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Difficulties in Understanding and Teaching the Definition of the Kilogram in the Revised SI

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Summary:
Different options were discussed before reaching the final agreement on the new definitions of the SI units, especially with regard to the kilogram. A definition of the kg based on a mass, such as an atom or the electron, would have been preferable for ease of understanding, among other reasons. In this paper we will discuss some educational experiences on ways to teach what is now a kilogram to different audiences, including people that is rather unaware of the Planck constant.

Keywords: metrology, SI, definitions, kilogram, education.

Addressing questions on the new definition of the kilogram

Now we have to explain to a wide audience, including technicians and university graduates from the most diverse disciplines, who do not necessarily know what the Planck constant *h* is, that the kilogram is no longer the mass of “the weight that was in Paris”, but it is defined by taking the fixed numerical value of *h* to be 6.62607015 × 10^{-34} when expressed in the unit Js. It was already known from the very beginning of discussions around the redefinition of the SI units how difficult it would be to explain what a kilogram is based on a fixed value of *h*. The question of understandability was present in several important publications, at least since 2007, until shortly before the final approval of the redefinition [1,2]. One of the two prevailing arguments to support the finally adopted definition of the kilogram was the need of electrical metrology to bring into the SI the realizations of the volt and the ohm, providing exact numerical values for the Josephson constant $K_J=2e/h$ and the von Klitzing constant $R_K=h/e^2$. The second was that *h* is a constant more fundamental than the mass of an elementary particle.

An evasive way to explain what a kg is would be not to answer exactly what the new definition says, telling instead that one of the possible ways of “realizing” the new kilogram is by counting atoms. Most of that people may have some idea of what an atom is, so they can imagine that by putting together a huge amount of atoms one obtains a mass similar to the one of “the weight that was in Paris”. So far the explanation could become understandable even by elementary school pupils. The following immediate question will be of course how is it done to gather so many atoms. This paves the way for explaining the efforts made with the silicon sphere. The answer is not incorrect, since both realizations, the so called silicon route or atomic kilogram and the electric kilogram using the Kibble balance, provide a link between the Planck constant and a macroscopic mass [3].

A friendly way we use to address the very definition of the kilogram for those requiring a prior introduction to the Planck constant is to motivate them with the question of why does a fluorescent tube emits light. Next we introduce Bohr's atom model, the difference in energy ΔE between two levels, and the emission of a photon with frequency ν, presenting the Planck equation $\Delta E=h\nu$. Primary school students will have to wait to be more advanced.

Once introduced *h*, the unavoidable next question will be what the relationship of *h* with a mass *m* is. A possible answer is bringing to light Einstein's equation $E=mc^2$. In this way the connection between *m* and *h* was even presented for a time on the BIPM website, linking Einstein's equation with that of Planck. Nevertheless, care should be taken when combining both equations. The mass *m* in Einstein’s equation refers to the rest mass of an object. The frequency *v* in Planck’s equation usually refers to photons emitted with that frequency. Because photons are massless particles, equating both energies to show the relationship between *h* and *m* requires a particular consideration with respect to the mass to which *m* refers. This mass *m* could be, for example, the change in mass Δm of the particle when it emits a photon of frequency *v*. The students we appeal so far may be already thinking about the university education that they will choose.

A second answer to the question of the relationship of *h* with a mass *m* may be explaining the realization of the electric kilogram via Kibble balance. Using any version of didactic watt balances one may explain the operation principle of the same, but not the relationship of the mass that is being weighed with *h*. To do this, it is inevitable addressing the equations of Josephson effect and quantum Hall effect to determine *h* from the measured product of K_J^2 and R_K. According to the experience gathered in our chair of metrology during more than 20 years teaching the SI, it is not required that the audience necessarily have completed a course in quantum physics. The essence of both quantum effects can be explained to those with basic knowledge in natural sciences, without developing the results starting from the Schrödinger equation. Our students are already in the university, but not following law, accounting, humanities, or architecture.

Hands-on Learning

In 2015 two experimental educational solutions for the realization of the kilogram were published; one for the electric kilogram [4] and a second for the atomic kilogram [5], both to 1% relative uncertainty or less.

The first is a watt balance of LEGO blocks constructed at the National Institute of Standards and Technology. It allows explaining how the value of a mechanical force is precisely given by electrical measurements. In the words of its authors: “Unfortunately, it still requires some abstraction to explain how electrical power is related to the Planck constant via the Josephson effect and the quantum Hall effect”. That is the bridge to be crossed in order to understand the relationship between mass and *h*. Learning by doing is not only a matter of children.

The second is a rather simple experiment conceived by R. Davis [4]. After measuring the dimensions and mass *m* of a high purity aluminium cube, he estimated the number *N* of aluminium atoms inside the cube, taking the edge dimension *a* of the aluminium unit cell as determined in 1955 by X-ray diffraction. Next the atomic mass of aluminium $m_a(\mathrm{Al})$ is estimated, also $m_a(^{12}\mathrm{C})$, the atomic mass of carbon-12 and the atomic mass constant m_u. As the molar mass constant was exactly 1g/mol before the revision of the SI, a value for the Avogadro constant N_A is calculated from the measurement of m_u. Using the equation for the ionization of a hydrogen-like atom, N_A and *h* appear linked themselves and with other constants known to very small uncertainty. From the measured value of m_u results also a value for *h*. We found it more interesting and less expensive to implement this latest experiment, coming this way with various metrological applications to engineering students and also to a pre-university technical education level. With a homogenized aluminium cube (not free of imperfections and impurities) specially prepared by an Argentine manufacturer of electrolytic aluminium, the difference between the mass calculated counting atoms and the mass measured by weighing turned out to be 0.1%, or less.

A long term task

Educating for the new kilogram can be a task for decades. Meanwhile, the atomic masses community will continue using the non SI unit dalton instead of the kilogram. This scenario of living with two different units of mass may change with the irruption of a third technology quite different from the watt balance and the silicon experiments [6]. After retiring "the weight that was in Paris" we will no longer have another 140 years without changing the way we teach what a kilogram is.

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