# The New Definition of the Mole

By Juris Meija

**Q What is the recent change in the definition of the mole?**

A The need to redefine two base units of the International System of Units (SI), the kilogram and ampere, has been discussed for several decades. There are many reasons to revise the present definitions of these units, most notably the inherent long-term instability of the artifact that serves to define the kilogram. Following the success of the 1983 definition of the meter, which is now based on the speed of light in vacuum, the International Committee on Weights and Measures has decided that this is also an opportune time to recast the definitions of all seven SI base units in terms of the most stable things known to scientists — physical constants.

## AVOGADRO CONSTANT

The Avogadro constant has been called many things, from one of the most important physical constants to the constant of a lesser breed. Einstein devoted one of his annus mirabilis articles to the Avogadro constant, and Jean Perrin received the 1926 Nobel Prize for determining its value. Now, the numerical value of the Avogadro constant — known as the Avogadro number — will be used to define the mole. The importance of determining the Avogadro constant is attested to not only by the 1926 Nobel Prize but also by the fact that Perrin was nominated nearly 50 times by eminent scientists of his time.

In 1926, Perrin was awarded the Nobel Prize, to oversimplify, for providing the estimate of the Avogadro constant between $6.5 \times 10^{23}$ and $6.9 \times 10^{23}$. Somewhat similar to Moore's law, which observes the doubling of the number of transistors on integrated circuit chips every two years, the uncertainty of the Avogadro constant has been decreasing by an order of magnitude every two decades. Thus, a century of measuring the Avogadro constant has brought us now to relative uncertainties of few parts in $10^8$. Today, the best estimate of the Avogadro constant comes from the Planck constant determinations at the National Research Council of Canada: $6.022\,140\,772 \times 10^{23}$ with the uncertainty of 9 parts in $10^9$ (Planck and Avogadro constants can be interchanged through the Rydberg constant). This remarkable precision now enables us to rewrite the definition of the mole in the most absolute terms possible: by stipulating an exact number of entities in a mole.

> "The mole is the amount of substance of a system that contains $6.022\,140\,76 \times 10^{23}$ elementary entities."

## WHY DO WE NEED A NEW DEFINITION OF THE MOLE?

The 1971 definition of the mole implies that the amount of substance is best determined by measuring mass of substances. While most measurements of chemical amount are indeed measurements of mass, it does not follow that the definition of the mole must necessarily be tied with the definition of the kilogram. In 2011 the governing body of the SI — the General Conference on Weights and Measures — noted that it is, in fact, desirable to emphasize the distinction between amount of substance and the mass. Moreover, studies have shown that the amount of substance is often incorrectly identified with mass. Because many have argued that the present definition obscures the utility of the mole and because most chemistry textbooks already view the mole as an amount containing Avogadro number of entities, the new definition states just that:

*"The mole is the amount of substance of a system that contains $6.022\,140\,76 \times 10^{23}$ elementary entities."*

In this vein, the proposed new definition of the mole has the advantage of simplicity. In fact, in the new SI, the mole will become the only base unit that is defined independent of any other units.

### CONCERNS ON DEFINING THE MOLE

Serious discussions on redefinition of the mole started around 2005, and it took about a decade to reach international consensus. During this time, a gamut of topics has been raised regarding the way the mole should or should not be defined. Needless to say, not everyone likes the new definition. Some prominent voices argued, in fact, that the mole should be removed from the SI.

A resistance towards the Avogadro-based definition of the mole has largely been due to the belief that the Avogadro constant is not a universal constant of physics and that its numerical value has no particular physical meaning. While some constants are indeed more fundamental than others, one should not conflate 'being fundamental' with 'not being useful'. Like Avogadro, the Boltzmann constant too is viewed by many as a mere conversion factor with no deep physical meaning. It has acquired a status of a fundamental constant with its own dimension because scientists chose to distinguish thermal energy from temperature by creating a dimension we call temperature.

Ultimately, many of the decisions regarding the units reflect choices made out of practical considerations. The quantity "amount of substance" with its own dimension became part of the SI not out of a logical necessity but rather because the scientific community felt it was beneficial. Today we have both the Boltzmann and Avogadro constants because thermometers came before our understanding of statistical mechanics and because chemists were able to compare the amounts of chemical substances before knowing the actual number of atoms involved.

Perhaps one of the most difficult aspects of the Avogadro-based definition of the mole is the fact that the molar mass of carbon-12 will no longer be 12 g/mol exactly. It will come as a surprise to many chemists that, in fact, the molar mass of carbon-12 has never been exactly 12 g/mol so nothing will change in this regard. This is because the 1971 definition of the mole formally refers to unbound atoms. Chemists do not work with unbound atoms. Instead, they handle bound atoms and the cohesion energy ($E = mc^2$) reduces the total mass at the order of few parts in $10^{10}$.

Thus, to attain 12 g of pure graphite one has to have an additional $4 \times 10^{14}$ atoms compared to the same mass of unbound atoms, which together make for an additional 1 ng (approximately). In this context, the new definition of the mole is more fundamental than the 1971 definition. Like many other new SI definitions, the new definition will not affect everyday measurements, but it is likely to affect our everyday understanding of the mole.

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