REVIEW ARTICLE

The next 50 years of the SI: a review of the opportunities for the e-Science age

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Abstract

The International System of Units (SI) was declared as a practical and evolving system in 1960 and is now 50 years old. A large amount of theoretical and experimental work has been conducted to change the standards for the base units from artefacts to physical constants, to improve their stability and reproducibility. Less attention, however, has been paid to improving the SI definitions, utility and usability, which suffer from contradictions, ambiguities and inconsistencies. While humans can often resolve these issues contextually, computers cannot. As an ever-increasing volume and proportion of data about physical quantities is collected, exchanged, processed and rendered by computers, this paper argues that the SI definitions, symbols and syntax should be made more rigorous, so they can be represented wholly and unambiguously in ontologies, programs, data and text, and so the SI notation can be rendered faithfully in print and on screen.

1. Preamble—the development of the SI, ISQ and VIM

Historically, the use of units of measurement preceded the formal concept of physical quantity. Early science, such as the laboratory determination of the density of the Earth [1], reported relative measurements using the units of trade (length, weight, time), and used numerical value equations to describe physical phenomena.

In 1799, the French Government promulgated metric units based on platinum artefacts for the kilogram and metre. In 1873, the British Association for the Advancement of Science described a coherent system of CGS (centimetre-gram-second) units with prefixes of 10^{-6} through 10^{6}. The desire for international agreement on standards for length and mass was crystallized in 1875 with the formation of the General Conference on Weights and Measures (CGPM), and its supporting bodies the International Committee for Weights and Measures (CIPM) and the International Bureau of Weights and Measures (BIPM).

The first formal statement (but not a definition) of 'physical quantity' was published in a monograph on electromagnetism [2]. The modern concept of quantity ('independent of the mode of measurement', i.e. independent of what is now called a 'unit') was formalized in English [3] and the advantages of quantity equations were demonstrated in German [4]. The latter work led to the publication of a German Industrial Standard [5] describing the methods for writing physical equations based on a formal algebra of quantities, now known to metrologists as quantity calculus. In this system, a small number of well-known 'base quantities' are selected, and coherent derived quantities are formed from these by the equations which define physical quantities.

In 1948, the 9th CGPM directed the CIPM to develop a 'practical system of units' (i.e. of convenient size), and in 1960 the 11th CGPM declared the International System of Units (SI). In 1969, the International Organization for Standardization (ISO) published its own version of the SI, ISO 1000 [6]. In 1981, ISO published the corresponding system of quantities (ISO 31) (now known as the International System of Quantities (ISQ)) [7]. Problems with the ambiguous terminology of quantities and units led a consortium of standards bodies to develop the International Vocabulary of Metrology (VIM), published as ISO Guide 99 [8].

In the narrowest interpretation, the Proceedings (*Comptes Rendus*) of the CGPM (in French) are the definition of the SI, but in practice the BIPM's 'SI Brochure' [9], now in its 8th edition (henceforth 'SI8'), represents the international reference. The authorship of the VIM has expanded to include several scientific societies; the third edition (henceforth 'VIM3') was published recently [10]. ISO has periodically revised ISO 1000, ISO 31 and ISO Guide 99. The latest edition, ISO 80000 [11], now incorporates all three documents. Detailed histories of metrology, the ISQ, the SI and particular units and prefixes are described elsewhere [12–17].

2. Introduction

Scientists have now benefited from sharing a common system of units, the SI, for 50 years. Unlike the collections of customary units that it has largely displaced, the SI has one unit for each physical quantity, a structure of prefixes and base and derived units and a set of symbols. The artefacts, definitions and methods for realizing SI units are maintained by the BIPM, which coordinates metrological developments and comparisons by many national measurement institutes [18]. The ISQ and the SI have been described as 'the language of science' [19]; they are equally important to engineering, technology, commerce and everyday life.

The three-dimensional CGS unit systems (based on mass, length and time), previously used in science, were adequate for expressing coherent mechanical, electrical and chemical quantities, although many of the units had sizes which were impractical for laboratory use. The SI was declared in 1960 as an 'evolving' and 'practical' system of units. 'Evolving' is evidenced in the large amount of theoretical and experimental work that has been conducted on changing the standards for the base units from artefacts to physical constants, to improve their stability and reproducibility [20–25]. 'Practical', however, seems to have often been interpreted as 'pragmatic' and this has led to the adoption of some existing units, names and symbols with disregard for consistency and uniqueness. For instance, some SI symbols are ambiguous, and the base unit kilogram carries a prefix in exception to the other base units.

The result is that the SI contains significant inconsistencies and contradictions, which detract from its definition, utility and usability. The issues of definition and utility are mostly 'old' (though unresolved) metrological discussions; the issues of usability do not appear to have been identified systematically. It is unfortunate that the three closely related pillars of science—the ISQ, the SI and the VIM—are under the jurisdiction of independent bodies, with different memberships, legal frameworks and revision schedules.

To various extents, these issues can be accommodated by humans, who have differing levels of understanding of quantity and unit systems and who are used to ambiguity, uncertainty and to deriving meaning through context. The same cannot be said of computer systems, which are now universally used to collect, exchange, manipulate and present quantity and unit information. Thus, there are problems in representing the concepts and values of ISQ quantities and SI units in ontologies and data, problems in transferring, displaying and parsing the SI symbols, and limitations in conducting dimension-checking in computations. These issues are considered in more detail below, and opportunities for rectifying them are presented later. The representation of units in programming languages (a topic as old as programming itself, and still a hurdle for new scientific computing languages [26]) is a specialized subset of these problems and is not considered here.

3. Issues of definition

Issue 1: the metrological concepts in the VIM/ISQ/SI have not been adequately formalized

The definitions of 'quantity', 'kind of quantity' and 'quantity dimension' in the VIM3 are the foundational concepts of quantity calculus, although the VIM does not relate these to the foundational concepts of measurement expressed as nominal, ordinal, interval and ratio scales [27]. The SI uses the concept 'quantity' in the more general sense, i.e. corresponding to the VIM3 'kind of quantity'. An examination [28] of these concepts and their relations has found ambiguities and has suggested an object-oriented approach which could formalize the distinctions, rather than the arbitrary differences implied by the VIM3. A terminological analysis [29] reaches different conclusions. A philosophical analysis of SI8 and VIM3 [30] proposes an additional concept, that of 'parametric quantity', and differentiates 12 instances and classes of 'dimension/kind of quantity/quantity' which could resolve some of the dilemmas (discussed later) about the concepts 'mole' and 'quantities of dimension one'. These papers suggest there are omissions and contradictions in the concepts and language of the VIM, SI and ISQ.

Issue 2: the SI Brochure and ISO 80000 are inconsistent

Since 1969, ISO 1000 (editions 1 to 3) and the SI Brochure (editions 1 to 8) have published versions of the SI that are inconsistent, having different unit-unit product symbols, different 'non-SI units allowed for use with the SI' and different instructions for writing quantities.

Since 1991, the SI Brochure has allowed only the product symbols 'half-high dot' and 'space', and states 'Unit symbols are mathematical entities and not abbreviations. Therefore, they are not followed by a period except at the end of a sentence' (p 130). Since 1981, ISO 1000 has specified the product symbols 'half-high dot', 'space', ‘period’ and ‘implicit’ (e.g. ‘Nm’), with the note about the last ‘... provided that special care is taken when the symbol for one of the units is the same as the symbol for a prefix’. It is not immediately obvious that ‘take special care’ means ‘do not use’, and that not ‘one of’, but only the leading symbol needs to be unambiguous. In ISO 80000-1:2009, the period has been dropped, allowing only ‘half-high dot’, ‘space’ and ‘implicit’, with an extended note about ‘implicit’: ‘this is the case for m, metre and milli, and for T, tesla and tera’. While this example is useful, it does not address the ‘non-SI units accepted for use with the SI’, which introduces another two duplicate symbols, ‘d’ and ‘h’. Does ISO 80000 allow the ambiguous compound units ‘dlm’ (day-lumen or decilumen) and ‘hW’ (hour-watt or hectowatt)?

Although the SI Brochure is the ultimate authority for the SI, ISO standards are widely referenced in national legislations and ISO 1000 has been universally used by engineers and technologists in design, operations and reporting. This long use of the period and the implicit product symbol has leaked into common practice, where it yields

• unit symbols (such as ‘MWh’ or ‘N.m’) which can be correct in law but which are not valid CIPM symbols,

• ambiguous unit symbols such as ‘dlm’, ‘hW’, ‘mN’, ‘Tm’ (discussed further in issue 11).

The SI brochure and ISO 1000/80000 have differed for 30 years on which non-SI units are accepted for use with the SI. Currently ISO 80000 allows ‘min h d ◦ ha l/L t eV u/Da ua’ and SI8 allows ‘min h d ◦ l/L t Np B eV Da ua’.

Another subtle difference between these standards is the convention for expressing the value of a quantity (i.e. a numerical value followed by a space and unit symbol). The SI Brochure explicitly indicates that the space is a product symbol: ‘the value of the quantity is the product of the number and the unit, the space being regarded as a multiplication sign’ (p 133). This is important, because it emphasizes that the symbol is required, and also leaves open the possibility of changing the symbol if necessary. In ISO 1000, this was presented as a formatting rule: ‘... leaving a space between the numerical value and unit symbol’ (clause 6.1). As such, this is often ignored by writers wanting to compress text by concatenating the number and the unit. ISO 80000 is no improvement: section 6.5.6 ‘Other units’ contains an orphan sentence ‘To express values of physical quantities, Arabic numerals followed by the international symbol for the unit shall be used’; section 7.1.4 ‘Expressions for quantities’ is similar to the ISO 1000 formatting rule.

Issue 3: formal logic systems may not be able to represent the relationship between SI base quantities and SI base units

The VIM3 defines ‘base quantity’ as ‘quantity in a conventionally chosen subset of a given system of quantities, where no subset quantity can be expressed in terms of the others’ (definition 1.4). The SI8 asserts, ‘the base quantities are by convention assumed to be independent’ (p 104). However, four of the seven SI base units (metre, candela, mole and ampere) are defined in terms of other base units (in the same way as derived units), and as a base unit is simply an instance of a base quantity, this is in contradiction to the VIM3. This tiny logical fallacy may be difficult to represent in a formal logic system.

Issue 4: can the SI derived units be algebraically reduced?

Discussions of quantity calculus are complicated by different interpretations of the concepts ‘quantity’, ‘dimension’ and ‘unit’. De Boer [14] identifies two schools of thought, the Realists (in which units are regarded as real physical entities) and Systematists (in which the symbols for quantities, dimensions and units represent abstract mathematical concepts which may be manipulated algebraically). The latter view has prevailed, and is formalized in the axioms of quantity calculus in the ISQ:

(1) The dimension of a quantity, dim Q, is the product of the powers of factors corresponding to the base quantities of the system; in the SI

$$\dim Q = \mathrm{M}^{\alpha}\ \mathrm{L}^{\beta}\ \mathrm{T}^{\gamma}\ \mathrm{I}^{\delta}\ \Theta^{\varepsilon}\ \mathrm{N}^{\zeta}\ \mathrm{J}^{\eta}\ .$$

(2) A quantity Q is the product of a numerical value $\{Q\}$ and a unit $[Q]$:

$$Q = \{Q\} \cdot [Q].$$

(3) The product of two quantities is the products of their numerical values and units:

$Q1\ Q2 = \{Q1\}\{Q2\} \cdot [Q1][Q2]$ where $\{Q1\}\{Q2\} = \{Q1\ Q2\}$ and $[Q1][Q2] = [Q1\ Q2]$.

(4) The quotient of two quantities is the quotients of their numerical values and units:

$Q1/Q2 = \{Q1\}/\{Q2\} \cdot [Q1]/[Q2]$ where $\{Q1\}/\{Q2\} = \{Q1/Q2\}$ and $[Q1]/[Q2] = [Q1/Q2]$.

Thus, thermal conductivity is defined in the ISQ as 'areic heat flow rate divided by temperature gradient' [(W/m2)/(K/m)], which is then reduced to W/(m·K).

The realist view is that metrological division is different from arithmetical division and that the algebraic operations applied to abstract quantities cannot be applied meaningfully to concrete units. Simply put, there is no meaning to dividing metres by seconds, or multiplying metres by metres. This can be summarized as 'per' is not synonymous with 'divided by' [31]. In this view, the units of a derived quantity cannot be algebraically reduced, or they become units of a different quantity. (As an aside, common usage is split on this issue: the units of rainfall (m^3/m^2) are invariably reduced to m, but the units of automotive fuel economy (km/L) are never reduced to m^{-2}).

Issue 5: the unit and dimension 'one' have multiple meanings in the SI

The SI identifies three groups of quantities with dimension one: the first includes quantities such as friction factor, mass fraction, volume fraction, refractive index and characteristic numbers like the Reynolds number; the second is numbers that represent a count (number of molecules, degeneracy and partition function) and the third is the special SI names for the unit one, the radian and steradian.

The quantities in the first group, the ratio of two quantities of the same kind, are known in the SI as 'dimensionless derived quantities' and in the ISQ as 'quantities of dimension one'. SI8 states (p 105): 'The coherent derived unit for such dimensionless quantities is always the number one, 1, since it is the ratio of two identical units for two quantities of the same kind'. Hence the use of 'one' as a derived unit is a consequence of the axioms of quantity calculus [32]. The realist view [33] is that relative quantities such as mass fraction and volume fraction are clearly quantities of a different kind and are not comparable, so it can be argued the dimension and unit '1' is not very meaningful.

The SI states about the quantities in the second group: 'All of these counting quantities are also described as being dimensionless, or of dimension one, and are taken to have the SI unit one, although the unit of counting quantities cannot be described as a derived unit expressed in terms of the base units of the SI. For such quantities, the unit one may instead be regarded as a further base unit' (p 120).

The third group, as noted, comprises the SI units radian and steradian. There is vigorous argument that these are not in fact units of angle and solid angle. This is discussed later.

The logarithmic ratios neper, bel and decibel are outside the SI and are also considered dimensionless quantities. SI8 states (p 127): 'The units neper, bel, and decibel have been accepted by the CIPM for use with the International System, but are not considered as SI units', although they are not listed in table 6 'Non-SI units accepted for use with the SI'. It has been suggested that the neper should be adopted as a coherent derived SI unit [34, 35]. Another argument [36] is that these dimensionless ratios are of a different logarithmic nature (natural and decadic) and do not require units. In general, the use of some dimensionless units has led to confusion [37].

Issue 6: the concept and definition of the amount of substance and mole are problematic

In the 19th century, the gram-molecule ('mol') (an Avogadro number of entities) was used by chemists to calculate reaction stoichiometry in mass units, and by physicists in the kinetic gas theory to calculate the number of molecules in a volume [38]. It was a counting unit without a corresponding named quantity. In 1971, the 14th CGPM adopted the thermodynamic concepts 'amount of substance' and 'mole' as a base quantity and base unit of the SI, and the Avogadro number was changed to a constant of Nature with dimension mol^{-1}. 'Amount of substance' is not the same concept as the dimensionless 'number of entities', and was introduced to the SI to give a dimension to chemical quantities, so that, for example, amount concentration has a dimension of *amount volume*$^{-1}$ which conveys more information than *volume*$^{-1}$ [39]. These concepts have been controversial scientifically and pedagogically since; a number of conflicting views are listed here.

• The SI amount of substance is a redundant quantity that could be better represented as 'number of entities'; the SI mole has no relevance to practical chemical measurement, and has caused significant confusion to chemists and additional costs to advanced economies [40].

• The mole is clearly a different type of unit from the other base units. SI8 acknowledges that there is no single unit called simply 'mole', but there are as many units 'mole' as there are kinds of elementary entities. This leads to the conclusion that the SI has not seven, but an unlimited number of base units [30].

• The concept of the mole requires the number of entities comprising one mole, i.e. Avogadro's number, to be exactly equal to the gram-to-dalton mass ratio. Thus the mole, the kilogram and the dalton cannot all be defined independently, although this is the effect of a pending proposal to the CGPM [41].

• The quantity 'amount of substance' is poorly named—no other base quantity is called an 'amount of'. Similarly, the unit name 'mole' is used incorrectly as a quantity adjective (e.g. molar heat capacity)—the name of a derived quantity should be based on its quantity, not unit (e.g. the ISQ recommends 'massic', 'areic', 'volumic') [42].

• The amount of a substance and its mass are homologous concepts. Since the kilogram is defined as the base unit of mass in the SI, the mole cannot also be included in the SI as a unit of mass [43].

• The 'amount of substance' is an incomprehensible quantity, and is difficult to teach [44–46].

Issue 7: the base quantity luminous intensity is inconsistent with the other base quantities

Luminous intensity is not a physical quantity, but a photobiological quantity that exists in human perception. The quantity and the unit candela are inconsistent with the other base units that will soon be defined in terms of physical constants.

4. Issues of utility

Issue 8: the utility of the concept 'dimension' is limited

The concept of 'dimension' in the SI ('quantity dimension' in the VIM3) seems to be fundamental to unit systems, but is difficult to define and carries no more meaning than 'constituent base quantities'; indeed, the SI is often referred to as a seven-dimensional system, meaning it has seven base quantities. Dimensional analysis has provided useful physical insights into fields such as fluid mechanics, but has limitations [47].

It is well understood that the dimension (or units) of a derived quantity does not carry any quantity information, for instance the dimension $\mathrm{ML^2T^{-2}}$ (and unit 'N·m') may be a torque or energy, and the dimension $\mathrm{ML^2T^{-2}\Theta^{-1}}$ may be an entropy or Planck function. Thus it has been suggested that the concept of the dimension of a derived quantity is minimal, if not misleading [48].

This issue is well known to users of (engineering) computational software, in which dimensional similarity is applied to quantity addition and dimensional-reduction to multiplication. Dimensional similarity will identify one input with a wrong dimension, but is not guaranteed to identify two or more input errors. Of course, dimensional similarity does not prevent an energy variable being added to a torque variable, as this screen extract from a computational package demonstrates:

$E := 5 \cdot \mathrm{J}$
$T := 15\ \mathrm{N \cdot m}$
$\mathrm{Sum} := E + T$
$\mathrm{Sum} = 20 \cdot \mathrm{J}$

Similarly, dimension-reduction will return the unit of a result, but it is the responsibility of a human to understand that the corresponding quantity is energy, not torque:

$m := 2 \cdot \mathrm{kg}$
$c := 3 \times 10^{8} \cdot \mathrm{m \cdot s^{-1}}$
$E := m \cdot c^{2}$
$E = 1.8 \times 10^{17} \cdot \mathrm{J}$

Issue 9: the SI needs a unit of temperature difference

The difference between two instances of an extensive quantity is the same quantity; however, the difference between two instances of an intensive quantity is a different quantity. Thus temperature difference is a different quantity from thermodynamic temperature, although these two are given the same dimension and unit in the SI [49]. This is a separate issue from that of different extensive quantities (e.g. energy and torque) sharing the same dimension. This means that computational software cannot differentiate, for instance, between the 'T' in the ISQ quantity 'entropy' $S = \mathrm{d}Q/T$ and the 'ΔT' in the ISQ quantity 'coefficient of heat transfer' $K = \Phi/\Delta T$.

Issue 10: the SI needs a base unit of angle

'Angle' is as tangible a geometric quantity as length, but the SI does not have a corresponding base quantity or unit for angle. The radian is a derived unit in the SI, defined from the identity $s = r \cdot \theta$ (in which r is the radius of a circle and s is the length of the arc subtended by the angle θ). From this definition, the radian has the unit m/m, and is said to be a dimensionless derived unit [34]. This definition has several undesirable consequences for rotational quantities, for example the SI unit for a rate of rotation is a 'per second', without any reference to the angle through which rotation takes place, or its unit [50]. There is ongoing confusion in textbooks about when radian units should be inserted or deleted in quantity expressions [51, 52].

Issue 11: the SI notation is ambiguous

Most of the SI prefix, unit and product symbols were established long before the invention of computers and language parsing theory. We find today that the SI notation is syntactically ambiguous *in text*:

i. Four symbols (d, h, m, T) represent both units and prefixes.
ii. The space represents the digit separator, scientific-notation separator, number-unit product symbol and unit-unit product symbol.
iii. The implicit product symbol (ISO 80000) combining a leading ambiguous unit and other unit, forms ambiguous units (e.g. 'dlm' represents 'day- lumen' and 'decilumen'; 'hA' represents 'hour-ampere' and 'hectoampere'; 'mN' represents 'metre-newton' and 'millinewton'; 'Tm' represents 'tesla-metre' and 'terametre').
iv. The implicit product symbol combining two units forms another unit ('lm' represents 'litre-metre and 'lumen').
v. A prefix plus unit forms another unit ('cd' can be 'centiday' or 'candela').
vi. A prefix plus prefix forms another prefix ('da').

Consequently the SI notation cannot be unambiguously parsed and analysed by software [53]. An unambiguous SI notation is desirable, since it would enable the development of software which could, with guaranteed-correctness, check SI style in text and manipulate/verify quantities, SI units and prefix algebra in scientific and engineering computations.

5. Issues of usability

Mills [54] argues that a 'good system of units and conventions should be stable and familiar to all users'. While 'familiarity' is a desirable outcome, it is not an attribute of a system, and is influenced as much by the clarity as by the stability of the conventions, and so is not a benchmark for an important international system. A broader view [55] is that 'In any field of science and technology, the relevant vocabulary should be descriptive, systematic, unambiguous, internally consistent and relatively stable'. Another important requirement [37] is that units should be convenient, or they will not be adopted.

The SI vocabulary is examined here against the attributes 'systematic', 'consistent' and 'convenient'; 'stability' is discussed separately later. Some observations are specific to computer users, others relate to general convenience.

Issue 12: the systematization of the SI notation

The prefix symbols are not systematic. The prefix symbols are not systematic, requiring the memorizing of 20 symbols.

The case of the prefix symbols is not systematic. All the prefixes for submultiples are lower case; seven of the 10 prefixes for multiples are upper case (exceptions 'da', 'h', 'k').

The base unit 'kilogram' contains a prefix. The base unit of mass (kg) has a prefix in its name and symbol, so multiples cannot be formed by adding another prefix, e.g. 'kkg' for tonne.

Issue 13: the consistency of the SI notation

The symbols have inconsistent alphabets. Forty-nine of the SI prefix/unit symbols are Latin characters; two are Greek.

The prefix symbols have inconsistent length. Nineteen of the 20 prefix symbols are single-character (exception 'da').

The prefix names are inconsistent. Eight of the names of the 10 multiple prefixes are suffixed with -a (exceptions 'kilo', 'hecto'). Seven of the names of the 10 submultiple prefixes are suffixed with -o (exceptions 'deci', 'centi' and 'milli').

The units of plane angle are written without a space after the number. All SI unit symbols, including the SI unit of angle 'rad', must be separated from the number by a space (the symbol for number–unit multiplication, not a formatting convention); the unit symbols for plane angle of the 'non- SI units accepted for use with the SI' degree, minute and second (◦, ,) are attached to the number. While this is a long-standing notation of mathematics, it is problematic when writing physical quantities. Any exception causes confusion for humans; it also makes it more difficult to write a software parser. There is no guidance in the SI Brochure on how to write other derived quantities, such as angular velocity, using these units (e.g. is '2π rad/s' written as '360◦/s' or '360 ◦/s'?).

Issue 14: the convenience of the SI notation

Four symbols are not on a US keyboard. The four SI symbols '◦', 'µ', '·', 'Ω' are not represented on the US or Western-European keyboards. As the vast majority of scientific writing is in English/European languages, this creates unnecessary delays and difficulties for authors in generating these characters in different software by the use of special codes, key combinations or menus.

These four symbols are not fully represented in common character sets. These symbols are not represented in the legacy 7-bit ASCII. The 'Greek Capital Letter Omega' is not in the ubiquitous 8-bit ISO-8859-1 (Latin-1) or Windows CP-1252. One day, all operating systems and application programs will adopt 16-bit Unicode (which contains all these); meanwhile these omissions can cause errors in transferring the symbols between different computer platforms and in rendering in print or on screen ('omega' is particularly problematic in web pages).

6. Opportunities to improve the SI for the e-Science age

The issues discussed above detract from the SI's elegance, authority and ease of learning and use, but not necessarily from its compatibility with computer systems. Opportunities for resolving the issues are discussed below, with an emphasis on adapting the SI to the e-Science age.

Opportunity 1: harmonize the SI and VIM3 concepts and develop the OIM— the International Ontology of Metrology

A sound theoretical foundation is necessary before developing systems of measurement, quantities and units [56–58]. It seems that such a foundation may not yet have been developed, and that further refinement of metrological concepts and relations is justified.

To avoid misinterpretation, such a foundation should be represented in an unambiguous manner that can be formally checked for consistency. VIM3 includes (informative, not definitional) concept diagrams, to provide 'a possibility for checking whether the definitions offer adequate relations; a background for identifying further needed concepts; and a check that terms are sufficiently systematic' (p 54). However, concept diagrams are simply a visual aid, and cannot enforce any relation-checking. In informatics, an extension of the VIM's concept diagram is the ontology, a formal representation of classes, attributes and relations between concepts. An ontology is one element of a semantic toolkit to enable software to derive meaning from data streams and web pages.

Several property–quantity–unit ontologies have been developed [59–64]; some have reported problems in representing the concepts of quantity, kind of quantity and dimension, and some have rediscovered the metrological issues with angle, 'units of dimension one' and so on.

Without a sound, agreed standard ontology, many disciplines will develop their own pragmatic coding systems [65], mark-up languages [66] and software libraries [67], in a 21st century version of the competing unit systems of the 20th century. After the definition of the SI base units in terms of fundamental constants, this should be the most pressing priority for metrologists. It also requires the talents of scientists, engineers, informaticians and philosophers [68], the latter who specialize in the representation of knowledge. Yet another collaborative project to develop a comprehensive units ontology has recently commenced [69].

Opportunity 2: harmonize the CIPM and ISO specifications of the SI

It is desirable for engineers and scientists to have a common standard for writing SI compound units. This could easily be achieved by revising ISO 80000-1:2009, to deprecate the 'implicit' product symbol, and by adding an explicit requirement for the value–unit product symbol. Similarly, harmonize the 'non-SI units allowed for use with the SI'.

Opportunity 3: proposed new standards will remove the interdependence of base units

The CIPM has commissioned a proposal [70] to base the kilogram on a fixed numerical value for the Planck constant, the ampere on a fixed numerical value for the elementary charge, the kelvin on a fixed numerical value for the Boltzmann constant and the mole on a fixed numerical value for the Avogadro constant. This will remove the interdependence of these base units, and relate them to constants of Nature. This proposal may be presented to the 24th CGPM in 2011 [18]. Interestingly, the proposal also outlines a scheme for defining directly the seven base units and 22 named derived units, eliminating the distinction between base and derived units. This would require a reformulation of quantity calculus, and might be an opportunity to address some of its limitations.

Opportunity 4: carefully consider whether derived units can be algebraically reduced

Emerson [31] proposes that the SI units of derived quantities should not be algebraically reduced because then they become units of another quantity; or in the ISQ notation:

$[Q1][Q2] \neq [Q1\ Q2]$ and $[Q1]/[Q2] \neq [Q1/Q2]$.

Johansson [30] argues that the ISQ definition of a quantity is deficient, and that quantities are actually tripartite entities (e.g. 'the table is 3 metres long.') which should be represented as

$Q = \{Q\} \cdot [Q] \cdot (\dim Q)$.

Therefore, the expression for a derived quantity is

$Q1/Q2 = \{Q1\}/\{Q2\} \cdot [Q1]/[Q2] \cdot \dim(\dim Q1/\dim Q2)$,

where the dimensional expression $\dim Q1 / \dim Q2$ is irreducible. This is formally equivalent to Emerson's proposal. These claims need to be addressed and resolved to allow progress on other issues, primarily #1 and #5.

Opportunity 5: revise the definition and name of 'quantities of dimension one'

In the case of relative quantities, Johansson [30] argues that since the numerator and denominator belong to the same kind- of-quantity and dimension, '*no actual general standard unit is needed*, since each of the two magnitudes at hand may be taken as a temporary and local standard for the other one'. Thus, the relative quantity can be represented by the bipartite expression:

$Q1/Q2 = \{Q1\}/\{Q2\} \cdot \dim(\dim Q/\dim Q)$.

Hence, he proposes that these quantities do indeed have a dimension and should be named 'unitless quantities' rather than 'dimensionless quantities'.

In the case of counting quantities, Dybkaer [71] supports the SI8 view that 'number of entities' is a base quantity in any unit system, and proposes that it should be formally listed with the other SI base quantities, with a base unit 'one'. Accepting these two propositions would eliminate the contradiction that the unit 'one' is both a base and derived unit.

Lastly, there is the related matter of how to write the unit one. As it is stated in the SI that the unit 'one' is not written, there have been suggestions [72] to give it the special name 'uno' (symbol U) for use with the SI prefixes in place of terms such as 'percent' and 'parts per million'. Others claim [73] that while this might reduce the misuse of the terms in science, it would create more confusion in other disciplines.

Opportunity 6: rename 'amount of substance' and clarify the status of the mole

The ongoing controversy surrounding these concepts needs to be resolved so that they can be comprehended and represented accurately in information systems. The current proposal to define the base units in terms of fundamental constants, proposes to redefine the mole in terms of a fixed numerical value for the 'Avogadro constant'; however, the Avogadro constant (unit mol^{-1}) is not a physical constant, simply a scale multiplier. Becker explains the proposal as 'it is proposed that the Avogadro constant be converted to a [dimensionless] number, the 'Avogadro number', and that the mole be linked to this number. The unit of the amount-of-substance would be this particular number of specified, identical entities. This would not only bring greater clarity and simplicity to the SI, but would also lead to a better understanding of the mole by the physics and chemistry communities, as well as by the general public.' [74]. It seems to the author that this proposal is returning to the original definition of the mole as 'an Avogadro number of entities'. However, the proposal does not address all of the objections listed in issue #6 of this paper.

Leonard proposes the atomic scale unit 'ent' as a 'non- SI unit allowed for use with the SI', and the kilomole as the base unit, in order to avoid factors of 10^{-3} or 10^{3} appearing in relationships involving both mass and amount of substance expressed in base units [75].

Johansson [30] suggests that the VIM3 and the SI would benefit from the introduction of the concepts 'parametric quantity' and 'parametric unit'. He argues that the base quantity amount of substance is a parametric quantity that should be replaced by another quantity of the same dimension, *elementary entities,* using the same symbol *n*, with a base (counting) unit of 'one', symbol *E*p . The mole would become a 'non-SI unit allowed for use with the SI'.

At a terminological level, there are various suggestions (quant, chemiance, chemical mass, chemical amount) for renaming amount of substance [42, 76–78]. The name 'chemon' would allow systematic naming of the 24 'molar' quantities in the IUPAC Green Book quantities as 'chemonic' [79].

Opportunity 7: leave the candela alone

The candela is clearly a derived unit, since it is a function of radiant intensity (power per unit solid angle) and the maximum of the luminosity function. It is not a coherent derived unit, and so should logically belong to the class 'units accepted for use with the SI'. However, changing its status from a (conventionally independent) base unit would change the status of its coherent derived units lumen and lux, which would cause confusion.

Opportunity 8: formalize the utility of the concept 'dimension'

The utility of the concept 'dimension' alone will probably remain marginal. In engineering computational software, physical quantities are represented as 'dimension–unit–value'; the limitations of this scheme are shown earlier. An obvious scheme is to extend the dimension 'length' into orthogonal components (L_x , L_y , L_z), to incorporate vector information into the dimension of mechanical quantities (e.g. $ML_x^2 T^{-2}$ for energy, $ML_xT^{-2}L_y$ for torque). A more general scheme, discussed widely in engineering software forums, and summarized by Ochkov *et al* [80], proposes the representation 'kind of quantity–dimension–unit–value') to allow quantity-checking (e.g. to differentiate energy versus torque, etc). In any case, the concept of dimension and its operations should be revisited and formalized.

Opportunity 9: establish a derived quantity and unit of temperature difference

The definition of this quantity is $\Delta T = T2 - T1$. The axioms of the ISQ do not distinguish between intensive and extensive quantities, thus the ISQ dimension of temperature difference is

$\dim (T2 - T1) = \dim (T2) = \dim (T1) = \Theta$.

Since temperature difference is a different kind of quantity to temperature, a new axiom is needed for intensive quantities (Qi):

$\dim (Q_{i2} - Q_{i1}) = \Delta Q$.

The obvious unit symbol is ΔK, but it is suggested earlier that using non-keyboard symbols introduces usability problems to the SI. Perhaps a suffix to the base unit K such as K* or K' would be suitable.

Opportunity 10: redefine the radian as a base unit with dimension 'angle'

Plane angle is defined as ‘part of a plane limited by two rays emerging from one point’, and a simple derivation shows that it has a unit, and thus a dimension [81]. Declaring ‘angle’ as a base quantity would recognize that it is as physically significant as length, and is not a trigonometric abstraction.

It would be possible to adopt the base unit ‘revolution’, but this would require revising the defining equations of the coherent derived units for other angular quantities. A practical compromise would be to redefine the radian as the base unit of angle, so that, for instance, rotationally speeds would be given as ‘rad/s’, rather than the ambiguous s^{-1} currently in use. The SI unit for solid angle, the steradian, would be redefined as the special name for the unit rad^2. Engineers, in particular, would benefit from this scheme because their computational software could treat angle consistently with other quantities.

The side-effect of giving the radian a dimension is that the standard rotational equations would become dimensionally incorrect. Two basic solutions have been proposed. The first [82, 83] suggests changing the units of some quantities (e.g. changing the unit of radius to m/rad). The second [52, 84] introduces a constant k (of dimension $angle^{-1}$) into the equation $s = k \cdot r \cdot \theta$, where k can be understood as a universal constant, which relates translational to rotational mechanics. The existing rotational equations are maintained, with the unit of rotational speed being rad/s and the unit of rotational acceleration being rad/s^2.

The author’s view is that the physical equation which defines the radian $s = r \cdot \theta$ is misinterpreted, and that the quantity s does not represent ‘arc length’, but is an unrecognized derived quantity ‘arc’, with unit rad·m. This interpretation allows existing rotational equations and units to be retained. To convert to linear mechanics requires the use of the previously defined constant k; for example length of arc, l, is defined as $l = k \cdot r \cdot \theta$.

Opportunity 11: disambiguate the SI notation

Disambiguating the SI notation requires only a few changes, and could be accomplished in several ways. It is not necessary to have different symbols for units and prefixes, though this would be desirable for simplicity. If only the SI units are considered, then it is sufficient to replace the prefix ‘da’ with ‘D’ and disallow the period and implicit product symbols.

If the ‘non-SI units allowed for use with the SI’ (min h d ◦ l Lt eV u ha Da ua) are also considered, there is a syntactic collision between the symbol for candela (cd) and the unit centiday (cd) (although this unit is semantically disallowed). This requires a new symbol for candela (perhaps ‘Cd’) or day (perhaps ‘day’).

Opportunity 12: there is no informatics imperative to make the SI notation more systematic

Renaming the prefixes for the sake of a systematic structure would create too much confusion. However, any new prefixes should be adopted as upper/lowercase pairs, as the 19th CGPM did in 1991, declaring zetta ($Z = 10^{21}$), zepto ($z = 10^{-21}$), yotta ($Y = 10^{24}$) and yocto ($y = 10^{-24}$).

The replacement of the prefix symbols da, h and k by the upper-case single letters, D, H and K is an obvious improvement in systematization, but has been rejected by the Consultative Committee for Units (CCU) of the BIPM [85].

It is probably too late to rename the kilogram with its historical name ‘grave’ [86], or the mooted ‘Giorgi’, symbol ‘G’ [87], although this idea is periodically revived, e.g. at CCU18 [88].

In both cases, there is no informatics imperative to make the SI notation more systematic, although having a non-prefixed symbol for the kilogram would make it easier for programmers to write unit-parsing software.

Opportunity 13: there is no informatics imperative to make the SI notation more consistent

The prefix ‘da’ should be replaced by ‘D’ for ease of parsing (see Opportunity 11) but otherwise there is no informatics imperative to make the SI notation more consistent.

Opportunity 14: make the SI notation more convenient and printable

Replace mu and omega (μ, Ω) with the Latin ‘u’ and ‘Ohm’; these symbols have a precedent as they were recommended for ‘systems with a limited character set’ in a withdrawn ISO standard [89]. This leaves the two characters ‘degree’ and ‘mid-dot’ as non-keyboard characters, with no obvious keyboard analogues. At least they are available in ISO-8859-1 and Windows CP-1252, and so can be transferred and rendered reasonably reliably.

7. Should the SI be 'stable'?

Standards-setting bodies are conservative about change. Resolution 12 of the 21st CGPM states that '. . . while the proliferation of special names represents a danger for the SI, exceptions are made in matters related to human health and safety'. The CCU reported at the 21st CGPM '. . . the CCU feels that changes to the SI should be kept to a minimum, and should only be made when there are very strong reasons for change. The SI is of worldwide importance, and to make many small changes at frequent intervals may lead to confusion amongst our many different users' [90]. The CCU reiterated this view [85] regarding the prefixes h, da and k, that 'The CCU decided to leave this matter in abeyance. . . The reason for making no change in the prefixes is that any change, even small changes, will have extensive implications for the many documents in several languages derived from the Brochure, with consequent dangers of confusion. The committee feels that even small changes should only be made when there is a strong case for change'.

There is also opposition to SI changes in the scientific community. The CCU's current proposal to change the definition of the mole has been criticized as an unnecessary change to 'a scientific and cultural good such as a unit of measurement' [91].

An insight into the CCU's preference for stability over consistency is found in the minutes of CCU18, which record '... reservations with the description of the systematic view of the origin of a system of units as dependent on first defining a system of quantities. . . this is an idealised view, and is not how things actually developed' [88]. Thus, the CCU seems to regard the SI as a pragmatic improvement on the previous 200 years of metric unit systems, which is not bound to reflect fully the idealized concepts and structures of the ISQ and VIM3. On this basis, the CCU is wary about any changes to the SI, even if they improve its consistency, structure or usability. The danger in this viewpoint is that not only is the SI frozen with historical anomalies and compromises, but it is also exempted from adapting to new requirements.

The issues discussed above build a strong case that the SI should evolve to meet the new challenge of the pervasiveness of computers, software and informatics. The author has discussed the principles of a tiny change to the SI notation to eliminate its syntactic ambiguity [92]; these are also valid for larger changes:

- Citizens of industrialized countries are used to continual change in technology, society, legislation and workplace.

- A block of changes with a clear purpose can be presented positively and managed with version numbering.

- The harmonization of the ISO and CIPM definitions of the SI is as important as their stability.

- Change is best done sooner rather than later when the user base is expanding, since fewer people need to adjust to the change (the world population has grown by about four billion since the SI was established [93]).

8. SI, *postera crescam laude?*

The SI, as the language of science, should enable humans and computers to communicate unambiguously and conveniently about quantities and measurement. Like a spoken language, it also has the power to shape our thinking about quantities and measurement. Is the SI a 'good-enough' technology? Given the shortcomings listed above, it is the author's opinion that it is not, and that it needs a serious overhaul in order to serve humans for another century or more. On the SI's 50 birthday, it is time to review its state and to make it a rational, elegant system that reflects the rationality and elegance of science.

It is easy to conceive of a shiny new logical, consistent, unambiguous quantity and unit system. Admittedly, introducing such a creation would be expensive and difficult, and it would likely become the Esperanto of unit systems, admired but ignored. Therefore, there is a need to compromise, and modify the SI to address the new digital demands on it, improving its deficiencies in definition, utility and usability. The eight editions of the SI Brochure could be viewed as SI versions 1 to 8. It is time to harmonize and declare named versions of the SI and its supporting documents the ISQ and VIM, so that users and software can agree on the rules applying to a certain piece of text or data file. Software users are inured to version increments; perhaps it is time to adopt that nomenclature and declare a major version change to SI9 or SI2015 at the 25th CGPM.

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