Commission Electrotechnique Internationale
International Electrotechnical Commission
Международная Электротехническая Комиссия

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Geneva, Wednesday 25 September 2019

Subject: **IEC report to CCU for the 24th CCU meeting, 8 October 2019**

Dear Dr Stock,

Please find here under a summary of the activities on going in IEC which are of interest to the CCU.

1. New SI Brochure implementation in IEC

The new definitions of the units are in the process of being updated in the IEC IEV. The IEC IEV is the International Electrotechnical Vocabulary which is published also as a set of publications in the IEC 60050 series. This is the largest set of terminology dedicated to electrotechnology. The IEC has a free on-line version called Electropedia.
Workshop on "The revised SI and its impact on the IEC": At its yearly General Meeting, IEC has organized a workshop to spread the information about the new definitions of the units and its impact on standardization work. The IEC General Meeting is the biggest IEC meeting. It will be held in Shanghai, will last two weeks and more the 3000 IEC Experts are expected.
IEC TC 25, “Quantities and units” is currently jointly working with ISO to revise the ISO 80000-1 and take into account the changes in the new SI. The impart on other parts of this series has also been analysed and other revision projects are under way accordingly.

2. Unit as Quantity

Several discussions have taken place at BIPM about this topic and more work will be needed to develop a consensus position about this topic. IEC intends to develop and publish (IEV & Electropedia) a set of terms which is coherent. When working to implement the new Unit definition some incoherencies appeared and an in-depth analysis was conducted by experts under the lead of Prof Luca Mari, Chair of IEC TC 1 “Terminology”. The result of this work is presented in annex to this document.

IEC is in the opinion that this is a terminology topic which needs to be handled by the JCGM (Joint Committee for Guides in Metrology) Working Group 1 (Working Group on the International Vocabulary of Metrology).

3. GCJM Membership

Following the resignation of Dr Michel Krystec in WG 2, IEC has undergone a review of the IEC membership in JCGM WG 1 and WG 2. Now, the three IEC representatives in WG 1 and WG 2 maintain close connections with TC 1 and TC 25. In order to ensure that the IEC representatives properly raise the position of IEC in WG1 and WG 2, the IEC Central Office has established the “IEC Coordination group for measurement science”. The group membership includes the IEC

representatives in JCGM WG1 and WG2, the TC 1 and TC 25 Officers, IEC Central Office staff and an ISO liaison.

Yours sincerely,

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Annex: A terminological analysis of the definitions of the base units in the revised SI

MAR/TO

A terminological analysis of the definitions of the base units in the revised SI

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Abstract: This paper analyses the structure of the new definitions of the base units in the revised SI and discusses the possible strategies of definition which leads to provide information about the SI units that is (I) in conformity with the 2018 CGPM Resolution 1, (ii) terminologically correct, and (iii) as understandable as possible to standards writers and users, translators, textbook writers, and the general public.

1. Introduction

With Resolution 1 of the 26th (2018) General Conference on Weights and Measures (CGPM), "On the revision of the International System of Units (SI)", the revised SI is a reality, and since 20 May 2019 the new definitions of the SI base units have come into effect. The fundamental novelty is that the whole system[1] is now explicitly based on a set of constant quantities, from whose fixed values the definitions of the seven base units are deduced. In particular the kilogram is now defined in relation to constants (the Planck constant, together with the constants that define the metre and the second) instead of as the mass of a given artefact, thus achieving a substantial improvement in stability and universality. With the aim of emphasizing this "explicit constant" (also called "constants first") approach, the 2018 CGPM Resolution, and then the new edition SI Brochure (BIPM, 2019), present the SI according to a new structure, in which a distinction is made between the new *explicit constant* and the traditional *explicit unit* definitions of units.[2]

While the correctness of the metrological content of these definitions is not under discussion, the way they are presented has been considered with some concerns (Mari et al, 2017), in view of their very role to communicate measurement information meaningfully and widely to everyone, "from the Nobel Prize winner to the proverbial man and woman in the street" (Petley, 1990). Making the revised SI widely understandable was recognized by the CGPM itself as an important task at least since 2011 (CGPM, 2011), and the recommendation became explicit in 2014 to present "the revised SI in a way that can be understood by a diverse readership without compromising scientific rigour" (CGPM, 2014).

Of course technical standards play a key role in such a dissemination activity. As a result, the sentences by which the units are defined in the revised SI *need to be carefully reviewed* in view of their inclusion in a terminologically correct document, such as the standards series IEC 60050, published as the International Electrotechnical Vocabulary (IEV) / Electropedia and the standards series ISO 80000 and IEC 80000, "Quantities and units". While several conditions need to be taken into account in the formulation of a terminologically correct definition (several ISO standards are devoted to this – see in particular ISO 704, 2009), it is sufficient to consider here that a definition should not be circular: "if one concept is defined using a second concept, and that second concept is defined using the term or elements of the term designating the first concept, the resulting definitions are said to be circular" (ISO 704, 2009: entry 6.5.2), where it is then noted that "circular definitions make it impossible to fully understand the concept and shall be avoided". Together with circularity, another challenge posed by the explicit constant definitions of the revised SI is that

[1] The International Vocabulary of Metrology (VIM; JCGM, 2012) includes the definitions of the key concepts – 'system of quantities' [def. 1.3], of which the International System of Quantities [def. 1.6] is the relevant case, and 'system of units' [def. 1.13], of which the International System of Units [def. 1.16] is the relevant case.

[2] "The new definitions [...] are intended to be of the explicit constant type, that is, a definition in which the unit is defined indirectly by specifying explicitly an exact value for a well-recognized fundamental constant" (CGPM, 2011). The novelty of this structure has been widely analyzed and discussed. See for example (Milton 2007), (Mohr 2008), (Cabiati, Bich, 2009), (Mills et al, 2011), (Newell 2014).

they are more abstract in their formulation than the traditional explicit unit definitions, so that some readers not familiar with fundamental physics would plausibly find them harder to understand.

The purpose of this paper is to analyse the structure of the new definitions with respect to terminological correctness and meaningfulness and to identify a strategy of definition which leads to provide information about the SI units that is

α. in conformity with the 2018 CGPM Resolution 1,

β. terminologically correct, and

γ. as understandable as possible to standards writers and users, translators, textbook writers, and the general public.

The outcome of the analysis is that there is a trade-off between conformity with the explicit constant approach (i.e., condition α above) and understandability to a general readership (condition γ), an important condition for technical standards to fulfil in general and, as remarked, particularly for the meaningful communication of measurement information. Given that terminological correctness (condition β) is a requirement, this constrains the set of the structural options that may be adopted to identify a strategy of definition. This paper has then also the specific purpose of presenting this controversial situation in order to stimulate and seek comments and suggestions.

2. The structure of the previous definitions

With the aim of identifying the features of the new structure of the definitions of the units in the revised SI, let us consider the simple example of the metre,[3] for which the revised SI changed only the structure of the definition, not its physical content.

Before the revision (SI Brochure, 8th edition – extract from 2.1.1.1):

> The metre is the length of the path travelled by light in vacuum during a time interval of 1/299 792 458 of a second.
> It follows that the speed of light in vacuum is exactly 299 792 458 metres per second, $c_0 = 299\,792\,458$ m/s.

whose conceptual structure is:

> (A) The metre is the length of the path travelled by an entity moving at a constant speed c in $1/n$ s.
> (B) It follows that the constant speed c has the value n m/s.

From a terminological perspective it is important to point out that there is only one definition in this structure, i.e., sentence (A). The constant speed c referred to in definition (A) is not defined here, but only assumed to be somehow identifiable (as a physical quantity, not in its value) independently of the definition of the metre, so that sentence (B) provides additional information about the value that such constant speed c has *after* the metre has been defined.[4] Furthermore, definition (A) includes a reference to another unit, the second, whose definition would require an analogous analysis. Hence, even though (B) includes a reference to (A), this kind of structure does not constitute a circular definition, so that adapting it to a terminological context such as the IEV / Electropedia was not a problem (IEV 112-02-05:2010-01):

> **112-02-05**
> m
> **metre**

[3] All the definitions in the revised SI have the same structure, and therefore one example is sufficient to illustrate this.

[4] And were the constant speed to be defined in the same context, the definition shall not refer to the unit metre in order to avoid the circular situation of a unit defined in terms of a constant quantity and that constant quantity defined in terms of that unit. In fact, this condition is not currently fulfilled in Electropedia, where speed of light is defined as “fundamental physical constant the value of which has been fixed at exactly 299 792 458 m/s with the definition of the metre in SI” [IEV 113-01-34]. Independently of the changes related to the revised SI, this should be rectified.

meter, US
SI unit of length, equal to the length of the path travelled by light in vacuum during a duration of 1/299 792 458 of a second

Finally, it should be noted that the metre – and the same holds for all seven base units – is defined as a property *of something* (the path travelled by light in vacuum during a given fraction of a second), and this makes the definition simpler to understand.

On this basis let us now analyse the new structure of definitions, as presented in the 2018 CGPM Resolution and thence adopted in the revised SI, and how they can be adapted to a terminological context.

3. The structure of the new definitions

After the revision (26th CGPM Resolution 1):

> The International System of Units, the SI, is the system of units in which (...) the speed of light in vacuum c is 299 792 458 m/s. (...)
> Starting from [this] definition(, the) definitions of each of the seven base units are deduced (...):
> 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 c to be 299 792 458 when expressed in the unit m/s, where the second is defined in terms of $\Delta\nu_{Cs}$.

whose conceptual structure is:

> The SI is the system of units in which (...)
> (C) the constant speed c has the value n m/s. (...)
> Starting from the definition of the SI in terms of fixed numerical values of the defining constants, the definitions of each of the seven base units are deduced (…):
> (D) The metre is the length such that the value of the constant speed c is n m/s.

Differently from the previous situation, here both (C) and (D) are definitions, and *this generates a problem of circularity*: in (C) the constant speed c is defined in terms of a value whose unit includes the metre; in (D) the metre is defined in terms of the value of the constant speed c. The problem here is not that the concepts (of 'metre' and 'speed of light in vacuum') are wrongly defined, but only that the phrasing of the CGPM Resolution *cannot be taken verbatim in a terminologically correct document*. Before proposing a solution to this problem, let us justify this claim. And since this is a structural issue, for better highlighting what is structural in the problem, let us consider the structurally even simpler definition of the unit of time in the revised SI (26th CGPM Resolution 1):

> 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 $\Delta\nu_{Cs}$ is 9 192 631 770 Hz (...)
> Starting from the definition of the SI in terms of fixed numerical values of the defining constants, the definitions of each of the seven base units are deduced (...):
> The second, symbol s, is the SI unit of time. It is defined by taking the fixed numerical value of the caesium frequency $\Delta\nu_{Cs}$, 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}.

whose conceptual structure is:[5]

> The SI is the system of units in which (...)
> (C') the constant period Δt_{Cs} has the value n s. (...)
> Starting from the definition of the SI in terms of fixed numerical values of the defining constants, the definitions of each of the seven base units are deduced (…):
> (D') The second is the duration such that the value of the constant period Δt_{Cs} is $1/n$ s.

[5] As a further structural simplification, we rephrase in terms of period, and therefore duration, what the definition says in terms of frequency.

As phrased, these definitions are circular: the constant frequency of the caesium 133 atom is defined in terms of a value whose unit is the second, and the second is defined in terms of the constant frequency of the caesium 133 atom, thus making the two definitions *formally* devoid of content. But let us interpret them.[6]

The definition (C') is about the relation between two durations, Δt_1 and Δt_2 (where $\Delta t_1 = 1/\nu_{Cs}$ and Δt_2 = s), and asserts that their ratio is a given numerical value, $\Delta t_1 / \Delta t_2 = n$. It is fundamental to acknowledge here that Δt_1 and Δt_2 *are two empirical quantities, not their values*: this makes the equation meaningful. Indeed, were both Δt_1 and Δt_2 given, their ratio could be obtained by a suitable empirical process, basically aimed at discovering the number n of times the duration Δt_2 needs to be repeated to equate the duration Δt_1. Of course, this is the task of measuring Δt_1 in the unit Δt_2. But in this case the equation is to be interpreted inversely: given are one duration, Δt_1, and the number n, and this is sufficient to identify the other duration Δt_2. In other terms, the actual meaning of (C') is $\Delta t_2 = n^{-1} \Delta t_1$, i.e., the second is the duration of n^{-1} durations Δt_{Cs}. This is a perfectly acceptable definition,[7] thus showing that the two definitions (C') and (D') are *substantially* correct: the formal circularity derives entirely from the way they are phrased, and is a result of emphasizing the explicit constant approach. Thanks to their homogeneous structure, the same conclusion applies to all definitions.

Moreover, the fact that the units are now defined as functions of values of constant quantities has the consequence that it is not necessary that they are defined as properties *of something*. In fact, the second is still explicitly referred to a phenomenon, given that the constant in reference to which it is defined is the constant quantity of a phenomenon, i.e., a duration related to a given transition of a given atom.

But that a fundamental constant always needs to be a property of something is not so clear, particularly without a specific knowledge, as in the case in particular of the Planck constant, in reference to which the kilogram is defined. Let us quote on this matter Resolution 1:

> The International System of Units, the SI, is the system of units in which (...) the Planck constant h is $6.626\,070\,15 \times 10^{-34}$ J s, (...)
> Starting from the definition of the SI in terms of fixed numerical values of the defining constants, the definitions of each of the seven base units are deduced (...):
> The kilogram, symbol kg, is the SI unit of mass. It is defined by taking the fixed numerical value of the Planck constant h to be $6.626\,070\,15 \times 10^{-34}$ 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 $\Delta\nu_{Cs}$.

Here the Planck constant h, i.e., the quantum of action, is not presented as a property of something, and that there is something of which h is a property is not so obvious.[8] This adds a challenge to the terminologist who would like to write definitions that are simple to understand to a general readership: should the new definitions be phrased so that, at least whenever possible, units are defined as properties of something?

[6] There is a notational issue here to be decided, about the symbol by which the caesium frequency is referred to, being a photon frequency ν corresponding to the transition between two atomic energy levels and obtained through the Planck–Einstein relation, $E = h\nu$, where h is the Planck constant. In the 8th edition of the SI Brochure the symbol ν(hfs Cs) is used for the caesium frequency. For the same quantity the CGPM Resolution adopted instead the symbol $\Delta\nu_{Cs}$, which is not consistent with the usual assumption that Δx denotes a difference in the quantity x. For the sake of comprehensibility by the wide readership of technical standards, who are also laboratory technicians, practitioners, teachers, etc., and not only theoretical physicists and metrologists, we believe that the notation ν_{Cs}, thus without the delta, is clearer, and therefore we propose to adopt it.

[7] And in fact it is substantially the definition before the revision (SI Brochure, 8th edition) – extract from 2.1.1.3: "The second is the duration of 9 192 631 770 periods of the radiation corresponding to the transition between the two hyperfine levels of the ground state of the caesium 133 atom.".

[8] Even the familiar case of the constant c is not simple, though for different reasons. While usually presented as the speed of light in vacuum – as indeed is the case in the quoted CGPM Resolution – c enters into the equations of physics in diverse ways, sometimes where a motion of light is not explicit, as in $c^2 = \mu_0\varepsilon_0$.

4. Towards terminologically correct definitions

The analysis above has highlighted a trade-off between conformity with the explicit constant approach of the revised SI (condition α) and understandability (condition γ), a condition that is specifically important given the aim of IEC and ISO to produce technical standards which effectively support the communication of meaningful measurement information.[9] On this basis we introduce and discuss *four structural options* of SI unit definitions, which set the space for the decision to be made. The definitions of the second, the metre, and the kilogram are sufficiently representative of the problems to be solved to fulfil conditions α, β, and γ, and therefore these are the units analysed here (for maintaining the focus on the conceptual structure the numerical values are omitted).

Before the revision (as currently in Electropedia (IEV 112-02-04, -05 and 06:2010-01))

second	metre	kilogram
duration of n_1 periods of the radiation corresponding to the transition between the two hyperfine levels of the ground state of the caesium 133 atom	length of the path travelled by light in vacuum during a duration of $1/n_2$ of a second	mass of the object called the "international prototype of the kilogram" kept at the International Bureau of Weights and Measures (BIPM)

For the sake of completeness, the first possibility we consider – let us call it *Option 0* – takes the text of the CGPM Resolution 1 (2018) verbatim.

Option 0: CGPM Resolution 1 (2018) verbatim

second	metre	kilogram
duration such that the fixed numerical value of the caesium frequency v_{Cs}, the unperturbed ground-state hyperfine transition frequency of the caesium 133 atom, is n_1 when expressed in the unit Hz, which is equal to s^{-1}	length such that the fixed numerical value of the speed of light in vacuum c is n_2 when expressed in the unit m/s, where the second is defined in terms of v_{Cs}	mass such that the fixed numerical value of the Planck constant h is n_3 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 v_{Cs}

As already commented, these definitions are phrased in a circular way, and therefore, not fulfilling condition β, cannot be included in a document that is expected to be terminologically compliant with the current rules assumed by IEC and ISO.

The second possibility is obtained by referring to the theoretical structure of the CGPM Resolution 1 (2018): as commented above, once the values of the defining constants are set, the definitions of the units can be deduced: "starting from the new definition of the SI described (...) in terms of fixed numerical values of the defining constants, definitions of each of the seven base units are deduced by taking, as appropriate, one or more of these defining constants" (SI Brochure, 2019, Appendix 3). But if the definition of *y* can be deduced from the definition of *x*, and *x* is defined, there is no need to define *y*. Hence, according to this possibility – let us call it *Option –1* – the task is to phrase in a terminologically appropriate way the definitions of the defining constants but *not to define the units* any more.[10]

[9] As defined in the ISO/IEC Directives, IEC Supplement:2019, Annex SK.

[10] Admittedly, this is not what the CGPM Resolution states: though only in an Appendix, it contains the definitions of the units quoted in *Option 0*, and what more in the main body of the Resolution it is explicitly written that "the Appendices (...) have the same force as the Resolution itself". This redundancy, of definitions that can be deduced from other definitions and nevertheless are assumed to have "the same force as" the primary definitions, may be interpreted as a sign of cautiousness, in favour of maintaining some continuity with the previous strategy of definitions. An analogous message is obtained from the 9th edition of

Option –1: rephrase and do not define the units

– the value of the unperturbed ground state hyperfine transition frequency of the caesium 133 atom v_{Cs} is n_1 Hz;

– the value of the speed of light in vacuum c is n_2 m/s;

– the value of the Planck constant h is n_3 J s.

Even hypothesizing that the task of *Option –1* is fulfilled, the idea of not providing definitions of the units, but only their derivation from defining constants, definitely clashes with condition γ of wide understandability.

Both the third and the fourth possibilities – let us call them *Option 1* and *Option 2* respectively – assume that the definitions of the units in the CGPM Resolution are rephrased in order to remove circularity, so as to fulfil condition β, and interpret in a complementary way the trade-off between condition α and condition γ. *Option 1* privileges the conformity with the explicit constant approach, and therefore maintains definitions whose wide understandability is questionable.

Option 1: rephrased explicit constant definitions

second	metre	kilogram
duration such that the numerical value of the caesium frequency v_{Cs} is n_1 when the unit of duration is this duration	length such that the numerical value of the speed of light in vacuum c is n_2 when the unit of speed is this length divided by the second	mass such that the numerical value of the Planck constant h is n_3 when the unit of action is this mass multiplied by the metre squared and divided by the second

Vice versa, *Option 2* privileges the wide understandability of the definitions, at the price of hiding the explicit constant approach, and in fact phrasing definitions according to the traditional explicit unit strategy.

Option 2: explicit unit definitions

second	metre	kilogram
duration of n_1 periods of the unperturbed ground-state hyperfine transition of the caesium 133 atom	length of the path travelled by light in vacuum in a duration of $1/n_2$ s	---

That the difference between each of these explicit unit definitions and the corresponding explicit constant definition is a matter of emphasis, and not of physical content, is acknowledged by the SI Brochure itself. In the case of the second, after the definition as in *Option 1* it is said that "the effect of this definition is that the second is equal to the duration of n_1 periods of the radiation corresponding to the transition between the two hyperfine levels of the unperturbed ground state of the ^{133}Cs atom" (2.3.1), which is in fact the definition as in *Option 2*. And in the case of the metre, after the definition as in *Option 1* it is said that "the effect of this definition is that one metre is the length of the path travelled by light in vacuum during a time interval with duration of 1/299 792 458 of a second" (2.3.1), which is in fact the definition as in *Option 2*.[11]

Given that, as commented above, the explicit constant definition is in turn the result of a deduction, and therefore both *Option 1* and *Option 2* may be intended as "derived options", from *Option 0* and in fact from

the SI Brochure, in which the relation of deduction between definitions is presented as a relation of "construction between quantities": "all units (...) may be constructed directly from the defining constants" (2.3).

[11] Note a difference in the way these two sentences are phrased: "the effect of this definition is that *the* second is..." and "the effect of this definition is that *one* metre is" (emphasis added): since the reference here is to physical quantities, and not their values, the first phrasing is more correct.

Option –1,[12] in this trade-off we consider that *in the context of technical standards the wide understandability of the definitions is to be privileged over the literal conformity with the explicit constant approach*. At the same time, it must be acknowledged that the possibility of formulating explicit unit definitions in the revised SI is contingent, given that the defining constants are not necessarily properties of something. As mentioned at the end of the previous section, this is a problem in particular for the kilogram, for which *Option 2* does not seem to be applicable.[13]

Admittedly, the situation is complex, also because the three conditions that we have proposed to take into account – conformity with the 2018 CGPM Resolution 1 (α), terminological correctness (β), and wide understandability (γ) – are conceptually orthogonal and fulfilling all of them just does not seem to be possible, with the consequence that in any case the optimum solution would be the result of a compromise. By presenting this controversy we also hope to gather comments and suggestions.

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[12] A modified version of *Option 2* acknowledges that, from the definitions of the defining constants, multiple explicit unit definitions of the same unit may be derived. For example, while in astronomy or geodesy the metre might be defined by interpreting c as the speed of light in vacuum, in spectroscopy the metre might be defined by interpreting c in reference to an interferometric wavelength.

[13] And in fact the 9th edition of the SI Brochure does not give any hint in this direction: while for the second and the metre it suggests that "the effect of [the] definition is that the [unit] is equal to" the multiple of a given phenomenon, nothing similar is said for the kilogram. Of course, some hypotheses consistent with the definitions of the defining constants may be proposed, for example through the equations $E=h\nu=mc^2$, and then $m=h\nu/c^2$ (so that the kilogram would be the equivalent mass of a photon of a given frequency), but this might be considered as one of the possible ways for realizing the definition of the unit. This seems to be a plausible interpretation of what the SI Brochure itself suggests, for example when stating that "The use of a constant to define a unit disconnects definition from realization. This offers the possibility that completely different or new and superior practical realizations can be developed, as technologies evolve, without the need to change the definition." (2.2.1).

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