How Should General Chemistry Teaching Faculty Handle the New SI Base Unit Definitions?

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Abstract:

Chemistry is an empirical science and the units of measurement that underlay the quantification, preservation and communication of chemical observations are typically one of the first concepts covered in the introductory chemistry classroom. In November of 2018 new definitions for the SI base units were approved during the General Conference on Weights and Measures. The new definitions will be based on physical constants that are considered as invariants of nature. Please see Peter Rusch's 2017 CCCE Newsletter article for information leading up to this change; Textbook and the SI Base Units, A Challenge for Authors and Editors .

The new definitions go into effect on May 20, 2019. The purpose of this paper is to look into these changes from the perspective of chemical education, with the goal of initiating a discussion that will assist teaching faculty as they approach this topic in their future classrooms. To facilitate this, a section on the Units of Measurement in a LibreText was updated to reflect the new definitions, and that content should be discussed concurrently with this paper.

Introduction

On November 16, 2018 the *Conférence Générale des Poids et Mesures* (CGPM) voted to adopt new definitions to the SI base units, which go into effect on World Metrology day, May 20, 2019. Although there will be continuity within the metrics and a kilogram will still be a kilogram, there is a fundamental change in the way the base units will be defined. In the past they were defined by an artifact (kilogram), or a measurable experimental-phenomena, like the triple point of water (kelvin). Now they will be based on seven physical constants that are considered to be invariants of nature, and the values of those constants will be treated as exact numbers, and the SI base units will in turn be defined by applying those "defining constants" to various measuring technologies like the Watt balance (kg) or the atomic clock (s).

This topic was initially brought up for discussion in the Spring 2017 CCCE Newsletter article by Peter Rusch, "Textbooks and the SI Base Units. A Challenge for Authors and Editors", which gave an overview on why the SI base units are being revised and the challenges facing educators. Interested readers are encouraged to review that article, as that material will not be repeated here. The truth is, few if any textbooks have been updated and most students this summer and fall will be learning the old retired definitions, and be completely ignorant that they changed.

Bob Belford has been developing a LibreText for his general chemistry class at UA-Little Rock and is tackling the new SI units in the "Units of Measurement" section for general chemistry 1. This is work in progress and you are requested to read that section as part of this paper, and discuss it here, as it is hoped that through the discussions of this paper, we can generate material that anyone can use, as they approach this topic in their upcoming classes. Accordingly, a PDF of the "Units of Measurement" material will also be attached to this article, but that will not reflect updates and revisions like the LibreText page will.

The LibreText HyperLibrary is an Open Education Resource where faculty can develop a wide variety of textbooks that students can access for free, and which other faculty can adopt and revise as desired. It evolved out of the ChemWiki and there have been three CCCE Newsletter articles on LibreText over the past five years.

- 2017 Newsletter: Come Join the Party! Recent Progress of The Community Based LibreTexts (née ChemWiki) Project
- 2015 Newsletter: Why the ChemWiki?
- 2014 Newsletter: The ChemWiki: A Free Online Substitute for Commercial Chemistry Textbook

Anyone is welcome to reuse the material in the Libretext for noncommercial purposes and so by posting this material to LibreText (in contrast to a mock textbook section in this paper), the material developed for this paper is available to all.

Why Write this Paper?

The need for this paper becomes clear when one notes that on May 9, 2019, not a single one of the top 10 Google search results for "*SI base units*" returned the new definitions, and only three results even acknowledged the new definitions (only two of which provided links to revised material; NIST & Wikipedia). In fairness, this is 11 days before the revised definitions go into effect and so the old definitions still stand, but 70% of the top 10 hits did not even acknowledge the new ones.

NIST is probably the best current resource for information on the revised definitions and has provided a plethora of material on their SI Redefinition site, https://www.nist.gov/si-redefinition. Their content has a strong public relations flavor though (fig.1), and the material does not really target the needs of introductory chemistry education. As one would anticipate, Wikipedia is also actively being updated and it too is a useful resource, but like the NIST site, does not target the needs of chemistry students.

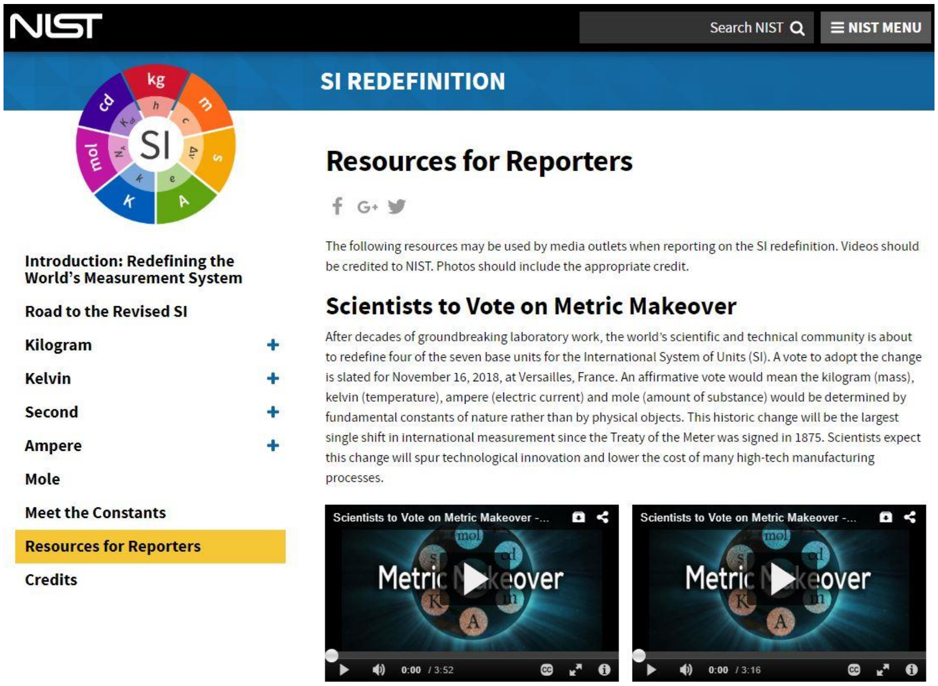
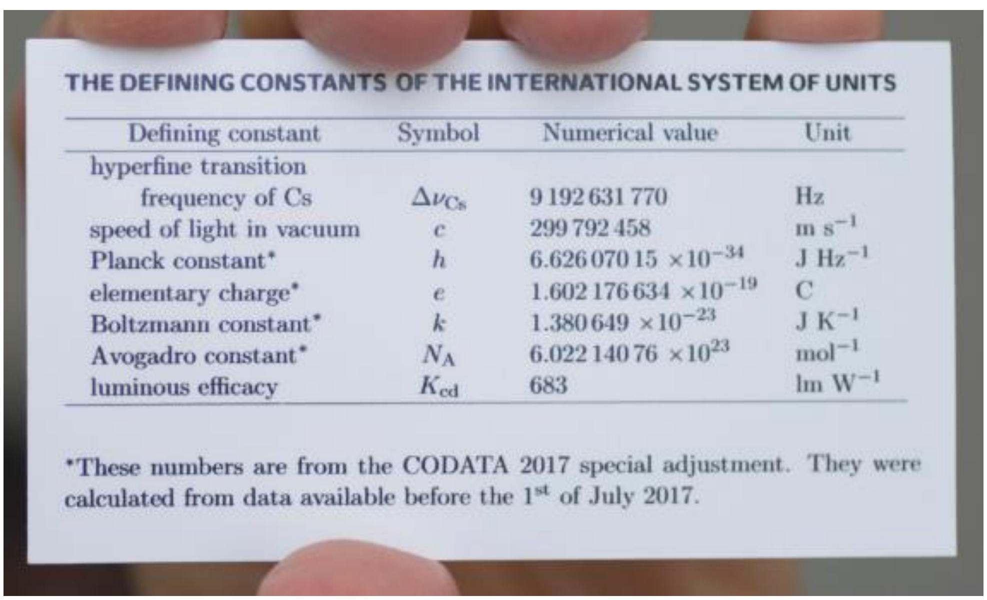


Fig. 1: NIST web resources on SI redefinition

Seven Defining Constants

The seven defining physical constants are considered as "invariants of nature" and are being treated as exact numbers. These in turn are used to define the seven SI base units.



THE DEFINING CONSTANTS OF THE INTERNATIONAL SYSTEM OF UNITS

Defining constant	Symbol	Numerical value	Unit
hyperfine transition frequency of Cs	$\Delta\nu_{Cs}$	9 192 631 770	Hz
speed of light in vacuum	c	299 792 458	$m\ s^{-1}$
Planck constant*	h	$6.626\,070\,15 \times 10^{-34}$	$J\ Hz^{-1}$
elementary charge*	e	$1.602\,176\,634 \times 10^{-19}$	C
Boltzmann constant*	k	$1.380\,649 \times 10^{-23}$	$J\ K^{-1}$
Avogadro constant*	N_A	$6.022\,140\,76 \times 10^{23}$	mol^{-1}
luminous efficacy	K_{cd}	683	$lm\ W^{-1}$

*These numbers are from the CODATA 2017 special adjustment. They were calculated from data available before the 1st of July 2017.

Figure 2: Seven defining constants (Stoughton/NIST)

Table 1 is material adopted from Wikipedia and contrasts the current definitions with the prior ones, thus giving a good perspective of the revisions.

Table 1: SI Base Unit Definitions

(Adopted from)

- The International System of Units, 8th ed. Section 2.1.1, BIPM (old definitions)
- Appendix 3, Resolution 1 of 26th CGPM (new definitions)

Meter

- ***Previous definition:*** *The metre is the length of the path travelled by light in vacuum during a time interval of 1/299,792,458 of a second.*
- ***2019 definition:*** *The metre, is defined by taking the fixed numerical value of the speed of light in vacuum c to be 299,792,458 when expressed in the unit m/s, where the second is defined in terms of* $\Delta\nu_{Cs}$

Kilogram

- ***Previous definition:*** *The kilogram is the unit of mass; it is equal to the mass of the international prototype of the kilogram*
- ***2019 definition:*** *The kilogram is defined by taking the fixed numerical value of the Planck constant h to be* $6.626{,}070\ 15 \times 10^{-34}$ *when expressed in the unit J·s, which is equal to* $kg \cdot m^2 \cdot s^{-1}$*, where the metre and the second are defined in terms of c and* $\Delta\nu_{Cs}$.

Second

- ***Previous definition:*** *The second is the duration of 9,192,631,770 periods of the radiation corresponding to the transition between the two hyperfine levels of the ground state of the cesium 133 atom.*
- ***2019 definition:*** *The second is defined by taking the fixed numerical value of the cesium frequency* $\Delta\nu_{Cs}$ *, the unperturbed ground-state hyperfine transition frequency of the cesium 133 atom, to be 9,192,631,770 when expressed in the unit Hz, which is equal to* s^{-1}.

Ampere

- ***Previous definition:*** *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 × 10−7 newton per metre of length.*
- ***2019 definition:*** *The ampere is defined by taking the fixed numerical value of the elementary charge e to be* $1.602{,}176{,}634 \times 10^{-19}$ *when expressed in the unit C, which is equal to A s, where the second is defined in terms of* $\Delta\nu_{Cs}$.

Kelvin

- ***Previous definition:*** *The kelvin, unit of thermodynamic temperature, is the fraction 1/273.16 of the thermodynamic temperature of the triple point of water.*
- ***2019 definition:*** *The kelvin is defined by taking the fixed numerical value of the Boltzmann constant k to be* 1.380649×10^{-23} *when expressed in the unit* $J \cdot K^{-1}$*, which is equal to* $kg \cdot m^2 \cdot s^{-2} \cdot K^{-1}$*, where the kilogram, metre and second are defined in terms of h, c and* $\Delta\nu_{Cs}$.

Mole

- ***Previous definition:*** *The mole is the amount of substance of a system which contains as many elementary entities as there are atoms in 0.012 kilogram of carbon 12.*
- ***2019 definition:*** *.The mole is the SI unit of amount of substance and contains exactly* $6.02214076 \times 10^{23}$ *elementary entities. This number is the fixed numerical value of the Avogadro constant,* N_A,

Candela

- ***Previous definition:*** *The candela is the luminous intensity, in a given direction, of a source that emits monochromatic radiation of frequency 540 × 1012 hertz and that has a radiant intensity in that direction of 1/683 watt per steradian*
- ***2019 definition:*** *The candela is defined by taking the fixed numerical value of the luminous efficacy of monochromatic radiation of frequency* 540×10^{12} *Hz,* K_{cd}*, to be 683 when expressed in the unit* $lm \cdot W^{-1}$*, which is equal to* $cd \cdot sr \cdot W^{-1}$*, or* $cd \cdot sr \cdot kg^{-1} \cdot m^{-2} \cdot s^3$*, where the kilogram, metre and second are defined in terms of h, c and* $\Delta\nu_{Cs}$.

Four of the definitions have changed in a substantive way, but they all have changed. At first glance, one might think that the definition of the second and meter have not changed. But on closer look it becomes clear that how they are defined has changed. The new definitions explicitly define the constants, while the old ones defined the unit.

Although the purpose of this article is not to go over the SI base unit definitions, but discuss how to teach them to general chemistry level students, it is prudent to look at the challenge teaching them would impose. For example, the Watt balance, which balances electromagnetic forces against gravitational forces was used to calculate h, Planck's constant, a concept from quantum mechanics that is introduced much later in the semester. This is done through the use of two quantum electrical effects, the quantum Hall effect and the Josephson effect, all of which are clearly beyond the scope of a typical general chemistry class. Once this was done, the value of h was set as a fixed value, and the balance could then be used to measure mass. For those who are interested in learning more, the article "A LEGO Watt Balance: An apparatus to determine a mass based on the new SI" is a worthwhile read.

LibreText Textbook Content

As this paper is about how the new definitions could be integrated into curricular material like textbooks, we have developed a section of the LibreTextbook at UALR to accompany this paper, section 1B.1: Units of Measurement. This material is being developed by Bob Belford, who started this work in 2017 when the Department of Chemistry was using the 9th edition of "Chemistry and Chemical Reactivity" by Kotz et. al.. As Belford was one of six faculty who teach the class, and all the other faculty were using Kotz, he needed to align his content with the other sections, and so started with a textbook map of Kotz's book, which is essentially a map through LibreText content that aligns with Kotz's table of contents. After lectures he would make videos and post them to the sections, and this LibreText is under active development this summer. It is hoped that people will review the LibreText material and comment about it on this paper. Criticism is welcome, as unlike a commercial textbook, there is no review process, and this is being developed on top of a normal teaching load.

The table of contents for the "Units of Measurement" section (figure 3) shows the general strategy. The SI base units are not taught in a void, but in the context of units of measurement, and their relationship to the nature and practice of science. The strategy is to introduce the need for measurement and metrology in a historical context that would be of interest to the average student in Arkansas (U.S. citizen). From there build up the SI system and its associated challenges, and thus frame these definitions in their evolving historical context. The seven defining constants were introduced as an image in a business card and not as a table, so the students could see them, but not panic over trying to understand [read: memorize] them.

That is by parsing the SI definitions in a historical context we are giving the students a feel for how science is practiced, that it is evolving, and yes, that science is not dead, but sort of exciting. I mean who would have imagined that something as basic and boring as the concept of a kilogram is still being figured out, and not so basic or boring!

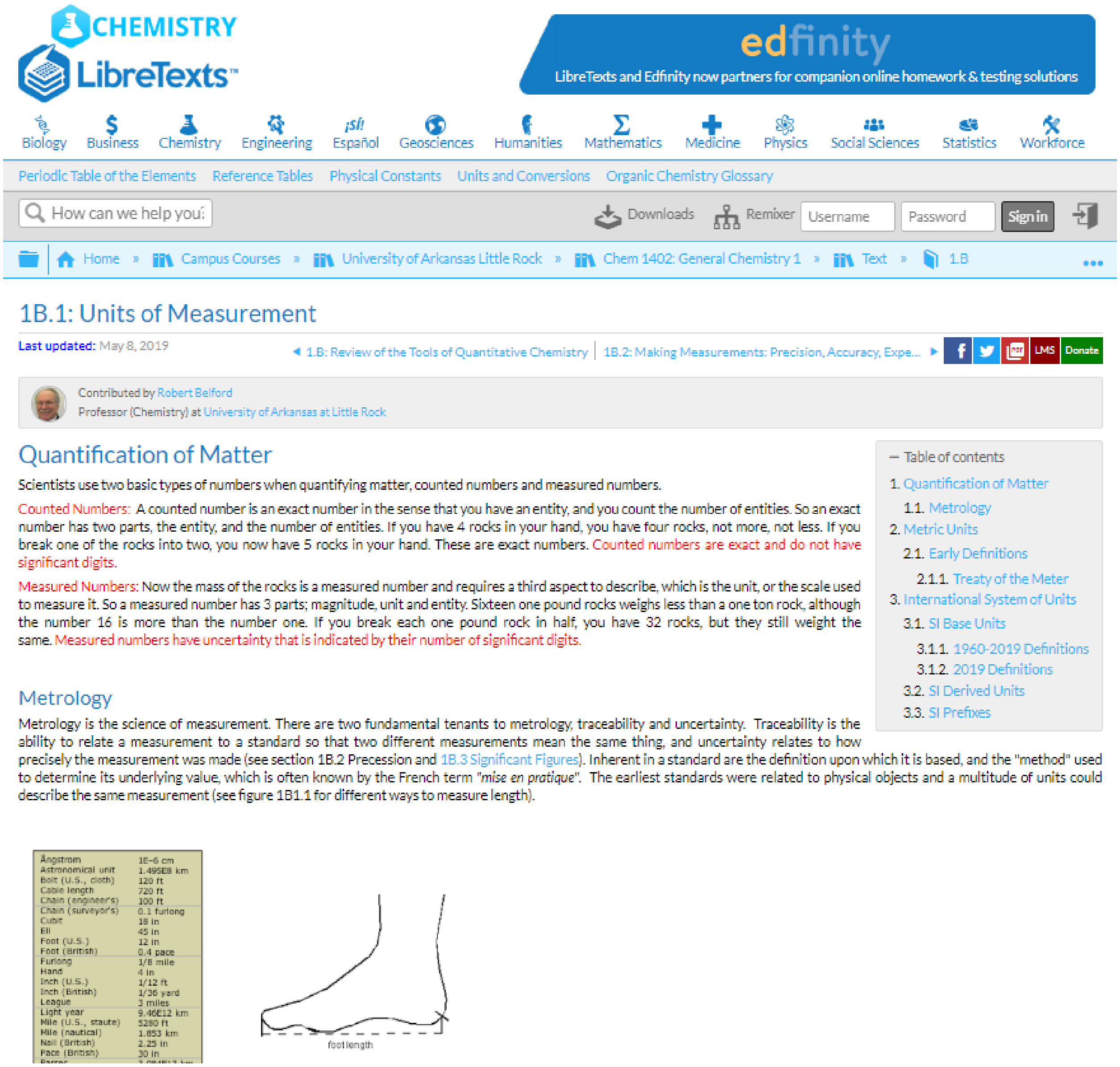


Fig. 3: UA Little Rock LibreText section on Units of Measurement.

The purpose of this paper is not to state that the material in LibreText is the right way to cover the new SI definitions, but to try and bring up a discussion of that content. In fact, this is a great use of LibreText, taking advantage of the collaborative nature of the wiki to allows an author to communicate with others on a topic of interest (the redefined SI base units). So please read through the [LibreText material on the SI base units](#) and use this paper to discuss that material.