, $\boldsymbol{K_{cd}}$, is 683 lm W^{-1}.

This is a complete definition of the new SI [11, 14]. This definition is supplemented by the comment [14]: "*where the* hertz, joule, coulomb, lumen, *and* watt, *with unit symbols* Hz, J, C, lm, *and* W, *respectively, are related to the units* second, metre, kilogram, ampere, kelvin, mole, *and* candela, *with unit symbols* s, m, kg, A, K, mol, *and* cd, *respectively, according to* $\mathrm{Hz} = \mathrm{s}^{-1}$, $\mathrm{J} = \mathrm{kg\,m^2\,s^{-2}}$, $\mathrm{C} = \mathrm{A\,s}$, $\mathrm{lm} = \mathrm{cd\,m^2\,m^{-2}} = \mathrm{cd\,sr}$, *and* $\mathrm{W} = \mathrm{kg\,m^2\,s^{-3}}$".

In the new SI, the order in which units are presented has been changed so as not to introduce a definition of a basic unit depending on another in the further position. The definitions of the units are as follows:

— The **second**, symbol **s**, is the SI unit of time. It is defined by taking the fixed numerical value of the caesium frequency $\Delta\nu_{\mathrm{Cs}}$ of the unperturbed ground-state hyperfine transition frequency of the caesium 133 atom, to be 9 192 631 770 when expressed in the unit Hz, which is equal to s^{-1}.

— The **metre**, symbol **m**, is the SI unit of length. It is defined by taking the fixed numerical value of the speed of light in vacuum $\boldsymbol{c}$ to be 299 792 458 when expressed in the unit m s^{-1}, where the second is defined in terms of the caesium frequency $\Delta\nu_{\mathrm{Cs}}$.

— The **kilogram**, symbol **kg**, is the SI unit of mass. It is defined by taking the fixed numerical value of the Planck constant $\boldsymbol{h}$ to be $6.626\,070\,15\times10^{-34}$ when expressed in the unit J s, which is equal to kg m^2 s^{-1}, where the metre and the second are defined in terms of c and $\Delta\nu_{\mathrm{Cs}}$.

— The **ampere**, symbol **A**, is the SI unit of electric current. It is defined by taking the fixed numerical value of the elementary charge $\boldsymbol{e}$ to be $1.602\,176\,634\times10^{-19}$ when expressed in the unit C, which is equal to A s, where the second is defined in terms of $\Delta\nu_{\mathrm{Cs}}$.

— The **kelvin**, symbol **K**, is the SI unit of thermodynamic temperature. It is defined by taking the fixed numerical value of the Boltzmann constant $\boldsymbol{k}$ to be $1.380\,649\times10^{-23}$ when expressed in the unit J K^{-1}, which is equal to kg m^2 s^{-2} K^{-1}, where the kilogram, metre and second are defined in terms of h, c and $\Delta\nu_{\mathrm{Cs}}$.

— The **mole**, symbol **mol**, is the SI unit of amount of substance. One mole contains exactly $6.022\,140\,76 \times 10^{23}$ elementary entities. This number is the fixed numerical value of the Avogadro constant, N_{A} when expressed in the unit mol^{-1} and is called the Avogadro number. The amount of substance, symbol $\boldsymbol{n}$, of a system is a measure of the number of specified elementary entities. An elementary entity may be an atom, a molecule, an ion, an electron, any other particle or specified group of particles.

— The **candela**, symbol **cd**, is the SI unit of luminous intensity in a given direction. It is defined by taking the fixed numerical value of the luminous efficacy of monochromatic radiation of frequency 540×10^{12} Hz, K_{cd}, to be 683 when expressed in the unit $\mathrm{lm\,W^{-1}}$, which is equal to $\mathrm{cd\,sr\,W^{-1}}$, or $\mathrm{cd\,sr\,kg^{-1}\,m^{-2}\,s^{3}}$, where the kilogram, metre and second are defined in terms of h, c and $\Delta\nu_{\mathrm{Cs}}$.

Logo of the new system is shown in figure 1 [14, 15].

Fig. 1. Logo of the new SI.

5. Practical realization

Practical realization of the units with the highest accuracy is difficult. Few of the largest metrology institutes in the world were able to build adequate equipments and achieve the required accuracy. Thus, NIST in the United States, PTB in Germany, NPL in Great Britain, LNE in France, INRiM in Italy, and metrology institutes in Japan and China played a leading role. However, none of these institutes has the standards of all seven units of measurement. The International Bureau of Weight and Measures, aware of the difficulties associated with the implementation of units in accordance with the new definitions, recommended the relevant Consultative Committees to develop documents with a symbolic name *Mise-en-pratique* [16] each containing a set of instructions that allows to realize the definition in practice at the highest level. BIPM also published special issues of the journal

Metrologia containing articles on research that led to the redefinition of SI [17–20]. The document entitled *Information for users about the proposed revision of the SI* [21] discuss the effects of introducing the new definitions of units for science, technology and all those areas of everyday life in which we use measures.

6. Summary

The new SI, defined in terms of the seven fundamental physical constants, despite huge experimental difficulties and some critical voices [22, 23], has become a fact. On November 16$^{\text{th}}$, 2018, the 26$^{\text{th}}$ General Conference on Weights and Measures approved the new definition of the International System of Units proposed by the International Committee for Weights and Measures, recommending its implementation on May 20$^{\text{th}}$, 2019, at the anniversary of the signing of the Metre Convention.

Currently, extensive activities of metrologists are needed to disseminate knowledge about the new system in the whole world. Editorial work is also extremely important. The text of the new definitions must be translated into the languages of the signatories of the Metric Convention. In Poland, this task is carried out by the Central Office of Measures. For the correct editing of official documents, it is necessary to cooperate with specialists in physics and chemistry, as well as linguists.

The Institute of Low Temperature and Structure Research of the Polish Academy of Sciences in Wrocław has participated in research on the Boltzmann constant $\boldsymbol{k}$ determination in the frame of project 18SIB02 *Realising the redefined kelvin* (Real-K) managed by the National Physical Laboratory in United Kingdom. The Institute also conducted in Poland popularization activities in the form of lectures, publications, and conference presentations [24–27] .

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