Accred Qual Assur (2012) 17:215–219
DOI 10.1007/s00769-011-0857-z

DISCUSSION FORUM

No prospect for change

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Received: 1 October 2011 / Accepted: 30 November 2011 / Published online: 31 December 2011

Abstract A recent discussion by Martin Milton in the November issue of this journal was critical of many published objections to the proposed new International System (SI) measurement units (and in particular the definition of the mole) on the grounds that many objectors had proposed new terms in attempts to clarify thinking and that it is impractical to achieve consensus on such proposals. This discussion in response argues that those criticisms miss the point of the objectors' arguments and are perhaps more appropriately directed at both the current and the new SI itself. A primary example of a neologism in the SI is the term "amount of substance." The many substantive problems with the new SI remain unaddressed by its proponents. Many important consequences of exactly fixing multiple inter-dependent fundamental physical constants as the basis of the world's measurements would appear not to have been considered by the global institutions responsible for the world's measurement units.

Keywords New SI · Measurement units · Mole · Policy

Introduction

Martin Milton [1] has given cogent reasons for stability, clarity and general understanding in the evolution of our measurement systems. With this I agree completely and I commend the perception that units of measurement are scientific and cultural goods [2]. They are indeed that and very much more, underpinning and enabling modern civil society in all its socioeconomic complexity and technical prowess. Among other things, they are the other side of the coin to that other great human facilitator, currencies—the means of exchange.

We are seeing at the moment in our world the playing out of a loss of trust in money. It is vital we do not see it in measurement. Practicality, trust, principle and fitness for intended use all intricately combined are inseparable to our civilization's use of measurements. It is a tall socioeconomic order. All the more reason that measurement units should be considered with the greatest of thought and care in open collegial manner. Measurement system failures can have the gravest of long-term consequences, and prudent risk analysis is an absolute pre-requisite.

I profoundly disagree that the new International System (SI) of measurement units [3] is an exemplar of any of those principles. Its evolution has been in the opposite direction. It is proclaimed by its own proponents—to some audiences—to be radical and revolutionary [4]. It entails risks not worth the taking.

Neologisms, resignification and ambiguity: the case of chemical measurement in the SI

Many including myself deplore the practice of the unnecessary invention of new and incomprehensible terms that Milton also condemns. The grand neologism of twentieth century measurement was of course none other than "amount of substance" (in the German, "Stoffmenge"), a contradiction in terms with equal roots in ancient alchemy

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and medieval theology [5, 6]. It was a terminology stripped centuries ago of all rational, logical and empirical credibility by the rise of chemistry itself and the fundamental perceptions of stoichiometry. Yet, here it is in the twenty-first century, having been re-engineered in the twentieth by thermodynamics for the use of analytical chemistry [7]. There is no justification for the use of the term "amount of substance" to describe the quantity with which most analytical results are reported. It is firstly ad hoc and unnecessary. There is a perfectly well-understood and different concept, "number of things (or entities)" available for use. Secondly, it invites confusion with that simple and straightforward notion. Thirdly, the term "amount" is deeply ambiguous and depending on circumstances, may invite confusions with mass, volume or any of a large number of other distinct quantities. Fourthly, the term "substance" has an extremely long and worthy history throughout civilization in, for instance, ancient assaying, smelting, matter theory and the material sciences and industries of all kinds involving transformations of matter, the popular imagination, theology and alchemy [8]. It long predates "mass" as a fundamental concept in all the pre-modern sciences and had an associated meaning in theology where the term "quantitas materiae" lay at the base of the Doctrine of Transubstantiation in the Eucharist and the associated liturgy named "Mass"—referring to the "substance" of the bread. Both Kepler and Newton were heavily influenced by these theological ideas and linguistic usages and Newton in particular was also well known as a practitioner of the alchemical arts [5]. Many vestiges of those uses of the term "substance" remain even today. None of that history is consistent with the revelations of modern chemistry. Nor is its meaning in those contexts consistent with coupling the term "substance" with "amount." "Substance" to the premodern sciences of matter referred to the unmeasurable basis of things onto which all observable and measureable "forms and qualities" were impressed. By definition, it was not the kind of thing there could ever be any "amount" of. The term "amount of substance" is superfluous, confusing, ambiguous and a profoundly incomprehensible self-contradiction on many still common (mis)understandings. It is certainly not a term to be used when clarity of communication is important.

Apart from the invention of new terms, there is another project of linguistic engineering that should be undertaken only with care and skeptical economy. It is the invention of new and unusual meanings for existing well-understood terms. I shall call the practice "re-signification." Its grand example is of course the mole, to generations of simple chemists simply an Avogadro number of specified things. It was re-significated by committee in 1971 to refer to a unit of the above-mentioned invented quantity called "amount of substance."

"Amount of substance" is not "number of things." Apart from the simple logic that the first is continuous, the second granular and only expressible with integer numbers (there are no half atoms), it is also a truth emphasized by successive leaders of the Consultative Committee on Units (CCU) [9–12], who have despaired of the common misconception that the mole is just a name for a large given number of things, the "chemist's dozen" ever since the introduction of the term "amount of substance." There has recently been a subtle change in rhetoric toward inferring but avoiding saying directly that "amount of substance" is somehow or other like or similar to a number of entities. This has been notable in unpublished briefings by the proponents of the new SI, but a clear and citable example is [4].

> …a definition of the mole that will help eliminate the present poor understanding of the SI base quantity amount of substance, which is independent of mass, and its unit mole, ***which is a unit to count the number of entities*** (my emphasis)

This is misleading *in extremis*. It is entirely at odds with [9–12]. The SI unit the mole, as is explicitly stated in its definition, is a unit used to measure something quite different. It is called "amount of substance." It is wrong to suggest otherwise, as was emphasized to the chemical education community by [11], which gave a number of alleged reasons why "amount of substance" is preferable to "number of entities" for the reporting of chemical measurement results. Those reasons were the subject of a critical analysis in [13]. It should also be noted that analysts long ago ceased thinking in terms of mass. It is the number of relevant reactive units that do the damage, power our industry, pollute our environment, poison, heal and much else besides. Their masses and "amounts of substance" are of incidental relevance, a means only of finding out those more fundamental facts. The rules of stoichiometry stand behind the purposes of most modern chemical analysis.

It is a simple fact of well-acknowledged language use: there are currently two meanings for the term "mole." For teachers, textbooks, analysts and for users of their measurements, a mole is just an Avogadro number of specific entities. However, those who consult the SI brochure [14] find that it is a unit for a strange and different quantity called "amount of substance." This is neither good metrology nor is this comprehensible communication. Ambiguity is to be avoided just as much as neologism.

Some disquiet concerning the new SI

There is no doubt that the new SI is radical. It is a revolutionary and irreversible change to the very basis of the world's measurement systems. The fixing of multiple fundamental and inter-related physical constants as the anchors of the world's measurements is a global experiment with unexamined consequences.

Disquiet is widespread and across many disciplines. The resolve of the proponents of the new SI to ignore or misrepresent those concerns is disturbing indeed and is raising serious questions regarding governance of the Treaty of the Metre. The March issue of this journal, ACQUAL [15], in many articles, raised many questions concerning the treatment of chemical measurements and the principles of the new SI [16–24]. None have been convincingly addressed by the proponents of the new SI, despite repeated invitations to do so. In addition to the matters related to the "mole" and "amount of substance" referred to above and discussed in all the above articles, those issues include:

- Complexity, incomprehensibility to users, unteachability and incommunicability [16–24].
- Lack of robustness, relevance, practicality and adaptability in a closed and irreversible system [17, 19–22].
- Inability to add new kinds of quantities that may become important in the future (such as biological activity or information) as human understanding grows [17].
- Incompatibility with the currently well-accepted International System of Quantities [25] and with the 2008 International Vocabulary in Metrology [16–18, 26].
- Incompatibility in the relationships between the mole, the kilogram and the dalton [16, 18, 24].
- Lack of any base units or direct referential foundations [16, 17].
- Vulnerability to systematic error, circularity and interdependencies [16, 17, 21].
- Inevitable future metrological inconsistency and limitations to future achievable accuracy [16, 17, 21].
- Restriction of options for innovation and the future evolution of physical sciences and technologies [17].

Hill [27] also gave a list of eight serious flaws in the new SI and noted the censorship and suppression of such inconvenient matters by the International Bureau of Weights and Measures (BIPM) and the Consultative Committee on Units.

In addition Pavese [28] has recently pointed out that the procedure for exactly fixing multiple inter-dependent fundamental constants using only current data must necessarily involve inherently unknowable rounding errors that compound, propagate and multiply alarmingly in computer calculations. This imposes severe limitations on future reliability, consistency and accuracy.

Added to all of the above, there are well-known problems with the current SI [14] that remain unaddressed such as incompatibility with computer data systems and informatics generally [29], confusions in numerical expressions between integers and real numbers, basic errors in its account of dimensions, of unity, of entities and the counting thereof [13]. The subject of the identity of measurands—a central topic for chemical measurement—is unmentioned. There are well-documented problems, confusions and inconsistencies in the treatment of angular measures and rotations—some of the oldest and most basic measurements known to our species [30–34]. All of these are creating large difficulties for modern technologies.

Systematic error and the new SI

Finally and most profoundly worrying of all is the cavalier approach to future systematic error in our measurement systems. Major systematic errors far exceeding previously quoted precision (in the sense of reproducibility as understood by the definition of this concept in the International Vocabulary of Metrology [26]) have been frequently found throughout the very short history of the measurement of the constants now being proposed to underpin the world's measurements. They cannot be detected in the future under the new SI. Such systematic effects must be reflected instead in uncorrectable variations in the magnitude of units. The new SI by its very own procedure of exactly stipulating the values of inter-dependent fundamental constants merely on the basis of present accuracies guarantees such future systematic error and inconsistency.

It is quite possible that decades from now we will be unable confidently to know whether atmospheric carbon dioxide levels are greater or less now than then.

This is because systematic error may greatly exceed currently best quoted precision. Multiple inter-related systematic errors compound, propagate and multiply throughout all subsequent calculations. Such uncorrectable, inherently unknowable systematic drift in any measurement system means that measurements cannot be assumed to be comparable over time. There may be no common basis for long term comparison and we cannot check. We simply cannot know.

The most recent information on the Committee on Data for Science and Technology (CODATA) evaluations of physical constants [35] has shown emerging discrepancies between 2006 CODATA evaluations of important fundamental physical constants and the 2010 evaluations. They have a direct bearing on the new SI and illustrate the effects of systematic error. In some cases, the discrepancies are far larger than the 2006 uncertainties. Of special interest is the fine structure constant alpha, perhaps the most fundamental of all and itself a function of the speed of light, the electric charge and Planck's constant (all of which are to be fixed) and the electric/magnetic constants (formerly fixed as the basis of CODATA evaluations but under the new SI to be rendered newly measurable). Alpha's 2010 value is greater than the 2006 value by 6.4 times the uncertainty of the 2006 figure.

Questions that have not been given consideration include the following: how many more systematic errors might be uncovered as technology and understanding improves? Could they be uncovered at all in a fixed constant regime? What would be their effects on the world's high-technology measurement systems in the future?

The new SI is the opposite of robust and carries with it very considerable risks. They have been ignored. These are grave concerns, and they require serious response.

The guiding principle of the new SI

The fixing of multiple inter-dependent fundamental physical constants—rather than specific stable atomic phenomena—has been a particular enthusiasm of the administration of the Treaty of the Metre. It has been justified as the final achievement of the dreams of the great nineteenth century physicists. James Clerk Maxwell in particular is usually quoted as the originator of this *idée fixe*, and it is worthwhile looking at what he said. Here is the actual statement as often quoted by the proponents (e.g., [36]) of the new SI:

> Yet, after all, the dimensions of our earth and its time of rotation, though, relative to our present means of comparison, very permanent, are not so by physical necessity. The earth might contract by cooling, or it might be enlarged by a layer of meteorites falling on it, or its rate of revolution might slowly slacken, and yet it would continue to be as much a planet as before. But a molecule, say of hydrogen, if either its mass or its time of vibration were to be altered in the least, would no longer be a molecule of hydrogen.
> If, then, we wish to obtain standards of length, time and mass which shall be absolutely permanent, we must seek them not in the dimensions, or the motion, or the mass of our planet, but in the wavelength, the period of vibration, and the absolute mass of these imperishable and unalterable and perfectly similar molecules.
> James Clerk Maxwell, 1870 [37].

We should note that Maxwell suggests we seek anchors for our measurements in "the wavelength, the period of vibration, and the absolute mass of these imperishable and unalterable and perfectly similar molecules." Note that they are specific phenomena, such as the cesium transition that currently sets the unit of time interval, the second. Note also that the term "fundamental constant" is entirely absent. In his own day, he did not have Planck's constant to choose from, but he knew many other fundamental constants to choose. He chose not. He chose instead specific stable phenomena, directly related to the base quantities for which they were to be unit. The metrological use of multiple inter-related fundamental physical constants in the new SI cannot be justified by reference to such authority. It is a particular obsession of the International Committee on Weights and Measures (CIPM) and its Consultative Committee on Units. It has not been justified or argued for, it has been assumed as a physicists' imperative without regard for the fundamental purposes of a system of measurement units or the basic principles of practical measurement system design [23].

Conclusion

The new SI is the culmination of decades of development by self-selecting committees in the direction of obfuscation. A system of measurement units incomprehensible to its users is unviable. There is potential for large economic loss, asymmetry of information, transactional costs, strangling of innovation, fraud and of course potential for a renaissance in technical barriers to trade—which it was the original purpose of the Treaty of the Metre to overcome. It must never be imagined that complex and incomprehensible systems of measurement units cannot have consequences every bit as serious and as adverse as we are currently seeing in global finance. Every transaction depends upon a multitude of measurements. Trust is what holds them together and must never be taken for granted.

The new SI is simply not fit for its intended use, and there is no prospect for change. This is most deeply regrettable, but soothing misrepresentation does not alter anything. It requires urgent open and wise reconsideration well before irreversible actions are taken. The institutions responsible for our world's measurement units do not appear to have that systemic capability.

Acknowledgments I thank the anonymous reviewers who sought greater clarity, improving both text and the writer's understanding.

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