BP Leonard
425 E Caramillo St
Colorado Springs
Colorado, CO 80907

Ian M Mills
Department of Chemistry
University of Reading
Reading, RG6 6AD
UK

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Dear Ian:

Regarding your recent paper (with Mohr, Quinn, Taylor, and Williams), "Redefinition of the kilogram: a decision whose time has come," it's clear that there's general agreement among people concerned with this subject that the overall goal is to define all SI base units without referring (directly or indirectly) to a physical artifact, and without involving (explicitly or implicitly) any "constants" that must be determined by experiment—and whose numerical value would therefore need to be continually updated as experimental techniques improve.

Given this goal, there is *no* choice for the definition of the base unit for amount of substance:

> One *must* use the fixed-Avogadro-constant strategy for this—and the concomitant invariant definition of dalton—regardless of how the SI base unit for mass is defined. Otherwise, the numerical value of the Avogadro "constant"—which is basic to the definition—would have to be determined experimentally, thereby violating one of the above criteria.

For the SI base unit for mass, the choice boils down to be between:

1. Fixing the Avogadro constant *and* fixing the mass of the carbon-12 atom at exactly 12 Da. In this case, the value of the Planck "constant" would have to be determined by experiment.

and

2. Fixing the Planck constant, thereby requiring relaxation of the constraint on the carbon-12 atomic mass, which would then become a quantity whose value would have to be determined by experiment (just like the mass of all other entities).

Clearly, the fixed-*h* strategy for the invariant definition of the mass unit is the obvious choice: the Planck constant is a fundamental constant of physics; the mass of the carbon-12 atom is no more "fundamental" than that of any other entity. With an invariant definition of dalton as an exact fraction of the fixed-*h* base unit for mass (using the fixed-

N_A value to relate the two), the mass of the carbon-12 atom is no longer *exactly* 12 Da, but will have to be updated periodically—along with the appropriate numerical values of many properties of all entities. The masses of atoms, molecules, and other entities are then best expressed directly in terms of dalton—rather than "relative atomic (molecular, . . . , entity) mass." The latter becomes merely the *numerical value* of the entity mass when this is expressed in dalton. Thus, one dalton, an *exact* fraction of the SI base unit for mass (and, thereby, directly related to the Planck constant), becomes the reference quantity for atomic-level masses. This seems to be the logical evolution of the concept of "atomic (molecular) weight," etc.

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As you may know, I am strongly in favour of defining the kilomole (suitably renamed without a prefix) as the SI base unit for amount of substance, so that an extraneous (and, frankly, embarrassing) factor of 0.001 does not appear in the value of amount-specific mass when expressed in base units. Thus, in the proposed new base units, the amount-specific mass of carbon-12, for example, would be (*approximately*) 12 kg/kmol compared with (*approximately*) 0.012 kg/mol—the numerical value in the proposed new base units being that of the actual mass expressed in Da.

I also strongly believe that the new base unit for amount of substance (replacing kilomole) should be renamed avo (symbol Av), honouring Avogadro, for obvious reasons. Thus, the new definition would read something like:

> The base unit for amount of substance is the avo, consisting of exactly $6.022\,141\,527 \times 10^{26}$ specified elementary entities, which may be atoms, molecules, ions, electrons, other particles or specified groups of particles, including formula units.

In addition, it makes sense to introduce an "atomic-level" unit for amount of substance paralleling dalton, the atomic-level unit for mass. This unit would (obviously) be called entity (symbol ent). Thus, one entity (1 ent) is the amount of substance consisting of exactly one (specified) elementary entity. Therefore:

$$1 \text{ Av} = 6.022\,141\,527 \times 10^{26} \text{ ent, exactly}$$

This parallels directly the definition of dalton in terms of kilogram (suitably renamed without a prefix):

$$1 \text{ G} = 6.022\,141\,527 \times 10^{26} \text{ Da, exactly}$$

where kilogram has been renamed gali (symbol G), honouring Galileo, again for obvious reasons (see PS & PPS, below). Of course, the numerical value involved would be chosen as the best available for seamless transition at the time of adoption.

Note that dalton and entity would have the status of “units in use with SI.” Also in this category (in the spirit of liter), for convenience, we keep mole: 1 mol = 1 mAv (milliavo); and gram: 1 g = 1 mG (milligali); and sub-multiples of these using SI prefixes—but not super-multiples. For example, we then have amount-specific mass units as follows:

Da/ent = G/Av = g/mol = mg/mmol = . . .

[atomic-level units; SI base units; “convenience” units]

Again for convenience, we keep tonne (not “metric ton”): 1 t = 1 kG (kilogali); and super-multiples using SI prefixes—but not sub-multiples.

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Note that I avoid using the multi-word unit names, “unified atomic mass unit” and “metric ton,” as it is impossible to sensibly use SI prefixes with these. These two terms should be deprecated, replaced by dalton and tonne, respectively.

Also note that I avoid using physical quantity name modifiers involving terms derived from unit names—such as “molar,” for example. In this case, the term amount-specific is perfectly clear (and instructive for students).

> “Neither the name of the physical quantity, nor the symbol used to denote it, should imply a particular choice of unit.” [Mills *et al*., “Quantities, Units and Symbols in Physical Chemistry.”]

And, wherever possible, we should try to use capital letters for the symbols for extensive quantities and lower-case for intensive (or specific) quantities. Thus, (capital) N, for example, should be used for amount of substance, regardless of whether this is expressed in Av, mol, or ent. There is no need to distinguish between the *numerical value* of the number of entities (a pure number) and the amount of substance expressed in ent, where the number of entities is explicit. [In current practice, the *number* of entities and the amount of substance are related by the Avogadro constant.]

The numerical value of the Avogadro constant depends on the units being used for amount of substance. Thus:

$$N_A = 1 \ \text{ent}^{-1}$$

$$N_A = 6.022\,141\,527 \times 10^{23} \ \text{mol}^{-1}$$

$$N_A = 6.022\,141\,527 \times 10^{26} \ \text{Av}^{-1}$$

Since these are all equal, we have the following conversion factors:

$$1 \;=\; 6.022\,141\,527 \times 10^{23}\ \text{ent/mol} \;=\; 6.022\,141\,527 \times 10^{26}\ \text{ent/Av}$$

$$=\; 10^{3}\ \text{mol/Av} \;=\; 10^{6}\ \text{mmol/Av} \;=\; \ldots$$

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In summary, it seems that the *only* rational choice is as follows:

- Define the SI base unit for mass (seamlessly replacing kilogram) using the fixed-h strategy. [I think (h-2) is the most appropriate.] Change the name of the redefined kilogram to gali (symbol G). Retain gram: 1 g = 1 mG; and SI-prefixed sub-multiples, but not super-multiples. Retain tonne (not “metric ton”—which should be deprecated): 1 t = 1 kG; and SI-prefixed super-multiples, but not sub-multiples. The gram and the tonne are “units in use with SI.”

- Define the SI base unit for amount of substance (seamlessly replacing kilomole) using the fixed-N_A strategy. Change the name of the redefined kilomole to avo (symbol Av). Retain mole: 1 mol = 1 mAv; and SI-prefixed sub-multiples, but not super-multiples. The mole is a “unit in use with SI.”

- Define dalton (not “unified atomic mass unit”—which should be deprecated) as an exact fraction of gali, using the appropriate value related to the fixed value of N_A:

  $1\ \text{G} = 6.022\,141\,527 \times 10^{26}\ \text{Da}$, exactly

- Define a new atomic-level unit of amount of substance, entity (ent), so that:

  $1\ \text{Av} = 6.022\,141\,527 \times 10^{26}\ \text{ent}$, exactly

- The dalton and the entity are “units in use with SI,” taking any SI prefix.

- Since the mass of the carbon-12 atom is now a quantity whose value must be determined by experiment (rather than exactly 12 Da), the reference value for atomic-level masses is 1 Da. Relative atomic, molecular, . . .—i.e, entity—masses are simply the numerical value of the respective masses when expressed in dalton.

- Use appropriate names and symbols for specific quantities rather than adjectives derived from unit names. Thus: amount-specific (rather than “molar”), etc. Also, mass-specific, volume-specific, etc., for definiteness.

- At some stage (why not immediately?) the SI base unit for temperature should be redefined by fixing the value of the Boltzmann constant. Together with the fixed value of N_A, this would produce an exact value for the universal gas constant. The temperature (and pressure) of the triple-point of water would then be found, approximately, by experiment.

- Similarly, the definition of the ampere should be based on a fixed value of the electronic charge.

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I hope these comments are of some interest to you in the continuing quest for designing a rational system of SI base units and other convenient and appropriate units to be used in conjunction with SI.

Yours sincerely,

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BP ("Benny") Leonard
Emeritus Professor of Mechanical Engineering
The University of Akron

CC Peter Mohr, Terry Quinn, Barry Taylor, Edwin Williams, Jim Frysinger, Stan Jakuba, Bruce Barrow, Richard Davis.

PS The deli test: Would you feel comfortable walking into a deli and asking for "about half a gali of roast turkey and about 200 grams of Swiss cheese"? [Not too different from "about half a kilo . . ."—"kilo" being the most common colloquial term for kilogram used throughout the world today.]

PPS The term gali is easily transliterated into other languages. In Chinese, the closest transliteration, gaoli ( ), could be interpreted as "exalted weight."