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The objectivity of scientific measures

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ABSTRACT

The fundamental constants of nature, as presented by modern science, can be conceived as natural measures of the universe. In comparison, the standards of the International System of Units, including the kilogram and the meter, are mind-made and hand-crafted to meet the demands of human life. In this paper, the gap between the natural and the conventional is squeezed from two directions. In the first place, we come to understand why the metric measures were originally conceived, by the best of scientists, as being "taken from nature" and "in no way arbitrary". The kilogram of yesteryear was anchored in yesteryear's science and is reasonably considered natural with respect to that science. We also review a contemporary debate amongst physicists that questions whether any quantity, being necessarily written with units, can be truly fundamental. Modern notions of a fundamental constant are put under the spotlight; the kilogram emerges as bound up with contemporary science today as ever it was. In the picture being painted here, our measures are drawn as dynamic entities, epistemic tools that develop hand-in-hand with the rest of science, and whose significance goes much further than a metal artefact dangled from an abstract number line.

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1. Introduction

Is it meaningful to say that the speed of light is decreasing? The physics community is divided. Being a dimension*ful* constant, it has been argued that any change to the speed of light cannot be experimentally distinguished from a change to the units with which we have measured it. The argument has been taken one step further: because only the dimensionless constants of physics are truly fundamental, the standard view—that there are three fundamental units of nature—is to be abandoned. As a consequence of the position they take on these matters, physicists disagree in their judgment of the quality of a particular piece of work conducted in theoretical astrophysics. The debate matters, then, in determining the future direction of research in this area. It is an example of an ancient philosophical puzzle—the question of what constitutes real change from illusion and convention—with a pragmatic twist.

Giving some background to this debate and detailing its central argument (in Section 5) raises questions that once occupied Percy Bridgman: "What is the meaning of quantities with no dimensions?", "What kinds of quantity should we choose as the fundamentals in terms of which to measure the others?" and "In particular, how many kinds of fundamental units are there?"[2] I will, along the way, be suggesting that it is neither as easy nor as useful as it first appears to separate the dimensionless from the dimensionful in a metrological context. But I primarily turn to the debate to consider an assortment of ideals associated with the modern notion of a fundamental constant of nature (in Section 6). I only do so having already explored similar ideals in an earlier setting. The metric system was originally conceived, at the end of the eighteenth century, as "taken from nature", "perfect", "in no way arbitrary" and "true". Today, the kilogram and the meter appear to be decidedly conventional measures, set at convenient values by

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[2] Bridgman (1922), p. 16.

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methods chosen because they deliver with precision. By demonstrating that this has not always been the case, I intend to show that this is not an accurate description of the metric measures, even today. It still makes sense, as it did at their creation, to consider the latest metric measures to be more natural, fundamental or objective than their predecessors. Indeed, metrology would otherwise be senseless. Scientific standards are continually refined and redefined in order to reflect changing scientific knowledge. In particular, metrological progress cements theoretical claims about which aspects of nature are the most stable, reordering scientific knowledge and improving the harmony of science as it does so.

I am assuming throughout that the act of measurement is always a comparison of sorts and I use the noun "measure" without any refinement: a measure is any entity against which this comparison is made. I use the term to encompass not just the metal artefacts (or abstract definitions) of our standard scales, but also the tacit understanding of what kind of thing is being measured and how the measurement is to be performed. I use "standard" when I wish to emphasize the conventional character of a measure and "unit" when I wish to emphasize its size. In contrast, I use "constant" (not necessarily an invariable) to emphasize that a quantity or number has a special place in theoretical physics. This paper raises the question of how measures and constants are related, but I leave it open whether every constant is (or in some way generates) a measure and, conversely, whether a measure can be dimensionless. I use "natural" when discussing views of the eighteenth century and "fundamental" when turning to the modern era. Retaining the original terminology (used by scientists themselves) leaves open the possibility that the two notions may be more unlike than like, but this paper draws upon the similarities between the two, for both arise in the pursuit of objectivity.

I begin by asking why it was that the metric system came into being in the way that it did: with great effort and expense; amidst ostentatious fanfare and ceremony. A bankrupted country rounded up its best scientists over a ten-year period, spending 300,000 French pounds—three times the usual annual expenditure of the Académie des sciences at this time[3]—on a project that climaxed with the arrival of delegates from nine neighboring, friendly nation states to witness the creation of a new system of measurement. The resulting platinum artefacts—the meter des archives and the Kilogramme des archives—could have instead been ordered to a convenient size from ironmongers… or could they? I present (in Section 2) some of the evidence that the metric system was genuinely viewed by many of the best scientists of the time as *natural*, to follow up (in Section 3) with an explanation of what this meant and (in Section 4) a brief account of how the ideal of naturalness played out in the following two centuries. This will be a deliberately slow and round-about build-up, then, to the topic of what it takes for a measure to be fundamental, natural… or objective.

2. A curiously provisional determination of the kilogram

4 January 1793, 243 Boulevard de la Madeleine, Paris: Antoine-Laurent Lavoisier and René-Just Haüy floated a nine-inch, hollow, copper cylinder in a vase of filtered water taken from the Seine. The purpose of their experiment was to determine the mass of one cubic decimeter of pure, ice-cold water. Lavoisier and Haüy were working in their capacity as members of the Commission des poids et mesures, a subgroup of the Académie des sciences charged with the task of creating and installing a new system of measures for the emerging French republic. Two years earlier, the Commission had settled upon their preferred definitions: the French Assembly had duly declared the meridian arc from the North Pole to the equator to be ten million meters long; the *grave* had been defined as the mass of one cubic decimeter of distilled water, when at the melting point of ice and weighed *in vacuo*.[4] These definitions were highly abstract as they stood—more so, in fact, than their creators realized—and it remained to determine what they amounted to in terms of the more familiar standards of the times. Lavoisier and Haüy were the first to undertake the task of calibrating the new mass scale to the Pile de Charlemagne, a nested stack of thirteen copper weights belonging to the Paris Mint. Amidst the plethora of *livre* weights used across France, the Pile de Charlemagne delivered what was most commonly understood by the term: the entire stack defined 25 *livres*; a *livre* was composed of 9216 *grains*.

The copper cylinder floated entirely underwater, just a slender stalk screwed to its uppermost surface rose above the waterline. Lavoisier and Haüy added pellet weights (a mere 205 *grains*, the mass of approximately ten peanuts) to sink the cylinder to a fine mark filed horizontally across its stalk.[5] Because it floated perfectly in this way, the cylinder's mass (including that of the added pellets), together with its volume (including that of the stalk up to the mark), generated an estimate for the density of the water and thus a value for the *grave*. The Commission des poids et mesures announced the result two weeks later, in a report authored by Borda, Lagrange, Laplace, Condorcet and Monge: the *grave* had been found to be 18,841 *grains* with a possible error of up to 16 *grains*.[6] The French Assembly accepted the Commission's findings in a decree of 1st August 1793.[7] Almost two years later, the announcement was reiterated, by which time the mass standard had attained its more lasting name: the kilogram, it was declared on 25th April 1795, weighed 18,841 of the old French *grain*.[8]

The result was soon superseded: by the end of the decade, a new value of the kilogram stood in French law. As part of an international congress to validate the results of the metric experiments and thus witness the creation of the meter and the kilogram, Louis Lefèvre-Gineau (a member of the Académie des sciences and chair of mechanics at the Collège de France) and Giovanni Fabbroni (a member of the Accademia dei Georgofili and representing Tuscany at the congress) repeated the water-weighing experiment in the early months of 1799. In accordance with the result of this second experiment, the Kilogramme des archives, accepted in French law on 10 December 1799 as the first prototype of the kilogram, was fashioned to weigh 18,827.15 *grains*.[9] It was thus Lefèvre-Gineau and Fabbroni who went down in the history books as the men who first determined the kilogram.

There are good reasons for supposing that the second experiment was necessary because the first was insufficiently accurate for setting the new mass standard in the longer term, insufficient even to the extent of being incomplete. It had been brought forward to allow the currency of the newly emerging republic to be released: the *franc* was to be minted from a *centigrave* of silver. Working in haste, we know that Lavoisier and Haüy did not have enough time to distill the large amount of water needed to float their copper cylinder, merely filtering it through sandpaper instead.[10] In August 1793, Lavoisier wrote of the experiment that, "it remains to

[3] Alder (2002), p. 100.

[4] Borda, Lagrange, Laplace, Monge, and Condorcet (1791).

[5] Lavoisier (1862–1893) p. 683.

[6] Borda, Lagrange, Condorcet, and Laplace (1793).

[7] Mavidal, Laurent, Lataste, Claveau, Pionnier, and Ducom (1906), pp. 112–118.

[8] Guillaume (1904), p. 556.

[9] Trallès (1810), p. 579.

[10] Haüy (1793), p. 3.