

What Is a Kilogram in the Revised International System of Units (SI)?

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ABSTRACT: The definition of the kilogram, the unit of mass in the International System of Units (SI), has not changed in more than 125 years. The kilogram is still defined by the mass of a Pt–Ir cylinder conserved at the International Bureau of Weights and Measures. Science and technology have progressed to the point where it is likely the kilogram will be redefined in 2018 in terms of a constant of physics—the Planck constant, which is closely linked to the Avogadro and atomic mass constants. In this article, we illustrate by means of a simple experiment on how analytical chemistry is contributing to this project, how the new definition of the kilogram will be put into practice and what it may mean for chemists. Surprisingly, perhaps, this simple experiment allows us to determine the mass of an aluminum-27 atom, the mass of a carbon-12 atom (and the atomic mass constant), the Avogadro constant, and the Planck constant—all with uncertainty less than 1%—in close analogy to the way the most accurate experiment of this type achieves an uncertainty of parts in 10^8 . Finally, we point out that a very different area of modern technology, namely voltage and resistance measurements using quantum electrical devices, provides a second high-accuracy way to implement the new definition.

KEYWORDS: Upper-Division Undergraduate, Analytical Chemistry, Physical Chemistry, Hands-On Learning/Manipulatives, Nomenclature/Units/Symbols



Derive SI values of:

atomic mass of aluminum-27

atomic mass of carbon-12

atomic mass constant

Avogadro constant

Planck constant

■ BACKGROUND

The present definition of the kilogram is based on the mass of a cylinder made of a platinum–iridium alloy and placed into service in 1889. Known as the international prototype of the kilogram (IPK), it is conserved at the International Bureau of Weights and Measures (BIPM), in a suburb of Paris (Figure 1). Since 1889, the kilogram has been defined as “the mass of the international prototype of the kilogram”. As a consequence, all mass measurements made in units of the International System of Units, or SI, are traceable to the mass of the IPK.¹ This definition of the kilogram was fit for purpose in the late 19th century, but we can do better today.

As the needs of science and technology evolved, additional base units were added to the SI. In particular, the ampere (1954) filled a need to express electrical measurements easily in SI units, and the mole (1971) did the same for analytical and physical chemistry.

The SI meter and second have both been redefined in terms of physical constants for many years,¹ and there is no intention to change these definitions in the revised SI. We will see in the following how atomic masses on the one hand and quantum electrical devices on the other also provide a way to redefine the kilogram in terms of physical constants, which are inherently stable and universally accessible. In addition, the two seemingly different approaches—chemical and electrical—are actually complementary.

A simple experiment is described, which serves to make these ideas less abstract. The experiment is interesting in its own right because it shows how a single mass measurement made on the type of analytical balance found in most chemistry laboratories

can, when combined with measured or tabulated values of quantities that are independent of mass, yield values for the mass of a carbon-12 atom, $m_a(^{12}\text{C})$; the Avogadro constant, N_A ; and the Planck constant, h . The estimated relative standard uncertainties of these results are the same—about 0.5%—and to this uncertainty, all results agree with more accurate recommended values. This helps to clarify the issues involved in redefining the kilogram.

■ EXPERIMENT

We purchased a small rod of polycrystalline aluminum, marketed as 99.999% pure. A piece was cut from this rod by spark erosion and milled to be a cube. The average edge-length d was targeted to be 19.5 mm and measured with a calibrated micrometer to be $d = 19.538$ mm with uncertainty of 0.005 mm (Figure 2).

The mass of the cube was found to be 20.048 g by weighing on a calibrated analytical balance. The final mass has been corrected for the difference in air buoyancy between aluminum and stainless steel. (Like most analytical balances, ours is routinely calibrated with stainless-steel weight pieces whose mass values are ultimately traceable to the mass of the IPK.)

We now had in-hand values for the mass m of the cube and its volume V at room temperature, $V = d^3$.

For the next step, we wanted to find the mass, $m_a(\text{Al})$, of a single atom of aluminum. This task is made slightly easier than it would be for most other elements in the periodic table because aluminum has only one naturally occurring isotope,

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Figure 1. IPK (center) as it is stored in a vault at the BIPM with its six “official copies”. Photograph from BIPM and used with permission.

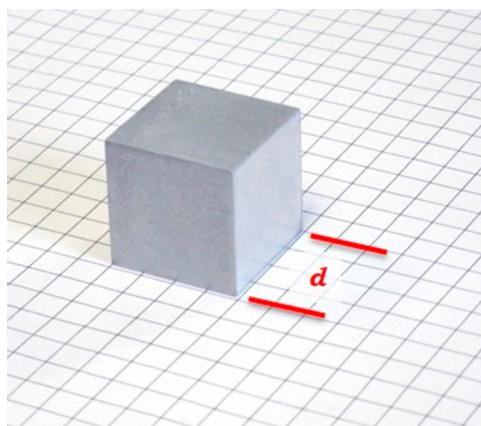


Figure 2. Aluminum cube as manufactured by a combination of spark cutting and milling. The edge-length d is approximately 19.5 mm.

aluminum-27. In essence, we want to determine the number, N , of aluminum atoms in the cube so that we can then use the relation

$$m = N \times m_a(\text{Al}) \quad (1)$$

to solve for the mass of a single aluminum atom.

Determining N

We use the same approach to find N that is used in the most accurate measurements of this type,² namely to estimate N as the volume of the cube divided by the average volume per atom within the cube. This is a much more plausible approach for a single crystal than for our polycrystalline block of aluminum, which is made of small single-crystal grains. Each grain is composed of aluminum atoms in a regular array that simply repeats the unit cell of a face-centered cubic crystal. The unit cell is itself a cube with edge dimension a and an aluminum atom centered on each of the eight corners of the cell and on the middle of each of the six surfaces (Figure 3). This atomic-

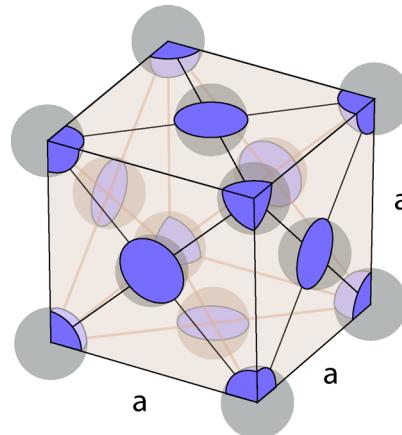


Figure 3. Unit cell of a face-centered cubic crystal. Atoms are centered on each of the eight corners and on each of the six faces of the cube. The edge length is nominally 405 pm for an aluminum crystal.

scale building block is repeated in all directions so that each corner atom of a unit cell is shared with seven neighboring unit cells; each atom centered on a face of the unit cell is shared with one neighbor. Therefore, each unit cell in a crystal has exactly four atoms (eight atoms shared among eight unit cells; six atoms shared between two unit cells, totaling $8/8 + 6/2 = 4$ atoms per unit cell).

The number N_i of atoms in the i th grain of a polycrystalline sample equals the volume V_i of the grain divided by the volume a^3 of the unit cell (the number of unit cells in the grain), times four (the number of atoms per unit cell):

$$N_i = 4 \frac{V_i}{a^3} \quad (2)$$

The total number of atoms in a polycrystalline sample is $N = N_1 + N_2 + \dots + N_f$ where “f” is the last crystal grain in the sum. We already know that the total volume of the cube is $d^3 = V_1 + V_2 + \dots + V_i + \dots + V_f$ so that

$$N = 4 \left(\frac{d}{a} \right)^3 \quad (3)$$

In this simple view, N is the same for polycrystalline or single-crystal samples of the same volume.

The disadvantage of a polycrystalline sample, and one reason that single-crystal material is obligatory to achieve the best possible results,² is that we can expect to have some empty spaces between the grains of a polycrystalline sample. The effect of these empty spaces is that eq 3 overestimates N . How serious is this error? According to one handbook,³ the density of a polycrystalline sample of pure aluminum is the same as that

of a single crystal to within 0.5%. This will be the dominant uncertainty of our experiment.

The edge dimension a of the aluminum unit cell is a property of nature. This means that we can take a precise value of a determined in 1955 by X-ray diffraction⁴ and it will describe the aluminum crystals in our sample, which was purchased in 2015. The measurement of a was reported at 25 °C. The wavelength λ of a particular X-ray emission of copper (referred to in X-ray spectroscopy as the CuK α 1 wavelength) served as the length standard. For the present work, we have corrected the temperature to 23 °C by using the thermal expansion of aluminum³ and used the most recently recommended value⁵ of λ . Both these corrections are minor. The resulting edge length is $a = 404.96 \times 10^{-12}$ m = 404.96 pm at 23 °C, to 0.01 pm uncertainty.

By inserting the values of d and a into eq 3, we have $N = 4.493 \times 10^{23}$, with relative standard uncertainty of about 0.5%.

Eqs 1 and 3 can be combined in a way that shows why this procedure is referred to as the X-ray crystal density method (XRCD⁵):

$$\frac{m}{d^3} = \frac{4 \times m_a(\text{Al})}{a^3}$$

The left-hand side of this relation is the density of the cube, and the right-hand side is the mass of four aluminum atoms with respect to the volume of the unit cell that they occupy, as determined by X-ray diffraction.

Atomic Mass of Carbon-12

We can now rearrange eq 1 to estimate the atomic mass of aluminum:

$$m_a(\text{Al}) = \frac{m}{N} \quad (4)$$

If we have measured m in grams (traceable to the mass of the IPK), then the value of $m_a(\text{Al})$ is also in grams because N is simply a number. Thus, we estimate the mass of a single aluminum-27 atom to be $m_a(\text{Al}) = 20.048 \text{ g}/4.493 \times 10^{23} = 4.462 \times 10^{-23}$ g, to about 0.5%.

More interesting is the atomic mass of carbon-12, $m_a(^{12}\text{C})$, because this is the gateway to determining the SI values of the Avogadro and Planck constants.

In this exercise, we are not allowing ourselves to use any external information given in terms of the SI unit of mass (kg, g, mg, etc.); m is the only mass required to be traceable to the IPK. However, we are free to use the atomic weights of the elements tabulated by IUPAC because these are dimensionless ratios⁶ and thus independent of any system of units. The atomic weight A_r (also known as the relative atomic mass) of any element or molecule X is defined as^{6,7}

$$A_r(X) = 12 \frac{m_a(X)}{m_a(^{12}\text{C})} = \frac{m_a(X)}{m_u} \quad (5)$$

In eq 5, m_u is the atomic mass constant defined to be 1/12th the mass of a carbon-12 atom.

Aluminum is a monoisotopic element, and $A_r(\text{Al})$ is accurately known: 26.9815386, with an estimated uncertainty of 8 in the last digit shown.⁶ From eq 5,

$$m_a(^{12}\text{C}) = 12 \frac{m_a(\text{Al})}{A_r(\text{Al})} = 12m_u \quad (6)$$

and values determined from the mass of the aluminum cube are

$$m_a(^{12}\text{C}) = 1.985 \times 10^{-23} \text{ g}, \text{ to about 0.5\%}$$

$$m_u = 1.654 \times 10^{-24} \text{ g}, \text{ to about 0.5\%}$$

By comparison, the currently recommended value⁵ of m_u is $1.6605... \times 10^{-24}$ g (trailing digits are not shown but are given in ref 5) with a relative uncertainty of 4.4×10^{-8} . Thus, the value of m_u that we determined from our cube is consistent with expectations. The use of a polycrystalline sample may explain that we have overestimated N (eq 3) with the consequence that $m_a(\text{Al})$ (eq 4) and $m_a(^{12}\text{C})$ (eq 6) have been underestimated.

Avogadro Constant

The relation connecting atomic mass, molar mass, and the Avogadro constant is

$$M(X) = N_A \times m_a(X) \quad (7)$$

where X is a chemical element, molecule, or other entity,⁷ $M(X)$ is the molar mass of X, and N_A is the Avogadro constant. The definition of the mole in the current SI^{1,7} has the effect of fixing the value of the molar mass of a particular nuclide, carbon-12:

$$M(^{12}\text{C}) = 12 \text{ g/mol (exactly)}$$

The SI value of the molar mass constant, M_u ($= M(^{12}\text{C})/12$), is 1 g/mol (exactly). This was a useful way to define the mole (in 1971) because $M(X)$ is found simply from tabulated values of the relative atomic masses.^{1,7} For a molecule, X,

$$M(X) = A_r(X) \times M_u = A_r(X) \text{ g/mol}$$

The experimental value of N_A is not required.

The SI defines the unit “mole” but does not define the quantity “amount of substance” (also known as “chemical amount”⁷). In general, the SI does not define basic quantities like mass, length, amount of substance, etc., which are commonly dealt with in textbooks,¹ only the respective SI units of these quantities are defined: the kilogram, the meter, the mole, etc.

By rearranging eq 7, we can obtain the value of N_A from our measurement of m_u ($= m_a(^{12}\text{C})/12$):

$$N_A = \frac{M_u}{m_u} \quad (8)$$

which is why the XRCD method⁵ to determine m_u is also referred to as the Avogadro method.²

Our measurement of the Avogadro constant inferred from the properties of the aluminum cube is

$$\begin{aligned} N_A &= (1 \text{ g/mol}) / (1.654 \times 10^{-24} \text{ g}) \\ &= 6.046 \times 10^{23} \text{ mol}^{-1}, \text{ accurate to about 0.5\%} \end{aligned}$$

According to ref 5, the recommended value of N_A is $6.02214... \times 10^{23} \text{ mol}^{-1}$ so that our experimental value is too high by about 0.5%, which at this point could have been predicted.

It is now possible to illustrate important features of the mole concept.⁸ We have everything we need to calculate the amount of aluminum, n_{Al} , in our cube from the most basic of all relations $n_{\text{Al}} = N/N_A$. We have determined N from eq 3 and N_A from eqs 4, 6, and 8. We find, however, that our measurement of N cancels out of this calculation and that N/N_A becomes

$$n_{\text{Al}} = N/N_A = m/(A_r(\text{Al}) \times M_u) = m/(A_r(\text{Al}) \text{ g/mol})$$

This formulation of n_{Al} in terms of m also follows directly from [eqs 1](#) and [8](#): first derive N/N_A from these two equations, and then substitute the SI value of M_u . To determine the amount of aluminum in our high-purity sample, we only needed to measure the sample mass in grams. Although the recommended value⁶ of $A_r(\text{Al})$ has already been quoted above, a good approximation is to take the atomic weight of aluminum-27 to be 27. The amount of aluminum in our cube is simply $20.046 \text{ g}/(27 \text{ g/mol}) = 0.74 \text{ mol}$.

Planck Constant

Quantum physics is essential to understand chemical processes at the atomic and molecular scale, and the Planck constant h is the fundamental constant of quantum physics. *J. Chem. Educ.* regularly publishes articles and book reviews on these subjects.⁹ A determination in grams of the atomic mass constant m_u leads to a determination of the value of h , as we now demonstrate.

The energy E of a photon is related to its frequency ν through the Planck constant by the well-known relation, $E = h\nu$. The ionization of a hydrogen-like atom can be described by an apparently simple formula:

$$h \times (c \times R_\infty) = \frac{1}{2}m_e \times (\alpha \times c)^2 \quad (9)$$

which bears considerable resemblance to Bohr's model of the hydrogen atom. Here m_e is the electron mass, c is the speed of light, and α is the fine-structure constant. The minimum frequency needed to completely ionize the atom is $\nu = c \times R_\infty$, where R_∞ is known as the Rydberg constant.⁵

The value of α is approximately 1/137 and has been measured to a relative standard uncertainty⁵ of 3.2 parts in 10^{10} . The recommended value⁵ of R_∞ has a relative uncertainty less than 10^{-11} . For the present discussion, the importance of [eq 9](#) is that it links h to m_e in terms of constants whose values are known to very small uncertainty. [Eq 9](#) becomes

$$\frac{h}{m_a(X)} = \left[\frac{\alpha^2 c}{2R_\infty} \right] \frac{m_e/m_u}{m_a(X)/m_u} = \left[\frac{\alpha^2 c}{2R_\infty} \right] \frac{A_r(e)}{A_r(X)} \quad (10)$$

for any X. If X is carbon-12, and recalling the definition of the atomic mass constant m_u given above, then

$$\frac{h}{m_u} = \left[\frac{\alpha^2 c}{2R_\infty} \right] A_r(e) \quad (11)$$

where both α and $A_r(e)$ are pure numbers and therefore independent of any unit system, and c has a fixed numerical value in both the current SI and the proposed new SI. In the following, we assign the symbol Q_u to the experimental value of h/m_u on the right-hand side of [eq 11](#). By making use of the identity $M_u = N_A \times m_u$, we can also write [eq 11](#) as

$$\frac{N_A \times h}{M_u} = Q_u \quad (12)$$

There are other experimental routes¹⁰ leading to a determination of Q_u and taking all of these into account, the current recommended value⁵ of Q_u has a relative standard uncertainty of 7.0 parts in 10^{10} . If both h and N_A are given exact values in the revised SI, as is the intention,¹¹ then M_u will continue to have the SI value 1 g/mol but with the negligible relative uncertainty of Q_u .

Using our experimental measurement of m_u gives a value for the Planck constant of $h = 6.600 \times 10^{-34} \text{ kg m}^2/\text{s}$ to a relative standard uncertainty of 0.5%.

The recommended value⁵ of h is $6.62607... \times 10^{-34} \text{ kg m}^2/\text{s}$. The value derived from the 20 g aluminum cube is about 0.5% from the known result, as expected.

Analogy to the "Silicon X-ray Crystal Density Method" Used by the International Avogadro Cooperation Project

Silicon XRCD⁵ is similar to our simple experiment with the aluminum cube but, by paying attention to all experimental details,¹² a relative standard uncertainty of 2×10^{-8} has recently been reported¹³ in the determination of m_u , N_A , and h compared to the 0.5% uncertainty we have achieved with the aluminum cube. Here is a partial list of measures taken to reach the target uncertainty of the Si XRCD experiment:

- (1) Use of almost perfect single crystals of silicon, with ultrahigh chemical purity.
- (2) Silicon crystals grown from material highly enriched in silicon-28. (Since silicon has three naturally occurring isotopes, the atomic weight of the silicon used to make each sphere can be determined to sufficient accuracy only if the relative abundances of two silicon isotopes can be determined by trace analysis).
- (3) Each crystal manufactured to be a near perfect sphere to achieve the lowest possible uncertainty on the volume, V , from the mean diameter of the sphere determined by laser interferometry ([Figure 4](#)).

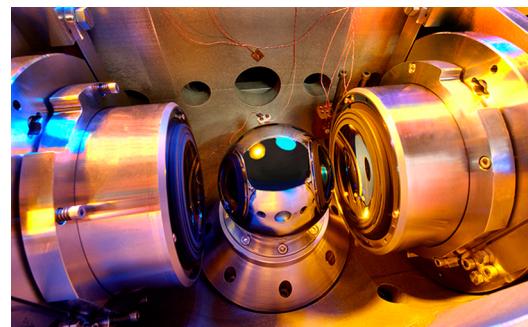


Figure 4. Near-perfect silicon crystal in the form of a near-perfect sphere, mounted for accurate determination of the sphere diameter (94 mm). Photograph from PTB/Stork and used with permission.

- (4) Edge length, a , of the unit cell determined from the same monocrystal used to fabricate the spheres.
- (5) Edge measurements of the unit cell and volume measurements of the sphere corrected to the same precisely defined reference temperature.
- (6) Corrections applied to account for the effect of surface oxides on the mass and volume of the spheres.
- (7) Mass determined in vacuum (against traceable standards) to eliminate the large air buoyancy correction between silicon and platinum–iridium.

KILOGRAM IN THE REVISED SI

The present definition of the kilogram based on the mass of the IPK will be replaced by a definition linked to a constant of nature, the Planck constant h , in the revised SI. The first step to doing this is to determine the value of h experimentally in the present SI to within a target uncertainty of 2 parts in 10^8 . We thus have the measurement sequence

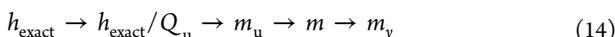


Each of these steps has been shown earlier for the simple example of the aluminum cube and a very similar procedure, the silicon XRCD experiment,¹² now has reached the target uncertainty.¹³

The sequence shown above starts with the mass of the IPK defined to be exactly 1 kg and leads to an experimental value of the Planck constant.

To redefine the kilogram, the Planck constant h will be assigned an exact value equal to its best available experimental value at the time the new definitions are adopted, so that upon redefinition of the kilogram $h_{\text{exp}} \rightarrow h_{\text{exact}}$.

In this new system, the mass m_y of any macroscopic object (including the IPK) will follow the traceability route



This “realization” of the new definition of the kilogram is represented by the sequence of measurements in 13 runs in the reverse direction, followed by routine calibrations of macroscopic masses. There are several advantages of the new definition:

- (1) Because of the necessity of quantum physics to help describe the phenomena of modern science and technology, many areas of metrology will benefit from a unit system in which the value of h is exact.
- (2) The magnitude of the kilogram is unaffected: a kilogram is still a kilogram.
- (3) The question of the long-term stability of the mass of the IPK will no longer be an issue.
- (4) The new definition is more universal. The mass of any suitable object can in principle be calibrated in terms of h_{exact} , including (but not limited to) the mass of the IPK.
- (5) Because Q_u has already been measured with experimental uncertainty less than 1 part in 10^9 , m_u and $m_a(^{12}\text{C})$ will have much reduced uncertainty in the “new” SI (more than an order of magnitude improvement compared to their present uncertainties⁵).

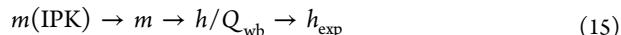
To an uncertainty of less than 1 part in 10^9 , we can then think of 1 kg as the mass of the number $1 \text{ kg}/m_a(^{12}\text{C})$ of carbon-12 atoms, with $m_a(^{12}\text{C})$ in kilogram traceable to h_{exact} . By coincidence, 1 part in 10^9 is approximately where the principle of the conservation of mass becomes problematic in chemical reactions.¹⁴

A different, yet equally accurate method to determine a macroscopic mass in terms of h_{exact} is discussed in the next section.

■ WATT BALANCE—ANOTHER CONNECTION BETWEEN THE PLANCK CONSTANT AND KILOGRAM

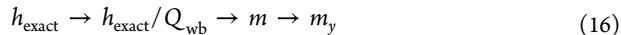
Quantum effects have been exploited to produce extremely precise electrical standards of voltage and resistance. The discovery of these effects by Brian Josephson and Klaus von Klitzing, respectively, led to a Nobel prize for each.^{15,16} Having an exact value for h (and an exact value for the elementary electrical charge e , which is also foreseen in the revised SI¹¹) will allow electrical metrology to take full advantage of the stability and precision of these quantum standards while simultaneously obtaining accurate results in SI volts and ohms.¹⁷

Today, the quantum electrical standards allow the determination of the Planck constant (or, indeed, of the atomic mass constant by adding eq 11) to the same accuracy as the silicon XRCD approach, but using a totally different technology:¹²



where Q_{wb} , which has the unit m^2/s , represents a combination of measurements made with a device known as a watt balance. The technological challenge of constructing a watt balance capable of determining the value of h to a relative uncertainty of about 2×10^{-8} is formidable. However, just as the aluminum cube provides a simple illustration of the experimental steps shown in sequence 13, a delightful watt balance¹⁸ constructed almost entirely of LEGO blocks allows its builder to measure h to better than 1% with respect to the mass of any calibrated standard in the range 1–20 g.

After redefinition of the kilogram, the watt-balance approach can be used to determine the mass of any macroscopic object m_y in terms of an exact value of h :



The watt balance will act as a very special analytical balance that is self-calibrating in terms of the Planck constant and auxiliary measurements of length and time (but not of mass). At present, analytical balances, like the one we used to determine the mass of the aluminum cube, are calibrated by mass standards ultimately traceable to $m(\text{IPK})$. In the future revised SI, the same balance will be calibrated by the same mass standards ultimately traceable to constants of nature: the Planck constant, and the constants used to measure Q_{wb} (watt balance) or Q_u and the dimensionless ratio m/m_u (silicon XRCD). The Q measurements are traceable to SI units¹ of time and length (but not mass).

Whether one uses sequence 13 or 15 to determine h_{exp} or, after the redefinition of the kilogram, whether one uses sequence 14 or 16 to determine the mass of the highest-level artifact standards, the results must be comparable within experimental uncertainties. Indeed, we chose a mass of 20 g for our aluminum cube so that it could also be used simply as a mass standard to determine an experimental value of h using the LEGO watt balance (Figure 5). The two values of h are the same to within experimental uncertainty. In using a watt balance to determine h , all one needs to know about the cube is its mass; the XRCD method dispenses with a watt balance but

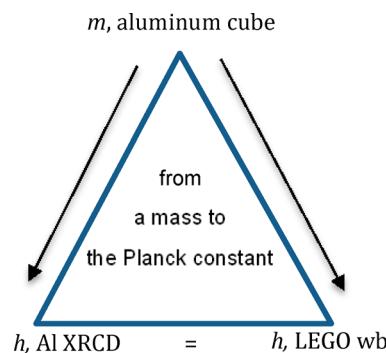


Figure 5. Our aluminum cube is small enough to serve as a mass standard for the LEGO watt balance in addition to allowing the determination of the Planck constant by the aluminum XRCD method. The two methods agree within their uncertainties, just as the most accurate versions of these two methods agree.

demands that more be known about the cube in addition to its mass. For an essay on how mass metrology based on the Planck constant might work in practice, see Pratt.¹⁹

SUMMARY

We have shown the basic principles behind realizing the new definition of the kilogram, which assigns a fixed value to the Planck constant. The new definition is expected to take effect at the end of 2018, provided that certain experimental and procedural goals are fulfilled.¹¹ The primary calibration of 1 kg standard objects (including the IPK) will then be realized by one of two equivalent methods. A simple version of one of these methods, based in part on knowledge of the X-ray crystal density of aluminum,²⁰ has been discussed in this paper. It is in many ways similar to the elegant silicon XRCD experiment,^{12,13} which connects the Planck constant to an atomic mass, and the atomic mass to the mass of a macroscopic object. The second technique, requiring a watt balance, has not been discussed in as much detail because the technology relies on electrical measurements rather than chemical measurements. However, the two methods succeed equally well and give the same result within experimental uncertainties.

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Notes

The authors declare no competing financial interest.

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REFERENCES

- (1) *The International System of Units (SI)*, 8th ed.; Bureau International des Poids et Mesures: Sèvres, France, 2006. http://www.bipm.org/utils/common/pdf/si_brochure_8_en.pdf (accessed Jun 2015).
- (2) Andreas, B.; Azuma, Y.; Bartl, G.; Becker, P.; Bettin, H.; Borys, M.; Busch, I.; Fuchs, P.; Fujii, K.; Fujimoto, H.; Kessler, E.; Krumrey, M.; Kuettgens, U.; Kuramoto, N.; Mana, G.; Massa, E.; Mizushima, S.; Nicolaus, A.; Picard, A.; Pramann, A.; Rienitz, O.; Schiel, D.; Valkiers, S.; Waseda, A.; Zikel, S. Counting the atoms in a ²⁸Si crystal for a new kilogram definition. *Metrologia* **2011**, *48* (2), S1–S13.
- (3) *Aluminum Properties and Physical Metallurgy*; Hatch, J. E., Ed.; American Society for Metals: Materials Park, OH, 1984; 10th printing, 2005.
- (4) Smakula, A.; Kalnajs, J. Precision Determination of Lattice Constants with a Geiger-Counter X-Ray Diffractometer. *Phys. Rev.* **1955**, *99* (6), 1737–1743.
- (5) Mohr, P. J.; Taylor, B. N.; Newell, D. B. CODATA Recommended Values of the Fundamental Physical Constants: 2010. *J. Phys. Chem. Ref. Data* **2012**, *41* (4), 043109.
- (6) Wieser, M. E.; Holden, N.; Coplen, T. B.; Böhlke, J. K.; Berglund, M.; Brand, W. A.; De Bièvre, P.; Grönig, M.; Loss, R. D.; Meija, J.; Hirata, T.; Prohaska, T.; Schoenberg, R.; O'Connor, G.; Walczyk, T.; Yoneda, S.; Zhu, X.-K. Atomic weights of the elements 2011 (IUPAC Technical Report). *Pure Appl. Chem.* **2013**, *85* (5), 1047–1078.
- (7) Cohen, E. R.; Cvitas, T.; Frey, J. G.; Holmström, B.; Kuchitsu, K.; Marquardt, R.; Mills, I.; Pavese, F.; Quack, M.; Stohner, J.; Strauss, H. L.; Takami, M.; Thor, A. J. *Quantities, Units, and Symbols in Physical Chemistry, IUPAC Green Book*, 3rd ed., 2nd printing; IUPAC & RSC Publishing: Cambridge, UK, 2008. <http://media.iupac.org/publications/books/gbook/IUPAC-GB3-2ndPrinting-Online-22apr2011.pdf> (accessed June 2015).
- (8) Fang, S.-C.; Hart, C.; Clarke, D. Unpacking the Meaning of the Mole Concept for Secondary School Teachers and Students. *J. Chem. Educ.* **2014**, *91* (3), 351–356.
- (9) See, for example: Tuchler, M. F. The Quantum in Chemistry, An Experimentalist's View (Roger Grinter). *J. Chem. Educ.* **2007**, *84* (6), 935.10.1021/ed084p935
- (10) Bouchendira, R.; Cladé, P.; Guellati-Khélifa, S.; Nez, F.; Biraben, F. State of the art determination of the fine structure constant: test of Quantum Electrodynamics and determination of h/m_u . *Ann. Phys. (Berlin, Ger.)* **2013**, *525* (7), 484–492.
- (11) Resolutions adopted by the CGPM at its 25 meeting (18–20 November 2014). *On the Future Revision of the International System of Units, the SI: Resolution 1*. <http://www.bipm.org/utils/common/pdf/CGPM-2014/25th-CGPM-Resolutions.pdf> (accessed June 2015).
- (12) Bettin, H.; Fujii, K.; Man, J.; Mana, G.; Massa, E.; Picard, A. Accurate measurement of the Avogadro and Planck constants by counting silicon atoms. *Ann. Phys. (Berlin, Ger.)* **2013**, *525* (8–9), 680–687.
- (13) Azuma, Y.; Barat, P.; Bartl, G.; Bettin, H.; Borys, M.; Busch, I.; Cibik, L.; D'Agostino, G.; Fujii, K.; Fujimoto, H.; Hioki, A.; Krumrey, M.; Kuettgens, U.; Kuramoto, N.; Mana, G.; Massa, E.; Meeß, R.; Mizushima, S.; Narukawa, T.; Nicolaus, A.; Pramann, A.; Rabb, S. S.; Rienitz, O.; Sasso, C.; Stock, M.; Vocke, R. D.; Waseda, A.; Wundrack, S.; Zikel, S. Improved measurement results for the Avogadro constant using a ²⁸Si-enriched crystal. *Metrologia* **2015**, *52* (2), 360–375.
- (14) For example, 1×10^{-9} kg is approximately the mass lost by relativistic effects (think $E = mc^2$) when 1 kg of free carbon-12 atoms form chemical bonds to become a graphite crystal. See: Davis, R. S.; Milton, M. J. T. The assumption of the conservation of mass and its implications for present and future definitions of the kilogram and the mole. *Metrologia* **2014**, *51* (3), 169–173.
- (15) *The Nobel Prize in Physics*, 1973. http://www.nobelprize.org/nobel_prizes/physics/laureates/1973/ (accessed June 2015).
- (16) *The Nobel Prize in Physics*, 1985. http://www.nobelprize.org/nobel_prizes/physics/laureates/1985/ (accessed Jun 2015).
- (17) Milton, M. J. T.; Davis, R.; Fletcher, N. Towards a new SI: A review of progress made since 2011. *Metrologia* **2014**, *51* (3), R21–R30.
- (18) Chao, L. S.; Schlamminger, S.; Zhang, X.; Newell, D. B.; Pratt, J. R.; Seifert, F.; Sineriz, G.; Cao, A.; Haddad, D. A LEGO Watt Balance: An apparatus to demonstrate the determination of a mass based on the new SI. *Am. J. Phys.* accepted for publication. See also <http://arxiv.org/pdf/1412.1699.pdf> (accessed Jun 2015).
- (19) Pratt, J. R. How to Weigh Everything from Atoms to Apples Using the Revised SI. *NCSLI Measure* **2014**, *9* (1), 27–38.
- (20) For a brief, entertaining account of why Americans do not refer to the element Al as “aluminium”, see: Kearn, S. *The Disappearing Spoon*; Little, Brown, and Co.: New York, 2011.