Journal & Proceedings of the Royal Society of New South Wales, vol. 150, part 2, 2017, pp. 143–151. ISSN 0035-9173/17/020143-09

Standards and units: a view from the President of the Royal Society of New South Wales

D. Brynn Hibbert

The Royal Society of New South Wales, UNSW Sydney, and
The International Union of Pure and Applied Chemistry

Email: b.hibbert@unsw.edu.au

Abstract

As the Royal Society of New South Wales continues to grow in numbers and influence, the retiring president reflects on the achievements of the Society in the 21st century and describes the impending changes in the International System of Units. Scientific debates that have far reaching social effects should be the province of an Enlightenment society such as the RSNSW.

Introduction

It may be a long bow, but the changes in the definitions of units used across the world that have been decades in the making, might have resonances in the resurgence in the fortunes of the RSNSW in the 21st century. First, we have a system of units tracing back to the nineteenth century that starts with little traction in the world but eventually becomes the bedrock of science, trade, health, indeed any measurement-based activity. Second, the RSNSW, similarly aged and arising out of the great Enlightenment push for understanding and knowledge, might not have underpinned quite such a wide movement, but is now finding its niche as a place for thoughtful people to meet, receive knowledge, and reflect on the modern and complex world we live in. Although science heavy, it is interesting that the Forums, where we come together with the four learned Academies in Australia have been on the bigger questions of "The Future of Work", "Society as a Complex System" and "The Future of Rationality in a Post Truth World". Each of these 'hard' problems is informed by science, but not solved by science alone. Our own Society embraces "science literature philosophy and art" and we see with increasing clarity that our business often spans all these fields. As we shall learn the choice of units with which to measure our world is driven by science, philosophy, history and a large measure of social acceptability, not to mention the occasional forearm of a Pharaoh.

Measurement

We take measurement for granted. Each of us has an idea of our height, weight, age, how far it is from Sydney to Brisbane, the freezing point of water, and so on. There is little need to reflect on how these concepts come about and how numbers can be put upon specific instances. We might remember there can be different systems of units; water freezes at the same temperature, but we can call that temperature 0 °C, 32 °F or 273.15 K.

Do we worry about measurement uncertainty? Our three freezing point temperatures imply very different levels of precision, as suggested by the number of digits used to give the numerical value. We might say that Sydney to Brisbane is 1 thousand kilometres, and be sufficiently correct to the nearest thousand (the crow-flies distance is 733 km, Google maps offers 922.3 km to drive). A high quality, single-frequency global positioning system (GPS) has an horizontal accuracy of less than 1.9 m for 95% of measurements (William J. Hughes Technical Center WAAS T&E Team, 2017), so if we wanted to we could measure the distance between points in Sydney and Melbourne to be, say, 733875.5 m with an uncertainty of ± 2.7 m (√2 x 1.9 m). Such are the achievements of the 21st century.

Metrology

Metrology (no, not meteorology), is the science of measurement and has an international infrastructure that maintains our understanding of this important human activity. Eight international organisations[1] come together in the Joint Committee for Guides in Metrology and through its two working groups prepares the *Guide to the Expression of Uncertainty in Measurement* (GUM) (Joint Committee for Guides in Metrology, 2008) and the *International Vocabulary of Metrology* (VIM) (Joint Committee for Guides in Metrology, 2012).

Figure 1: Pavillon de Breteuil, home of Bureau Internationale des Poids et Mesures (BIPM) (photo: D B Hibbert, 2012)

These bodies meet at the BIPM on the outskirts of Paris (Fig. 1), and for many years the author travelled twice a year to sit on the GUM working group representing IUPAC. It is a hard life, but someone has to do it.

This essay concerns the measurement of quantities the values of which are represented by a "number and a reference together expressing magnitude" [VIM 1.19][2]. The 'reference' is our unit without which the number has no meaning. (Consider if you were told water freezes at 0, 32 or 273.15). So far so good, but where do units come from?

A Brief History of Units

As soon as you want to pass on information about the magnitude of something the concept of an agreed example of that quantity to serve as a unit becomes evident.

[1] International Bureau of Weights and Measures (BIPM), International Electrotechnical Commission (IEC), International Federation of Clinical Chemistry and Laboratory Medicine (IFCC), International Organization for Standardization (ISO), International Union of Pure and Applied Chemistry (IUPAC), International Union of Pure and Applied Physics (IUPAP), International Organization of Legal Metrology (OIML), International Laboratory Accreditation Cooperation (ILAC).

[2] Where terms are defined in the International Vocabulary of Metrology (VIM) the entry number is given in square brackets [VIM x.y]. See Joint Committee for Guides in Metrology, 2012.

Figure 2: Papyrus showing weighing the souls of the dead and a copy of the Royal Cubit. (courtesy Paul De Bièvre)

Counting (enumeration) of objects predates measurement as such, where the unit is 'one thing', but very quickly after the introduction of writing we see references to standards of length, volume and weight appearing in the Middle East, particularly Ancient Egypt and Mesopotamia, and in China. For example the Royal Cubit (Fig. 2), the length of the Pharaoh's forearm and hand was used as a length standard in constructing the Pyramids and for monitoring the depth of flooding of the Nile in the period between 3000 and 2700 BCE (Clagett, 1999).

Very quickly the utility of standards spread and we find examples in every society (Fig. 3).

Figure 3: Chinese weight from the Warring States Period 244 BCE (Photo D B Hibbert)

Mediæval Europe and the need for standardisation of the standards

Kings were particularly keen on standards, no doubt something to do with taxes. Having standardised measures is prescribed in Magna Carta, and then at different times after that standards were issued by the crown. Edward I of England required each town to have an 'ellwand', a rod the length of an ell (about 46 cm or twice that depending on who you read). The ell was a realisation of the old cubit being about the distance from an elbow to the tip of the middle finger. Not surprisingly there were many versions of the ell named after the country or town of origin, and none were the same. The plethora of standards between and within countries would have been seen as an impediment to trade. Discussions of what would become the 'metric system' start with Bishop John Wilkins FRS (1614–1672), the first secretary of the Royal Society of London. He was asked by the Society to devise a universal standard of measure. In 1668, in Chapter VII in his book *An Essay towards a Real Character and a Philosophical Language*, which mostly dealt with the possibility of an international language, he proposed a system of measurement based on a decimal system (Wilkins, 1668). It was the French however who then made all the running.

Metric systems and the SI

The creation of the decimal metric system and the subsequent deposition of two platinum standards representing the metre and the kilogram, on 22 June 1799, in the Archives de la République in Paris can be seen as the first step in the development of the present International System of Units. Carl Friedrich Gauss (1777–1855) promoted the application of this decimal metric system, together with the second which was defined in astronomy, as a coherent system of units [VIM 1.14] for the physical sciences. The Metre Convention (Convention du Mètre), signed by delegates from seventeen countries on 20 May 1875, established, by Article 1, the Bureau International des Poids et Mesures, the BIPM (BIPM, 2007), charged with providing the basis for a single, coherent system of measurements to be used throughout the world. The General Conference of Weights and Measures (CGPM) was also established, and work began on the construction of new international prototypes of the metre and kilogram. Together with the astronomical second as the unit of time, these units constituted a three-dimensional mechanical unit system with the base units metre, kilogram, and second, the MKS system. The system developed and, in 1960, at the 11th CGPM it was called the International System of Units (Système International d'Unités), SI [VIM 1.16]. The SI has now seven base units [VIM 1.10] from which other units can be derived (for example the unit of energy, joule J which is kg m^2 s^{-2}). See Table 1 and (BIPM, 2014). It is the proposed revision of the SI to which I shall devote the rest of this address.

Table 1: Base units of the SI

Base quantity	Name of unit	Symbol
length	metre	m
mass	kilogram	kg
time	second	s
electric current	ampere	A
thermodynamic temperature	kelvin	K
amount of substance	mole	mol
luminous intensity	candela	cd

Definitions of units

The base units of the SI have been defined after much discussion of how best to obtain the following: "units should be chosen so that they are readily available to all, are constant throughout time and space, and are easy to realize with high accuracy" (BIPM, 2014). Falling foul of "readily available to all" the kilogram is defined as the mass of the international prototype of the kilogram, an object made of platinum and iridium, which is held in two safes under three bell jars in the basement of the BIPM. It has only been brought out on three occasions since its manufacture in the 1890s. Metrological traceability [VIM 2.41] of mass measurements to this artefact is achieved through six copies held at the BIPM, tens more distributed to the National Measurement Institutes of many countries, and then thousands of standard weights that are used to calibrate balances, even unto weighing potatoes at your local supermarket. The 'Big K', as it is affectionately known, is the only material object in the SI. The metre, the unit of length, once being defined by a standard platinum-iridium bar that was constructed to be a particular fraction of the distance between two points on the Earth, is now the distance light travels in a vacuum in 1/299 792 458 of a second. Even though you or I might find it difficult to create a metre so defined, this definition of metre no longer makes a single thing at a particular place on Earth the sole ultimate realisation of the unit. This definition also leads to the question of where we get the rather short time from, the answer being by knowing the speed of light with exceptional accuracy. In fact, if you consider it, if metre is defined as written above then the speed of light in a vacuum has to be exactly 299 792 458 m s^{-1}. More of fixing values of phenomena later.

Mise en practique

Reflecting on the discussion of how to define units you might have realised that the definition is one thing, but how is it to be used to actually measure a quantity in the real world is something else. The set of instructions on how to 'make' a unit at the highest metrological level is called the *mise en practique*. Although the kilogram is reviled for being an artefact, its *mise en practique* is quite clear, essentially being "take the Big K out of its bell jars and safes, buff it up with a chamois leather cloth and some propanol, and weigh one of its six copies against it." The potatoes in the supermarket gain the benefit of this practice by a long chain of subsequent comparisons of weights establishing the so-called metrological traceability chain [VIM 2.42] (De Bièvre et al., 2011). As for the rest their *mise en practique* can be quite tricky.

How to make a new SI

Replacing the kilogram

It is not just the dear old kilo that is on the nose. We also realised that the definition of the ampere, the unit of electric current, was not exactly easy to realise. (The ampere is that constant current which, if maintained in two straight parallel conductors of infinite length, of negligible circular cross-section, and placed 1 metre apart in vacuum, would produce between these conductors a force equal to 2 x 10^{-7} newton per metre of length.) Rather than the super-scientific application of the Enlightenment, it turns out that the SI is a bunch of nearly *ad hoc* definitions that work together, but only just. There are many reasons, not just scientific ones, that have led to the present SI, supporting my contention that what we do, even in the name of high science, is ultimately a human activity relying as well on "literature philosophy and art."

The "New SI"

Thank you for bearing with me. And now with a drum roll I give you news of the completely new SI. More than a decade in the planning (CPGM, 2007) and most recently resolved by the CGPM in 2014 (CPGM, 2014), the new approach has turned on their heads the concept of definition of a unit and measurement of fundamental constants. At present having set up a system of units we go into the world and measure quantities (mass of potatoes etc.). A set of quantities of great importance to science are so-called fundamental physical constants of Nature (NIST, 2014). We have already encountered the speed of light in a vacuum. Another is the Boltzmann constant, and another is the atomic fine splitting constant. Knowing, by measurement, these constants to the best accuracy we can manage is important to just about every activity in science. We can measure the values of these constants, with measurement uncertainty, because we have defined units in the SI. The point about fundamental physical constants is that we believe they are constant anywhere in the universe and for all time (since a bit after the Big Bang). We write

$$\text{quantity} = \text{number} \times \text{unit}, \qquad (1)$$

(e.g. the Planck constant, $h = 6.626\ 070\ 040(81).10^{-34} \times$ joule second, where (81) at the end gives the standard measurement uncertainty [VIM 2.30] in the last two figures). The value has uncertainty because the quantity is measured. Now suppose we decide that the measured value is the very best we can obtain and so can be fixed without uncertainty. We assert that the actual quantity in Nature is fixed in value, and now we have a fixed number. Et voila! According to Eq. (1), if two out of the three terms are fixed, the third – the unit – is now defined without uncertainty. A definition of the unit joule second (symbol J s) would therefore be "The unit of action, J s, is that action for which the Planck constant has a value of exactly $6.626\ 070\ 040.10^{-34}$ × joule second." To avoid changing the base quantities for which we determine base units (Table 1) it has been decided to fix enough constants that the existing base units can still be defined. As will be decreed by the CPGM at its 26th meeting in 2018 (Richard and Ullrich, 2017), the (new) SI will be the system of units in which:

- the ground state hyperfine splitting frequency of the caesium 133 atom $\Delta\nu\ (^{133}\mathrm{Cs})_{\mathrm{hfs}}$ is exactly 9 192 631 770 × hertz,
- the speed of light in vacuum c is exactly 299 792 458 × metre per second,
- the Planck constant h is exactly $6.626\ 070\ 15.10^{-34}$ × joule second,
- the elementary charge e is exactly $1.602\ 176\ 634.10^{-19}$ × coulomb,
- the Boltzmann constant k_B is exactly $1.380\ 649.10^{-23}$ × joule per kelvin,
- the Avogadro constant N_A is exactly $6.022\ 140\ 76.10^{23}$ × reciprocal mole,
- the luminous efficacy K_{cd} of monochromatic radiation of frequency 540.10^{12} × Hz is exactly 683 lumen per watt,

where

> the hertz, joule, coulomb, lumen, and watt, with unit symbols Hz, J, C, lm, and W, respectively, are related to the units second, metre, kilogram, ampere, kelvin, mole, and candela, with unit symbols s, m, kg, A, K, mol, and cd, respectively, according to Hz = s^{-1}, J = m^2 kg s^{-2}, C = s A, lm = cd m^2 m^{-2} = cd sr, and W = m^2 kg s^{-3}.

Arguments for and against the New SI

Opinion was that the old SI had gone as far as it could, and perhaps something needed doing, at least for the ampere and kilogram. The chemists had never been comfortable with the quantity 'amount of substance' measured in mole or indeed the Avogadro constant with units mol^{-1}. We (I am an analytical chemist) have more or less ignored the SI as far as measuring the numerosity of atoms and molecules. Older concepts of 'gram mole' and an Avogadro number as a kind of chemist's dozen are still widely taught even by university lecturers, who in theory should know better.

Despite wide acceptance of the need for change and somewhat reluctant support for the proposed New SI, there is still a loud complaint from the periphery, outside the BIPM and National Measurement Institutes and the major international organizations. (Hill, 2011). Apart from moaning about lack of transparency of the process (many discussions are behind closed doors, but science was never a democracy), the main arguments against are:

- There are no more independent base units. The seven defining constants are taken together to make all units, base or otherwise. See Fig. 4. However, this interdependency means that errors in any one assignment will impact the rest, with the exception of the mole which only depends on the Avogadro constant.
- Are the constants of Nature truly constant? If one is not, even ones not immediately in the chosen seven, for example the fine

structure constant, because we have fixed the numerical value, and we no longer measure the constant, we can only infer changes through other measurements.

- Are these definitions teachable and understandable by all but the most sophisticated scientists? (Barański, 2013)
- Chemists have supported the unit of mass being related to the dalton (Da), which is presently defined as 1/12 the mass of an unbound ^{12}C atom with measured value 1.660 538 782(83) kg, rather than the Planck constant with its quantum mechanical associations. The gram to dalton ratio is the Avogadro number, but this definitional agreement will no longer hold in the proposed new SI, although practically nothing will change.

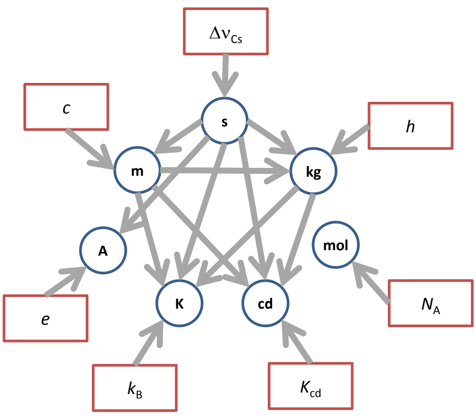

Figure 4: Relationships and dependencies among the seven base units of the SI (circles) and the defining fundamental physical constants (rectangles). See text for description of symbols.

These concerns are mostly answered:

- There is really no need to have base units anymore, although the new SI will be cast in terms of the old base units for continuity. The SI is a coherent system, and the correlation among units actually leads to smaller uncertainties of measurement.
- While there has long been discussion about the constancy of fundamental constants (Dirac, 1938) on the scale of the Universe, it is not likely that the values of the chosen constants will change appreciably any time soon.
- Some of the definitions might not be as straightforward as they used to be, but practically nothing will change. Australia will still have its national standard kilogram against which all weights in the country will be measured.
- The use of the Planck constant over the dalton is admittedly not the preferred option for chemistry but it works better for the SI as a whole with the set of constants chosen. Defining two out of kilogram, Avogadro constant and dalton is a matter of choice – sorry we didn't choose yours.

Realising the kilogram and Avogadro constant

An excellent result from the whole process is that a great effort has been put into realising the kilogram via the Kibble Balance (before called the watt balance) – see Chao et al., (2015) for a LEGO® version that can be constructed at home – and the Avogadro constant by the 'silicon route'. Chemists and metrologists, and particularly Australian chemists and metrologists, have undertaken a worldwide experiment in which the purest silicon 28 is made into the most perfect spheres. By X-ray diffraction the dimensions of the silicon unit cell are measured and then the volume of a weighed silicon 28 sphere (Fig. 5) is measured. The ratio of the molar volume to the atomic volume is the

Avogadro constant (Hibbert, 2008). Fig. 5 shows Australia's contribution to the project, which was to fashion the silicon spheres by, in the last stages, hand polishing with jewellers' rouge. Measurements of the sphere's diameter reveal an almost perfect surface.

Figure 5: Walter Giardini of the National Measurement Institute Australia holding a silicon sphere as part of the Avogadro project. (photo D B Hibbert)

Discussion and Conclusions

As I compiled this brief account of units, I see personal, national and international rivalry, and scientific arguments being made in wonderfully self-serving ways. The French were the problem in the old days. Before signing of the Treaty of the Metre in 1875 France had the prototypes of the metre and the kilogram, but the military successes of Germany and the commercial hegemony of Britain meant that offering them to the international community was the only way to keep the standards in Paris, albeit in the new international organisation BIPM. The USA was an original signatory to the Treaty, but has cleaved to its version of British Imperial units ever since. Britain, although attending the metre convention in 1875, wouldn't have a bar of the new Treaty, even though they had pioneered the idea, and a British company, Johnson Matthey, made the prototypes and copies of the kilogram and metre. Britain did join in 1884, and Australia became a formal member in its own right in 1947.

The anarchy of the debate around the most recent changes in the SI has detracted from the great effort the world is putting into global standards. Early attempts to steamroller the changes caused a backlash that has taken years to sort out. I happened to vote for the changes presented without warning at an IUPAC (International Union of Pure and Applied Chemistry) meeting in Glasgow in 2009, the support endorsed by the IUPAC Council. Realising I had not made a considered decision my division mounted opposition for the next four years until IUPAC created a union-wide project to consider the changes to the SI. This reported in 2017 (Marquardt et al., 2017), after extensive consultation in the chemical community, recommending again acceptance of the proposed changes but with a new suggestion for the definition of the mole.

Perhaps only a society that boasts the breadth of interest as the RSNSW is equipped to advise and debate the most momentous issues of the day. If climate change had not been fought over as a purely scientific proposition, but from the start the social and political aspects had been properly integrated into the debate, we might be in a better place. The Royal Society of New South Wales has a serious future in supporting the 'whole of human activity' approach to problems, and I have valued my part in bringing this about.

References

Barański, A. (2013) The prospect of the dalton in the new SI: an educator's point of view, *Accreditation and Quality Assurance*, 18, 5, 441-445.

BIPM (2007) *The International Bureau of Weights and Measures*, www.bipm.org, BIPM, Accessed: March 2017.

The International System of Units (SI) Updated 8th Edition (2014), BIPM, Intergovernmental Organisation of the Convention of the Metre, Sevres, France.

Chao, L. S., Schlamminger, S., Newell, D. B., Pratt, J. R., Seifert, F., Zhang, X., Sineriz, G., Liu, M. & Haddad, D. (2015) A LEGO Watt balance: an apparatus to determine a mass based on the new SI, *American Journal of Physics*, 83, 11, 913-922.

Clagett, M. (1999) *Ancient Egyptian Mathematics*, American Philosophical Society, Philadelphia.

CPGM (2007) *On the possible redefinition of certain base units of the International System of Units (SI)*, BIPM, Sevres, https://www.bipm.org/en/CGPM/db/23/12/, Accessed: 31 October 2017.

CPGM (2014) *On the future revision of the International System of Units, the SI*, BIPM, Sevres, https://www.bipm.org/en/CGPM/db/25/1/, Accessed: 31 October 2017.

De Bièvre, P., Dybkaer, R., Fajgelj, A. & Hibbert, D. B. (2011) Metrological traceability of measurement results in chemistry: concepts and implementation (IUPAC Technical report), *Pure and Applied Chemistry*, 83, 10, 1873-1935.

Dirac, P. A. (1938) A new basis for cosmology, *Proceedings of the Royal Society of London A: Mathematical, Physical and Engineering Sciences*, 165, 921, 199-208.

Hibbert, D. B. (2008) The Avogadro project and the definition of the kilogram, *Materials Australia* 41, 3, 58-59

Hill, T. P. (2011) Criticisms of the proposed "new SI," *Accreditation and Quality Assurance: Journal for Quality, Comparability and Reliability in Chemical Measurement*, 16, 8, 471-472.

Joint Committee for Guides in Metrology (2008) *Evaluation of measurement data — Guide to the expression of uncertainty in measurement*, BIPM, Sèvres

Joint Committee for Guides in Metrology (2012) *International vocabulary of metrology — Basic and general concepts and associated terms VIM*, BIPM, Sèvres

Marquardt, R., Meija, J., Mester, Z., Towns, M., Weir, R., Davis, R. & Stohner, J. (2017) A critical review of the proposed definitions of fundamental chemical quantities and their impact on chemical communities (IUPAC Technical Report), *Pure and Applied Chemistry*, 89, 7, 951-981.

NIST (2014) *CODATA Internationally recommended 2014 values of the Fundamental Physical Constants*, https://physics.nist.gov/cuu/Constants/index.html, Physical Measurements Laboratory, NIST, Accessed: 31 October 2017.

Joint CCM and CCU roadmap for the adoption of the revision of the International System of Units (2017), Richard, P. & Ullrich, J., BIPM, Sevres, 3.

Wilkins, J. (1668) "Measure," *An essay towards a real character, and a philosophical language*, The Royal Society of London, London, 190 - 194.

Global Positioning System (GPS) Standard Positioning Service (SPS) Performance Analysis Report (2017), William J. Hughes Technical Center WAAS T&E Team, William J. Hughes Technical Center, Atlantic City International Airport, NJ, 146.