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REVIEW

A skeptic's review of the New SI

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Abstract Proposals in draft form have been circulated for new Système International (SI) measurement units that are expected to be official instruments of the Treaty of the Metre by 2015. This review outlines the substance of the proposals and examines some of the consequences of the continuing evolution of the SI toward inter-dependence of base units and quantities since its introduction in 1960. The proposals in question fix at an exact value a number of inter-related fundamental natural constants such as the speed of light, the Planck constant, the elementary charge and Boltzmann's constant. All SI units are then so defined that their magnitude is set by those fixed values. Notably, the ongoing confusions about chemical measurements and the thermodynamic 'mole' are exacerbated. On the big principles of the basic purpose of the SI to facilitate communication and the fixing of fundamental physical constants of nature, there are significant problems and unanswered questions. They risk: damage to the enterprise of science; wide economic loss including increased transaction costs and barriers to global trade; barriers to new technologies and to improvements in measurement accuracy; loss of measurement compatibility or consistency; and a circular global measurement system vulnerable to undetectable systematic errors with serious adverse consequences for environmental decision making among many other vital human activities. The New SI requires frank and open discussion throughout science, technology, industry, trade, and global policy well before irreversible decisions are made.

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Introduction

How we anchor our measurements is a matter of some moment. Traceability to common measurement units enables us to communicate and compare measurements across time and space, abilities of vital importance to our civilization. As it is with ships, an anchor that moves around excessively is a problem. The International Committee on Weights and Measures (CIPM) has a vision to anchor measurement in our world to the fundamental physical constants of nature [1]. It is a seductive vision. Planck's constant, Boltzmann's constant, the speed of light, and elementary charge are currently widely believed to be among the most constant things we know of. Fixing constants exactly by committee decision enables the definitions of Système International (SI) measurement units to be based on them, and the controlled production of the relevant phenomena allows realization of those units to calibrate measurements. The constants themselves are all elegantly inter-related and coupled by the equations of physics as we know them today. It is neat and complete.

However, the fixing of fundamental physical constants of nature is also a matter of great moment and one in which all of science, technology, industry, and trade must take a vital self-interest. Once fixed, there is no going back. Central aspects of our knowledge of the physical world are rendered beyond further empirical test [2]. It is an irreversible step. Nor has any case been made that fixing the fundamental constants will necessarily enable more accurate and more stable measurement than using less 'fundamental' definitions. Indeed, there are good reasons to suppose the reverse [3]. We all should look very carefully at the assumptions behind such a momentous change and then consider all its implications.

A draft copy of the relevant Chapter 2 of the proposed new ninth SI brochure has been made available on the Web site of the International Bureau of Weights and Measures (BIPM) [4]. Everybody on our planet who relies on measurements should read it for themselves and ask: “Do I really understand this?”

It is a vital question to ask of any system of measurement units. Measurement units are indispensable instruments for communication. We should be very clear as to the role of the definition of measurement units in the processes of measurement and the communication of results. A definition of a measurement unit is (by definition) something we say and it is (again by definition) exact. It is linguistic in nature and can have no inherent measurement uncertainty. However, the physical realization of a unit (in the French, an etalon) will be a material experiment or action of some kind. It is something we do. It may be a physical reproduction of the definition, or it may be a more inferential process depending on other physical phenomena and our knowledge of them, but it will always have some level of uncertainty attached. There is another step not often mentioned. It is something we construct: a measurement scale. It is this that is used to make actual, practical measurements. Scales are constructed according to the specific purposes of the measurement, and they may be of many kinds: nominal, ordinal, interval, ratio, linear, geometric, exponential, logarithmic, complex or imaginary, to name just a few. The SI recognizes only ratio scales, a matter of great difficulty in an age of instrumentation and sensors where scales of all kinds are used appropriate to their purpose. Whatever the kind of scale employed, its construction necessarily entails assumptions and judgements about the most appropriate arithmetic to apply to the phenomena for the purposes at hand and necessarily introduces further sources of uncertainty. This step is often called calibration. The final step is a comparison of scale and the specific phenomenon being measured, and this also introduces sources of uncertainty. The way that these things are in practice achieved is of course crucially dependent on the skill, knowledge, and judgment of the measurer, from your local butcher to the Astronomer Royal. But what is always the final aim is a comprehensible linguistic expression to the user of the result that is indeed, in physical fact, what it actually purports in words to be. Clear and concise and accurate communication to the users of measurement results is the utterly central purpose of any system of measurement units. Units that cannot be understood by the users of measurements deny completely their most fundamental purpose.

I will summarize the general approach adopted by what has become known as the New SI starting with a brief description of the current (‘old’) SI, with which all readers will have some acquaintance. The draft is intended to be read alongside the existing eighth SI brochure [5]. The draft is the new text replacing the old definitions of units in chapter 2, with the rest of the current SI brochure left largely untouched.

The current SI has seven base units and seven corresponding quantities. Combinations of those units give derived units. Which are base and which others derived is currently a matter fixed by convention, not nature or logic. But what is not conventional and is required by the logic of the old SI is the existence of a genuine distinction between basic and derived units. Exactly how it is drawn is what is open to collective decision. It is also important to understand that a great many measurements of interest to modern science, technology, industry, and trade are entirely outside the ambit of the SI. Even the multitudinous derived SI quantities are but a subset of all quantities widely used today. Information and biological activity are only two of a great many examples of non-SI quantities vital to twenty-first century science, technology, industry, and trade. The SI is effectively self-limited by its basic presuppositions to the quantities of classical mechanics, electrodynamics, and thermodynamics. The addition of qualitatively new kinds of basic quantities is problematic [6, 7], and the system is effectively closed.

The seven base quantities (and their SI units) are as follows:

1. time (second),
2. length (meter),
3. mass (kilogram),
4. electric current (ampere),
5. thermodynamic temperature (kelvin),
6. ‘amount of substance’ (‘mole’), and
7. luminous intensity (candela).

The definitions of base units refer wherever possible to readily accessible stable natural phenomena rather than artifacts (the kilogram being the exception which the New SI is intended to correct). There is a certain redundancy in this list—‘amount of substance’ is a second thermodynamic quantity and the ‘mole’ a thermodynamic unit, as the architect of the SI well understood and explicitly stated [8]. For clarity of communication, I will place ‘scare quotes’ around them whenever I refer to the official SI usages of these terms, since there are other common non-SI usages with which they should not be confused.

The New SI

The New SI in effect proposes by decree to fix exactly, to a specific numerical value within currently best known uncertainties, seven fundamental natural physical constants. All SI units are then so defined that their magnitude is set by those seven values. Thus, by fixing the numerical values of a set of fundamental natural invariants, a particular set of interlocking units is implied, in this case, the New SI. Clearly, the distinction between basic and derived units is no longer required by logic because all units, basic and derived, are now inter-related via the constants and the laws of physics. But it can be maintained by convention if desired for, say pedagogical purposes. The seven constants (and the current SI units in which they are expressed) chosen to 'set the scale' of the New SI are the following:

1. The ground-state hyperfine splitting frequency of the cesium 133 atom (Hz)
2. The speed of light in vacuum (m s^{-1})
3. The Planck constant (J s)
4. The elementary charge (C)
5. The Boltzmann constant (J K^{-1})
6. The Avogadro 'constant' (mol^{-1})
7. The luminous efficacy of monochromatic radiation of frequency 540×10^{12} hertz (lm W^{-1})

By way of initial comment, I observe that 1 and 7 are clearly not fundamental natural physical constants. They are specific examples among many of naturally occurring stable phenomena. I have included scare quotes for Avogadro 'constant' for the same reason I have included them for 'amount of substance' and 'mole'.

While the distinction between base and derived units is no longer essential, the New SI retains it for the time being as one of convenience, not necessity. The New SI definitions of the current (or old) base units are as follows: (the inclusion of X within a number means that it will be shortly updated when more accurate determinations are available using current definitions and before the new definition is declared):

1. The second, s, is the unit of time; its magnitude is set by fixing the numerical value of the ground-state hyperfine splitting frequency of the cesium 133 atom at rest and at a temperature of 0 K to be equal to exactly 9 192 631 770 when it is expressed in the unit s^{-1}, which is equal to Hz.
2. The meter, m, is the unit of length; its magnitude is set by fixing the numerical value of the speed of light in vacuum to be equal to exactly 299 792 458 when it is expressed in the unit m s^{-1}.
3. The kilogram, kg, is the unit of mass; its magnitude is set by fixing the numerical value of the Planck constant to be equal to exactly $6.626\ 06X\times10^{-34}$ when it is expressed in the unit s^{-1} m^2 kg, which is equal to J s.
4. The ampere, A, is the unit of electric current; its magnitude is set by fixing the numerical value of the elementary charge to be equal to exactly $1.602\ 17X\times10^{-19}$ when it is expressed in the unit s A, which is equal to C.
5. The kelvin, K, is the unit of thermodynamic temperature; its magnitude is set by fixing the numerical value of the Boltzmann constant to be equal to exactly $1.380\ 6X\times10^{-23}$ when it is expressed in the units s^{-2} m^2 K^{-1}, which is equal to J K^{-1}.
6. The 'mole', mol, is the unit of 'amount of substance' of a specified elementary entity, which may be an atom, ion, electron, any other particle, or specified group of such particles; its magnitude is set by fixing the numerical value of the Avogadro 'constant' to be equal to exactly $6.022\ 14X\times10^{23}$ when it is expressed in the unit mol^{-1}.
7. The candela, cd, is the unit of luminous intensity in a given direction; its magnitude is set by fixing the numerical value of the luminous efficacy of monochromatic radiation of frequency 540×10^{12} Hz to be equal to exactly 683 when it is expressed in the unit s^3 m^{-2} kg^{-1} cd sr, or cd sr W^{-1}, which is equal to lm W^{-1}.

The New SI states that the order of this list is arranged so that no definition involves units not previously defined. It claims that this procedure avoids circularity but this is logically erroneous—it is the relationships between terms that determine their logical properties such as circularity, not the order in which they may happen to be listed. However, to take the obvious example, the definition of the second involves the kelvin (0 K), not defined until much later in the list. This list, even on its own criteria, is circular, and I will later discuss in more detail the consequences of this.

I note also that the units in which the constants are expressed are derived units involving more than one unit and are hence inter-related, with the exceptions of 1 and 4 which involve the reciprocal of their respective single units. It is not explained what a 'per second' is, nor what constitutes a 'reciprocal amount of substance'. This is a significant puzzle since it would be much clearer for example if a second were defined by direct reference to a natural example of a time interval, rather than to its inverse. The decision to use the inverse has consequences other than the unnecessary puzzlement of students. The inverse of an exact integer numerical value is not in general itself an exact communicable numerical value—it may have an infinite number of decimal places. To communicate, one must truncate or round the expression at some point and say that further specification past the nth place is beside the practical point. But the algebra of rounded or truncated numbers is not identical to the algebras of real (exact) numbers or even of rational numbers. This is significant because a great deal of the already well-documented confusion in the SI is traceable back to its assumptions about the algebraic operations that may be legitimately performed on expressions of powers of units and dimensions [9, 10].

This writer can claim no experience in the metrology of luminous intensity, but I briefly note that unlike all other base quantities, this one has a something of a vector or directional characteristic, and for the casual reader at least, its New SI unit has a particularly abstruse definition. It raises the question of why it was included as a base unit. Mass, length, and time are quantities of common acquaintance, but luminous intensity has the appearance of having been included only for the reason that it cannot be derived from the other base quantities, rather than for any systemic principle.

My major experience in the metrology of time is the infrequent wearing of a watch, but this is relevant. There is an error of some significance in the claim that the second is the unit of time. That it is an error propagated through successive editions of the SI brochure makes it no less incorrect. It is an error that should be corrected before now. The second is the unit of time *interval*. Time in the modern world is an interval scale and unlike the other base quantities, not in fact a ratio scale. It is not as if the notion of interval scales is unknown to the New SI—the definition of the kelvin (Sect. 2.3.5 of [4]) for example discusses them in regard to the Celsius scale. The distinguishing characteristic of interval scales is that there is no natural zero that is approachable by physical means. Our measurements of time necessarily have a conventionally assigned zero, unlike the zeros for the other base quantities. This is not a minor or arcane point. The SI is actively (and unnecessarily) misleading in its phrasing. There are many differing ideas of time abroad in our world according to culture and history. Newton's notion of time was not ours. Many people today, even in the most technologically advanced and highly literate and educated economies, falsely believe time to be a ratio quantity and to have a natural zero or beginning. The most popular candidate in the anglosphere is about 6014 years ago, but there are many other creation beliefs. All suffer a major disadvantage as the basis of a ratio metric for time. Even the 'big bang' cannot provide any metrological basis for a natural zero for time, for a natural zero must be at least approachable, if not achievable, by physical experiment. A zero mass or zero length is readily achieved to a high degree of accuracy in this physical world, but there are considerable logical and practical difficulties in conducting an experiment yesterday, let alone some 13.7 billion years ago, despite the fancies of popular television shows. Time is irreducibly an interval scale. There should be no pretense that it is otherwise.

The SI definition of the second has one other, quite important characteristic. It is a reference, independent of other base units, to a specified example of the quantity at issue. The second is defined by reference to a stable time interval that is found in nature. No other quantities come into it (as noted above, thermodynamic temperature is an influence factor; however, it does not appear in the expression of the unit). That is an important principle that the other New SI definitions do not meet, apart perhaps from the thermodynamic 'mole', the referent of which is however unclear, inferred and not directly accessible, as I discuss later.

The definition of the ampere goes half way to meeting that principle of direct reference. The electrical quantity charge has a natural stable exemplar, *e;* however, the base unit that is defined is not a unit of charge alone but of electric current, which is as a consequence dependent also on the second.

However, the inter-relatedness of units in the New SI is quite evident in the use of Boltzmann's constant to define thermodynamic temperature. Boltzmann's constant is often referred to as a factor or constant of proportionality between energy in the micro-world of elementary entities and observable temperature in the macro-world. It is the ratio between the gas constant and Avogadro's 'constant', referred to later in the definition of the thermodynamic 'mole', and another example of circularity in the New SI. Like 'amount of substance', thermodynamic temperature is the subject of considerable confusion among students. The common notion of temperature, exemplified by the well-known Celsius scale, is an interval scale with a conventional zero, but the thermodynamic temperature defined in the SI is a ratio scale with a natural zero, albeit utilizing the same increments as the more common notion. It is a situation tailor-made for misunderstanding, the origins of which seem not so dissimilar to the confusions so distressingly evident in the thermodynamic 'mole'.

However, the most obvious source of confusion in the New SI will be the definition of the kilogram, which no longer makes any reference to any real mass of any kind, artefactual or natural. It refers instead to Planck's constant, which is a proportionality constant relating the energy of a photon and the frequency of its associated electromagnetic wave. Planck's constant is an extremely important cornerstone of our current understanding of the physical world, but its relationship with the common notion of mass will only be evident to postgraduate students of theoretical physics. It is a most unlikely candidate for clear, concise, unambiguous, and well-understood communication of practical measurement results.

The question of inter-dependence of measurement units requires much closer examination than is evident from Sect. 2.3.8 of the New SI, and I will return to that theme later.

The chemical mole and the Avogadro number: what do chemists measure?

An essential question, unasked by the CIPM, is “what do chemists measure and why do they measure it?” The special thing about chemical measurement is the fact of stoichiometry. Things react chemically with other things essentially according to the respective numbers of the things. That is our starting point, and it is important because things reacting with other things poison us, nourish us, power our industry, and pollute our environment (among many other things). The purpose of the vast majority of chemical measurements is to estimate a number of things, identified and specified according to the purpose of the measurement. That is the quantity we are usually interested in. It is sometimes called a number of entities [11], and this journal has also introduced the term “numerosity” to refer to it [12, 13]. It is not a pure number; it is a physical quantity and one familiar to all humanity. To estimate a large number of things, one does not need to serially count each individual thing. We can compare numbers of things to numbers of other things, in the manner of the Neolithic shepherd who, gesturing toward the pasture, could say “I have as many sheep as I have fingers on this hand”. It is a commonplace measurement performed routinely by all of us, every day. Counting need not be only simple sequential ordination. The fact that analysts count very large numbers of things using very clever techniques with which to compare does not alter in any way the fundamental principles involved [12]. We are seeking an estimate of a number of specified things. That is where we start. It is our aim and purpose and the reason for the existence of our measurement instruments and procedures. The multiple counting unit we used before 1971 was called the mole, and it referred to an Avogadro *number of things*. Note Avogadro *number* (note also *of things*). It was like a huge dozen. We did not need to know what the number is because we could reproduce it easily, simply, transparently, in a multitude of ways using a multitude of things, according to the measurement problem at hand. The mole was just a name for that number of things, chosen simply to cohere with the other measurement units in common use. It was simple, easily explained and understood, and ideal for the communication of chemical measurement results. In a world of complexity and obfuscation, it was clear, concise, and understood by all.

The thermodynamic ‘mole’, ‘amount of substance’, and the Avogadro ‘constant’

The scenario changed in 1971 when an entirely different thermodynamic unit for a different thermodynamic quantity was introduced to the SI, which is also called the ‘mole’. There needs to be complete clarity on this: the thermodynamic ‘mole’ is something quite different to the mole I have described above. That is official and quite explicit from the architect of the SI and his successors [8, 14, 15]. To begin with, it is not a unit for the quantity ‘number of things’. It is a unit for an invented quantity called ‘amount of substance’, a highly theoretical statistical property of ensembles utilized sometimes in thermodynamics. ‘Amount of substance’ is assuredly not a number of things. Proof of that lies in the fact that the first is a continuous quantity but the second is quantized. There are no half atoms. It bears repeating: the SI-defined thermodynamic ‘mole’ and its accompanying thermodynamic quantity called ‘amount of substance’ have little to do with most actual chemical measurement practice. We should stop trying to reconcile the irreconcilable, and we should be very clear: there are two different quantities (number of things and ‘amount of substance’) relevant to two different kinds of measurement (chemical and thermodynamic) with two different units (the chemical mole and the thermodynamic ‘mole’). They have the same name. The existence of two ‘moles’ is a deeply regrettable semantic confusion and one with very serious consequences. It is a confusion propagated with vigor by the New SI in its definition of the thermodynamic ‘mole’.

In order to retain consistency, in 1971, it was necessary to promote the lowly Avogadro *number* to a majestic physical *constant* of nature with its own unit of mole^{-1}. The Avogadro ‘*constant’* is a human artifact, not a universal fundamental physical constant. It was created by a committee, not nature, and its fixing defines the new thermodynamic ‘mole’. It is at best no more than a micro- to macro-scaling factor. Its relevance to chemical measurement is minimal (although the more common Avogadro *number of things* remains of central importance).

Only non-reasons have ever been advanced to justify this artificially complex and *ad hoc* means of communicating chemical measurement results. It is alleged it is preferable to report chemical measurement results in terms of ‘amount of substance’ rather than as an estimate of a number of specified and identified entities because: [15, 16]

1. ‘Amount of substance’ is proportional to number of entities. That is true. It is also true that pressure is proportional to temperature. Reporting chemical measurement results in official SI thermodynamic moles is like reporting pressure in degrees Celsius, with the added confusion of the same name for two different units of two different quantities.
2. We can measure in thermodynamic ‘moles’ without knowing the value of the Avogadro *constant.* This is

irrelevant. Before 1971, analysts every day measured in chemical moles without knowing the value of the Avogadro *number*.

3. Using thermodynamic 'moles', it is not necessary to report numbers of things at the human scale using numbers of the order of 10^{23}. This also is a *non-sequitur* and additionally contradicts its own assertion, showing by example how humans have invented practical conventions of arithmetic to concisely convey the meanings of large numbers of things.
4. Using 'amount of substance' enables the use of dimensional analysis in chemistry, which is another irrelevance. It is simple historical fact that many generations of analysts happily and usefully applied dimensional analysis without any knowledge of amount of substance. Indeed, before 1971, a grounding in dimensional analysis was an essential requirement of students in analytical chemistry.

It is clear that there is a great deal of confusion in SI brochures both old and new concerning chemical measurement. The historical account of the development of its concepts that is offered in the New SI is misplaced in its focus on mass. Reporting results in mass is both complex and misleading, for the simple reason that chemical identity for a purpose at hand does not necessarily correlate with mass. It is the reactive sites that do the damage, not their mass. It is true that chemical measurement uses mass. It also uses volume and electric charge and time and many other physical quantities. It uses instruments. It uses them all to estimate numbers of identified things in specific circumstances. They are means to the end of measuring numbers of things. The notion of a number of things has been completely excised from the New SI, and its definition of the 'mole' in terms of the fixed Avogadro 'constant' is even more inexplicable than the old definition in terms of the kilogram artifact. This is a major discouragement to students of chemistry as well as a deeply regrettable confusion for the users of chemical measurements.

The confusion between 'amount of substance' and what chemists actually measure has had adverse consequences. One of them concerns traceability. Before 1971, a great many chemical measurements were in fact traceable to the chemical mole, even if the exact terminology was not used then—as it was also not used in metrology generally. The term "traceability" is of more recent origin in metrology and only gained wide currency in the 1980s, after Belanger's classic discussion [17], but the concept itself may be found in many guises throughout the long history of measurement [18]. It is simply the principle that measures ought to be what they purport to be, and all that the principle entails. In many cases, traceability to an Avogadro number of things was quite straightforward and easily attained. Good analytical practice required it. Systems of appropriate standard solutions, carefully prepared from materials of known identity and purity, values expressed in chemical moles, were a commonplace, as were many other clever techniques to anchor analytical results in an Avogadro number of things. Before 1971, the miracle of the realization of the (chemical) mole occurred on a daily basis in all good analytical facilities across the globe.

But how do you achieve traceability to an 'amount of substance'? We do not even know what it is.

By fortuitous circumstance, a new industry arose to meet the problem. We are told that we must use externally sourced 'certified' reference materials. The problem is contracted out, at considerable expense. Rather than address the matter in situ using local knowledge, we must rely on the veracity and appropriateness of external certificates. Certificates are nice, but they do not solve real physical problems. Reference materials are sometimes useful in particular circumstances, although there are still many issues to be settled concerning their veracity, transparency, expression of values, appropriateness, production, characterization, distribution, and use. But it is clear that the industrial capacity does not exist to supply all reference materials required and appropriate to all analytes and matrices. In many cases, the simple truth is that it is more appropriate to use do-it-yourself, in-house, or tailored-to-the-situation means of establishing calibration and traceability, and there are very many ways to do this (e.g., the controlled production of a transient species, electrochemical methods, primary methods, intrinsic standards, reference measurements, reference instruments, etc.). These are options quite comprehensible to the measurer of a number of things. But the measurer of the inexplicable 'amount of substance' would do well to cover their rearward liabilities by ensuring that the paperwork exists to show they relied on an external certificate. The consequence is that more and more, the options for flexible and economic metrological control are ruled out.

As a final remark on matters of the 'mole' and 'amount of substance', it is also very worrying to find in the most authoritative statement of the bedrock basics of modern scientific measurement a quantity called "amount of substance". It is a phrase redolent with ambiguity and confusion. The notion of substance is among the oldest known to humanity, and it has a very specific meaning. It refers to a fictitious property-less 'stuff', an 'aether' that allegedly infuses everything and accounts for its 'being', a kind of cosmic ectoplasm permeating all Creation [19]. While it long predates Christianity, it was a staple of church scholarship in the middle ages. The development of chemistry completely stripped the notion of any empirical and rational credibility. Today, it still has its adherents in surprising places, and it is very worrying to find in the old and the New SI a term borrowed directly from medieval theology, not scientific practice. One does not expect the Spanish Inquisition. What is worrying is the interpretation that it will naturally be given by a large portion of the intended audience of the SI brochure. There is in the term 'amount of substance' ambiguity writ large. However, changing an ill considered name of a bad idea does not produce a good idea.

Practical problems new and old

There are many practical objections to the New SI. Its incomprehensibility is obvious to any casual reader. Its predecessor's uselessness as a means of communicating chemical measurements has been evident to many generations of chemical analysts. The New SI is even more obscure. Without reference to the kilogram, 'amount of substance' and the 'mole' have cleverly been made even more inexplicable to students or to a jury, referring now to an imaginary physical 'constant'. The notion of a number of things is nowhere to be found at all. This is unviable.

The all pervasive but mostly minor inconsistencies and ambiguities in symbolism and prefixes in the old SI that annoy everyone remain. They have the very damaging effect of making the SI both old and new effectively unusable in many computer data systems and in informatics generally. Foster has mounted a persuasive case that the questions of multiples, prefixes, and symbols need to be revisited to ensure computer compatibility [20]. The SI is not useable for communication with machines. It requires highly trained humans to interpret its exceptions, traits, and tics. This is a large problem in an age of sensors, instrumentation, and informatics.

Other aspects of both old and New SI are unsatisfactory, for example there are unwise numerical expressions that confuse integers, rational numbers, and real numbers. Egregious examples are found in Sect. 2.5.3, titled "Units for dimensionless quantities, also called quantities of dimension one" [4]. The role of dimensional analysis in the SI is still controversial, and what is clear is that the SI is very confused and confusing to the reader with talk of so-called dimensionless derived quantities, count quantities, so-called quantities of dimension one, unit one, and a number of logarithmic ratios that are also regarded as dimensionless. As Foster wryly remarks, in general, the use of some dimensionless units has led to confusion [20]. 'Dimension one' is a nonsense. One is not the sort of thing that can be a dimension, it is a number. A number *of things* may have a dimension, but it cannot be 'dimension one' and nor can it be dimensionless. Logic and mathematics tell us that, with certainty. A number of things is a quantity having its own dimension. It is not derivable from the other base quantities. It is of the integers or quantized, not continuous. If indeed it is the case that within the SI, one can be regarded as a further base unit (as the well-hidden comment on page 120 of the current SI brochure [5] allows), then it needs to be stated correctly and unambiguously (the number one cannot be a unit, but one specified thing can be) and the logical consequences need to be considered rather than contradicted by mere assertion.

Another related fundamental matter unmentioned in New and old SI is measurand identity (sometimes called nominal measurement), usefully discussed by White [21] and a subject of central importance to chemical measurement. There are in addition serious problems, confusions, and inconsistencies in the treatment of angular measures and rotations, creating large difficulties for modern technologies and the widespread but unnecessary befuddlement of students [20, 22–26].

The draft New SI has many specific inadequacies as a basis for measurement in the twenty-first century. We should however look beyond them to the principles employed. Is it just a matter of a few editorial corrections for the enterprise to be salvageable? There are two big principles to consider: the basic purpose of the SI and the matter of fixing fundamental physical constants.

The purpose of measurement units for communication

The purposes of measurement are practical. We should not be precious about this. The purposes may be profound or profane, but they are things we want to do or know. Measurement for its own purposes is an oxymoron, and so is communication by obfuscation.

There is a key party to the communication of measurement results. It is the audience. It is they who make decisions on the basis of the information communicated to them in a measurement result. This is an absolutely vital issue. Measurement units that cannot be understood by their audience deny their most fundamental purpose and their reason for being. They are the twenty-first century equivalent of a dead language. The casual reader of the New SI is immediately struck by an overwhelming impression of inexplicable complexity. The casual reader is correct. Educationists whose pedagogic skills command absolute respect regard the New SI to be literally unteachable at less than specialized postgraduate level. This is unviable.

Closer inspection shows that they are in many respects quite unnecessarily complex. They are also quite unnecessarily ambiguous. The 'mole', discussed above, is a case in both points. It is a serious question to be asked: why is the New SI so unnecessarily complicated, ambiguous, and inconsistent with common measurement practice? The purpose of the SI brochure is to communicate a system of measurement units to a very large audience encompassing all the skills, knowledge, and experience of humans on the globe today. It is in fact addressed to and understandable by a tiny fraction of a percent of that audience–in effect, a privileged priesthood unconnected with practical measurement. Nothing could be more calculated to discourage public and student interest in science and its disciplines. This is not a viable future for measurement in the twenty-first century, even if for no reasons other than the base economic ones.

The economist John Kenneth Galbraith once suggested a new metric to measure undiscovered economic losses due to fraud and called it the bezzle (a shortening of embezzlement) [27]. Weights and measures authorities are of course acutely aware of the bezzle: a small systematic error, an inappropriate setting of a zero or a playing of the tolerances on instruments can yield 'non market transfers' in widely traded goods and commodities amounting to many hundreds of millions of dollars in even a small to medium sized economy. The bezzle is not something restricted to complex high flying financial instruments. Consider a more inclusive metrological mirror to the bezzle. The boozle (a shortening of bamboozlement) is a measure of the economic losses due to misunderstandings by the parties to a transaction or mutual enterprise. Many specific boozles are also bezzles, and much fraud proceeds from misunderstanding by one party of the meaning of a key term (like a measurement unit) in a transaction, of which the counterparty takes dishonest advantage. But there are also a great many losses due to simple honest mutual misunderstanding–from the loss of the Mars Climate Orbiter space craft to everyday confusions of degrees Celsius and Fahrenheit and various shoe sizes. The boozle contributes much to asymmetry of information and transactional costs in an economy.

The New SI will certainly make considerable contributions to the boozle, and most likely to the bezzle, of the world's economies.

Then of course, there is in addition the very serious problem of the use of misunderstandings about measurement as technical barriers to trade, which it was the original primary purpose of the Treaty of the Metre to overcome.

It must not be imagined that complex and incomprehensible systems of measurement units do not have serious adverse economic consequences.

Fixing the constants

I turn now to the matter of fixing fundamental natural physical constants. We should first note that of the seven allegedly fundamental natural physical constants that are used to set the scale of the New SI, only four are genuine. The spectral characteristics of a specific atom and the luminous efficacy of a specific frequency are not fundamental, although they are certainly good examples of stable natural phenomena. The Avogadro 'constant' is dealt with above and in [13, 28, 29] among others. Leonard argues [30] that the integration of atomic and macro-levels of measurement requires that the number of entities comprising one mole must be exactly equal to the gram to dalton (Da) mass ratio and equal in turn to the Avogadro *number,* principles incompatible with the New SI. There are in fact only four (at most) genuine fundamental constants that the New SI proposes to fix: the speed of light, the Planck constant, the elementary charge, and the Boltzmann constant (a referee has presented additional arguments that the Boltzmann constant should also not be regarded as a *bona fide* physical invariant but as a conversion factor). However, these are the cornerstones of classical mechanics, electrodynamics, thermodynamics, and a significant part of the basic technologies of our civilization.

Another vital question unasked by the CIPM is: why use such absolutely fundamental invariants? The definition of the second is a perfectly good example of the proper use of a non-fundamental physical invariant and refers to an invariant natural example of the quantity time interval. However, the new kilogram, defined in terms of a fixed Planck constant, does not exist in our world. It is a virtual thing, conjured into existence, disconnected from the everyday notion of mass. This makes for considerable conceptual and pedagogical difficulties alone. No cogent reason has yet been given in favor of such complexity as the basis for a measurement system. There are however good reasons to avoid it.

A simple and well-known objection is that defining constants as constant and making them the anchor of our measurements must take them beyond empirical test [2]. All tests of the hypothesis of constancy must be circular. This matters a great deal. The evolution of the physical sciences is marked, almost as in geological layers, by the progressive changes in our understandings of fundamental constants and their inter-relations, changes arising hand in hand with new empirical probing of 'old' constants. Such experimental determinations are empirically meaningless and logically circular in the New SI. The result is dictated by the units we use to measure. There is much ongoing, *bona fide* discussion in advanced physics of the possibilities of changing or evolving physical 'constants' [2, 31–35]. The actual empirical evidence for the hypothesis of their constancy is meager (a century or so in the vicinity of a small planet on the outskirts of the Milky Way) and what there is is equivocal and marked by 'fluctuations' due to 'systematic error' [2, 31, 36–39].

An example of the dangers inherent in fixing fundamental constants is the dimensionless fine structure constant, alpha (α), which governs the strength of the interactions between electrons and photons. It is a simple relationship between the electronic charge, the speed of light, and Planck's constant, all of which are proposed to be fixed in the New SI. It is immensely important for example, to our understanding of spectral phenomena in atoms, the basis of many instrumental methods of chemical measurement. Being dimensionless like the geometric constant pi (π, the ratio of the circumference to the diameter of a circle), alpha has the value it has quite irrespective of what measurement units one chooses and for that reason lies at the very heart of some of the most profound but unsolved questions of modern physics. The possibility that alpha may change has been the subject of serious theoretical discussion for three quarters of a century [40–43]. It has not been unknowable as possibility. More recently, hard empirical evidence has been accumulating that alpha may not only vary according to time and distance [44–46] but also direction [47]. A discovery with such wide-ranging implications for our understanding of the physical world clearly needs strong confirmatory evidence from a wide range of independent experiments and phenomena [48, 49], and it is likely that the issue will not be settled unequivocally until the next generation of very large telescopes is operational toward the end of the second decade of this century, assuming that the promulgation of the New SI is not allowed to destroy this vital research program.

For according to the New SI, none of this is even possible. Alpha is fixed because its component constants are fixed. To make the speed of light, the Planck constant, the elementary charge, and the Boltzmann constant exact and constant by the definition of our measurement units is to effectively declare by administrative fiat the presuppositions of classical mechanics, electrodynamics, and thermodynamics to be the end of science, all else being variation on the theme or stamp collecting. The methodology of science emanating from the CIPM is that if empirical facts conflict with the New SI, then so much the worse for the facts.

Is the ninth SI brochure to be the death warrant of science?

There are more subtle objections, but they are neither less worrying nor less important. Pavese [3] has drawn important issues to attention. His basic argument implies that the very high degree of inter-relatedness of the fundamental physical constants is precisely what makes them profoundly unsuitable for metrological use as definitions of measurement units. He points out that the original aim of the SI was the metrologically correct one of a set of independent base units. If no one unit depends on any of the others, this is what guarantees their consistency—if none can be derived from the others, no self-contradictory combination can be constructed. But if some are dependent on others, this is no longer guaranteed. It must be verified empirically. Syntactic consistency is an important and very necessary thing, in all fields. If it happens to go missing, anything goes. The introduction of the 'mole' was the first serious breach of the independence of the SI units and it has since evolved, via the definition of the meter in terms of the speed of light, toward a far more inter-dependent set of units. The New SI proposals for using fixed fundamental constants for unit definition are a culmination: the complete elimination of the in-principle distinction between base and derived units. They are all now very highly inter-related.

For a set of measurement units, there is in addition to the requirement of logical consistency another important kind of 'metrological' consistency, which takes into account the unavoidable fact of uncertainty in all measurement. It is called metrological compatibility in Sect. 2.47 of the third edition of the International Vocabulary of Metrology (VIM) [50]. Humans are not granted god-like spectacles enabling exact measurement. Our results express a confidence that the exact value (if and when it exists) lies within an interval that has been obtained from our measurement and our assessment of its uncertainty. Where within that interval it lies, we do not know. To find out, we would need to do more accurate measurements and these would simply narrow the interval, never eliminate it.

Ten people are asked to measure the length of a given stick. Their measurements will be metrologically compatible if they agree to the extent that their respective uncertainty intervals intersect. If not, there are two possible explanations: that the stick has changed in length between measurements; or some of the measurements and their uncertainty evaluations were faulty in some way. The concept of metrological compatibility is thus of vital practical importance to fault finding and detection of systematic error in measurement systems. Note that metrological compatibility is a function of uncertainty. Measurements of the stick compatible at large uncertainties may well turn out to be incompatible when done at higher accuracies, but we have to do the measurements to find out.

The way to check metrological compatibility in a large and complex global system like the SI is to find common, interconnected universal parameters as 'sticks' and to compare measurements of them to within the best available uncertainties. The uncertainties associated with the values of those measurements determine empirically the verifiable degree of metrological consistency of the SI. These are none other than the fundamental constants that the New SI proposes to fix exactly as a basis for definition of units. The circularity of the procedure is quite evident, a matter I will discuss in my conclusion. But, as Pavese argues, not only is verifiable compatibility and consistency lost, but the procedure actively ensures that at some stage, the system of units must in fact become inconsistent. This is because it is quite impossible that the exact choices of values, within current uncertainties, that is made to fix the constants is in reality the actual consistent set all the way down to their respective zero uncertainties. Our choices must turn out to be wrong and inconsistent with each other at some future level of higher accuracy, and we now have no way of telling where that is. Having fixed the constants by definition, no other independent frame of reference exists to check the consistency of the system. This effectively limits achievable uncertainties. Far from making more accurate measurement possible, fixing the constants may make impossible the achievement of less uncertainty in the future. Accuracy is frozen in time because the choices to fix the constants we make today must impose limits to the measurement consistency and comparability across space and time that we can empirically verify in the future. This is a very serious problem to science, technology, and industry.

Conclusion: anchors aweigh!

However, these are all minor issues—relatively speaking. The critical issue and the one at the heart of the New SI is the distinction between basic and derived units and quantities. It is not a distinction from nature; it is entirely of our making and it is necessary that we make it so that our measurements may be both comprehensible and well anchored. The New SI is the culmination of several decades of evolution of the SI toward the dissolution of that distinction, which had been at the conceptual core of the original SI. With its dissolution has come increasing inter-dependence of units and quantities. In the New SI, there are no base units and quantities. The name ‘base’ is kept for reasons of familiarity alone, but the base units are no different in kind to any of the others, for everything is now connected to everything else, via the fundamental constants. There are many small practical reasons why this is not a wise path, and one very large one.

One of the smaller problems with an “everything-connected-to-everything” measurement unit system with no effective base units is that different people are at liberty to use quite different quantity sets, provided only that all those multiple systems are compatible with the defined constants [3]. Thus, person (a) might regard acceleration as a speed per unit of time, while person (b) sees it as a length per time squared. Neither is wrong, but it is another needless large step away from clarity and consistency of communication. Another practical difficulty is that if everything is connected to everything else, when problems arise, their source becomes hard to track down. Good metrological fault finding becomes impossible; problems of a systematic nature are not recognizable and become just “experimental” or “random” error. Rigorous evaluation of uncertainty becomes difficult because it becomes impossible to tell when double counting has occurred.

Similarly, what I have previously called the principle of direct reference is a very useful rule of thumb in practical measurement system design: start from the base of what people know and understand (mass, length, time, electric charge, temperature, a number of things, angular rotation or direction); make the definition of their corresponding units by reference to a natural exemplar of that quantity (as in the definition of the second); and build derived units from those. Add or modify units as our understanding of nature grows. It is simple, straightforward, readily understood, rigorous but flexible. Does it not make sense to have measurement units based on easily comprehended and practical concepts so that the definitions match relatively easily repeated realization procedures for uniformity of calibration? The SI has evolved in exactly the opposite direction, toward obscurity and complexity.

Overcoming circularity of reference is the central problem of metrology and the key to control of systematic error. The well-known fable of the retired sea captain in Zanzibar who fired a ceremonial cannon at noon exactly each day illustrates the problem. The captain was assiduous in setting his chronometer whenever he passed the window of the watchmaker in town. The watchmaker was equally punctilious and checked his watches daily against the cannon report of the eccentric captain. A circular measurement system is often informally described as a Zanzibar system. It means that systematic errors are undetectable, and it is a very particular problem in an everything-connected-to-everything measurement system, such as the New SI. The choice of the fundamental constants of nature as metrological anchors, as they are understood by current science, at current best accuracy values, runs a real risk of being a Zanzibar system of cosmic proportions. As argued previously, whatever set of values we choose today for the constants, we know that at some higher but now unknowable level of accuracy, that set must be inconsistent and the highest achievable accuracy of our measurements is frozen. What is also unknowable is what science, unhindered by the New SI, might have revealed about the further inter-relationships of the fundamental constants. Such discoveries in the past have been the essence of scientific change and technological evolution. It is clear that our current knowledge of the fundamental constants is incomplete. We know for example that the speed of light, electric charge and Planck’s constant are inter-related by the dimensionless fine structure constant, as I have discussed above. But we do not know its precise significance nor why it has the value it has, and nor whether it is in fact constant. It is entirely likely that the New SI is not only inconsistent but also circular. Metrology in our world is effectively set adrift, a rudderless ship drifting through space and time according to the currents and breezes of future systematic errors. We may well be unable confidently to say in 2021 whether there is more or less carbon dioxide in our atmosphere than now. The New SI is a blueprint for a global Zanzibar system. Good metrological principle seeks to minimize the inter-dependence of base quantities and units. That is what it means to anchor measurements. A base is a foundation or anchor. The New SI seeks to maximize inter-dependence and does away with the notion of a base unit. It has in reality and effect abandoned the very concept of an anchor, keeping only the rhetoric.

Whether or not the fixing of the fundamental constants is the end of science, it is certainly the end of metrology [51]. According to its very own logic, if it is serious, the introduction of version nine of the SI brochure must be accompanied by the dismantling of BIPM and all the apparatus of the Treaty of the Metre. If the rhetoric is to be believed, we are there. The shimmering symmetries of the New SI are not perfect, but they are close and all that needs be done is dot the i's and cross the t's. It is beautiful and complete, attributes that ensure it is unusable and static.

The worlds of science, technology, industry, and trade need to understand and act not just on the basis that these proposals are irrelevant and ill considered, but that they are profoundly dangerous. The risks have not been considered and assessed. If the global financial crisis has taught us anything, it is the truism that taking blind risks can have adverse consequences. It is as true in metrology as in high finance. While this reviewer has played *advocatus diaboli*, it is quite clear on even the most dispassionate of assessments that the proposals contained in the draft of the ninth edition of the SI brochure must be fully, forthrightly, and critically canvassed, discussed, and examined at the widest and the highest levels of the open literature of science, technology, and international trade and global policy, and well before any irreversible steps are taken. This has not happened. Our world cannot afford anything less. The fate of our civilization on our planet hinges on the integrity of measurements past, present and future. Fixing physical constants is very risky business and is perhaps something better done by deities than left to the foibles of committees [52].

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