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A revolution without tooth and claw—Redefining the physical base units

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ABSTRACT

A case study is presented of a recent proposal by the major metrology institutes to redefine four of the physical base units, namely kilogram, ampere, mole, and kelvin. The episode shows a number of features that are unusual for progress in an objective science: for example, the progress is not triggered by experimental discoveries or theoretical innovations; also, the new definitions are eventually implemented by means of a voting process. In the philosophical analysis, I will first argue that the episode provides considerable evidence for confirmation holism, i.e. the claim that central statements in fundamental science cannot be tested in isolation; second, that the episode satisfies many of the criteria which Kuhn requires for scientific revolutions even though one would naturally classify it as normal science. These two observations are interrelated since holism can provide within normal science a possible source of future revolutionary periods.

1. Introduction

Today, metrology, the science of measurement, may be best known for being easily confounded with meteorology, the study of the Earth's atmosphere. However, this relative neglect does not in any way alter the fact that metrology concerns a crucial component of the scientific method. Without a systematic analysis of the measurement process, a reliable link between the theoretical and the experimental levels of science cannot be established.[1] In this essay, a current major development in metrology is analyzed from a philosophical perspective showing the conceptual and methodological richness of the issues involved.

In Section 2, the case study is presented regarding a recent proposal to redefine four of the seven SI[2] base units, namely kilogram, ampere, kelvin, and mole, in terms of natural constants, respectively the Planck constant, the electric charge, the Boltzmann constant, and the Avogadro constant. The episode constitutes scientific progress of an unusual kind: unlike in most other developments in physics, the progress is not triggered by experimental discoveries or theoretical innovations, it sometimes correlates with major social and political changes, and it is governed by international treatises and a voting process.

In Sections 3 and 4, a philosophical analysis of the case study will be given resulting in two main claims. First, the case study provides strong evidence for the Duhemian themes of confirmation holism and theory-dependence of observation. Second, the episode, while clearly pertaining to normal science, exhibits many of the properties that Kuhn claimed to be characteristic of scientific revolutions. Section 5 concludes the essay by pointing out a link between the two theses in that confirmation holism provides a possible source of future revolutions within normal science.

2. The new SI

In the past, some of the best minds in science and especially physics have engaged with metrological issues. In the wake of the French Revolution, the French National Assembly decreed to set up a committee to organize the standardization of weight

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[1] Recent studies exploring a range of philosophical issues in connection with metrology are Chang (2004), Schlaudt (2009), and Tal (2012).

[2] International System of Units (French: Système international d'unités), which furthermore includes the second, the meter, and the candela.

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and length measures in France comprising renowned scientists like Joseph-Louis Lagrange, Pierre-Simon Laplace, or Nicolas de Condorcet. This endeavor eventually led to the establishment and proliferation of the decimal system. As another example, in the second half of the 19th century some of the best physical scientists in Great Britain, including William Thomson, James Joule, and James Clerk Maxwell, took on a similar enterprise in standardization regarding electrical units (Jenkin, 1873). While epistemological questions concerning measurement were always relevant to scientific progress, they became particularly pressing with the industrialization towards the end of the 18th century. The onset of mass-production with division of labor on an unprecedented scale required an increasing amount of coordination in the manufacturing process. Such coordination heavily relied on properly defined standards.

Hasok Chang's study on the development of the concept of temperature (2004) is a good starting point to understand, why metrology has played such a central role in the evolution of science. He aptly called his book 'Inventing Temperature', presumably to underline the constructive and creative elements in the process. No trivial, straightforward path leads from the human experience of heat and cold to the development of a reliable temperature scale on the basis of the expansion of mercury or gases and finally to the modern identification of temperature with the mean kinetic energy of molecular particles. Rather, the conceptual development of the notion of temperature and the establishment of its unit and metric cannot be separated from the development of a mature theory of heat itself.

Similar stories can be told about other fundamental quantities like the meter, the second, or the kilogram. At first sight, these could seem less interesting, since we have much stronger quantitative intuitions about length or duration than about temperature. However, this impression is misguided as shown by essentially metrological discussions in the history of science like the debate on the conventionality of space and time at the turn from the 19th to the 20th century involving amongst others Hermann von Helmholtz and Henri Poincaré.

Metrology is not an independent science, but is concerned with providing a theoretical and experimental framework for the quantification of crucial scientific concepts. It is thus an essential part of the conceptual development of all fundamental science when it comes to establishing the link between abstract theory and experience. Taking into account the crucial role of metrology in the establishment of fundamental concepts, it is no surprise that once scientific theories have reached a certain level of maturity then metrological questions, together with other foundational questions, move out of the focus. For example, since classical physics is so well-established nowadays, metrology is ignored by most physicists, but remains a domain of economic and technological interest, where it ensures coordination and efficiency. However, this does not exclude that changes to the metric system may have profound consequences for the scientific world view. After all, metrology remains the indispensable link between our more or less immediate experiences of the world and the theoretical picture we draw in science. Surely, any revision in metrology will entail a shift in the relation between these two levels, which makes it worthwhile for philosophy of science to monitor closely development in this field.

Still largely unnoticed by the majority of physicists and also by many philosophers of science, metrology is at the moment aiming for a considerable overhaul of the metric system. Around the world, major metrology institutes are working on new definitions of the kilogram, the ampere, the mole, and the kelvin in terms of fixing a number of fundamental constants of nature. Accordingly, the proposed new version of the SI is often referred to as an explicit-constant formulation. According to Terry Quinn, former director of the *International Bureau of Weights and Measures* in Paris, metrology is thereby finally close to achieving a long-term goal: 'a system of units that would meet the precept of James Clerk Maxwell, who famously said at the 1870 meeting of the British Association for the Advancement of Science: [...] "If, then we wish to obtain standards of length, time, and mass which shall be absolutely permanent, we must seek them not in the dimensions, or the motion, or the mass of our planet, but in the wavelength, the period of vibration, and the absolute mass of these imperishable and unalterable and perfectly similar molecules."' (Quinn, 2011, p. 3905)

The role model for these novel definitions is the current definition of the meter, as introduced in 1983 by implicitly fixing the value of the velocity of light: 'The meter is the length of the path travelled by light in vacuum during a time interval of 1/299 792 458 of a second.' (Taylor & Thomson, 2008, p. 18) In analogy, if the current proposals are realized, the kilogram will be redefined in terms of the Planck constant: 'The kilogram, kg, is the unit of mass; its magnitude is set by fixing the numerical value of the Planck constant to be equal to exactly $6.626\,06X \times 10^{-34}$ when it is expressed in the unit $\mathrm{s}^{-1}\,\mathrm{m}^2\,\mathrm{kg}$, which is equal to J s.'[3] (CCU, 2010, p. 7) Equally, the ampere will be redefined by fixing the value of the electric charge e, the kelvin in terms of the Boltzmann constant k_B, and the mole in terms of the Avogadro constant N_A.

Before attempting a philosophical analysis, let us take a brief look at the motivation driving the revision and at the process leading to the implementation of the new definitions. Regarding the former, maybe most striking is the absence of any major experimental discoveries, which usually in science precede revisions on this level of fundamentality. By contrast, while there is experimental progress connected with the proposal of a new SI, it is of a different kind. In particular, metrologists are currently aiming for ever improved measurements of natural constants in order to meet the precision requirements tied to novel definitions. This kind of experimental work should by no means be underestimated, since it requires a mix of the most advanced experimental techniques available in the respective fields. However, it clearly does not involve any ground-breaking discoveries or relatedly the establishment of novel theoretical concepts.

Metrologists discuss their motivation in terms of the accuracy and stability of definitions as well as the more theoretical concern of universality[4] alluded to in the Maxwell-quote above. But pragmatic and contextual factors are immensely important as well, in particular the availability, reproducibility, and applicability of the standards. In a review article written by a number of leading metrologists, the following guidelines are given: 'The desirable qualities for a good definition are that the reference quantity should be a true invariant, should be available to anyone at any time, should be realizable as accurately as the best measurements require and should preferably be as simple as possible both to comprehend and to realize.' (Mills, Mohr, Quinn, Taylor, & Williams, 2011, p. 3908) The pragmatic and contextual nature of these criteria is obvious.

Most metrologists agree that the kilogram constitutes the most problematic definition in the current SI. It remains the only base unit that is still defined in terms of an artifact, namely a platinum-iridium cylinder that is stored by the *International Bureau of*

[3] Here, X refers to a digit yet to be experimentally determined.

[4] As the definitions of the base units become more abstract, the practical realizations of these definitions become increasingly independent. Metrologists call them *mise en pratique*, and they essentially constitute 'a set of instructions that allows the definition to be realized in practice at the highest level' (http://www.bipm.org/en/si/new_si/mise-en-pratique.html, accessed 10.09.12). At some point, these practical realizations may turn into quite independent operational definitions.