The Objectivity of our Measures: How many Fundamental Units of Nature?

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In this paper, I consider different ways in which we might come to consider a unit of measurement to be fundamental. I am talking here only of *dimensionful* units, ignoring—at least for the most part—the nineteen dimensionless parameters of the Standard Model. I will be explaining why the nature and number of fundamental units has recently been debated by physicists. I believe that the time is right for a systematic critique by philosophers and that such work would benefit from a historical approach. It would be necessary, for example, to consider the relationships units have held to scientific theories through the ages. Ultimately, I will be suggesting that there is a very meaningful way—practical, pragmatic, operationalist—in which we can say there is only one fundamental unit of nature. In coming to this view, I have taken inspiration from the history of metrology. In particular, I'm building upon the views of the creators of the kilogram in the 1790s, who took the kilogram to be a natural unit.

The "standard view" presented in elementary physics text books is that there are three fundamental units of nature. Engineers speak of the "gram-centimetre-second system". Students learn dimensional analysis with the symbols *L*, *M* and *T*. Grams, centimetres and seconds are themselves not considered to be fundamental, but they can be related to two naturalised systems. The first of these was introduced by Stoney in the 1870s:

$$L_S = \frac{e\sqrt{G}}{c^2},\ M_S = \frac{e}{\sqrt{G}},\ T_S = \frac{e\sqrt{G}}{c^3}.$$

The expression for M_S is derived by equating the electric force (of Coulomb) with the gravitational force (of Newton). Those for L_S and T_S are derived from M_s, c, and e on dimensional grounds. Multiplying by the square root of the fine structure constant gives the units introduced by Planck in 1899:

$$L_P = \frac{\hbar}{M_p c},\ M_P = \sqrt{\frac{\hbar c}{G}},\ T_P = \frac{\hbar}{M_p c^2}.$$

We think of these as natural or fundamental systems of measurement because they are derived from constants of physical theories: e, G and c; or $\hbar$, G and c. Physicists would agree that G here is a place-holder for a more fundamental unit to emerge from a quantum theory of gravity. Nevertheless, the over-arching structure of a system of natural units is clear: our best theories present us with three dimensionful units, from which all other dimensionful units can be derived. The standard view tells us that three units are necessary and sufficient for the natural sciences.

Does science reveal to us in this way that there are three kinds of measurable quantities in the universe? In this paper, I will be arguing that the history of physics suggests the reverse logic has been in play: it is *because* we have assumed that there are three kinds of measurable quantities in the universe that we have searched for and found three fundamental units. Comparing Boltzmann's constant with Planck's constant, for example, leaves us in doubt whether we can justify taking only one of these as a fundamental unit.

I will be presenting and embellishing upon recent arguments made by physicists regarding what makes a unit fundamental: Lev Okun argues for the standard view; Gabriele Veneziano believes string theory makes one of these units redundant; Michael Duff argues that there are no fundamental units of nature at all. The debate has arisen in the last ten years as a result of physicists disagreeing about whether or not black holes provide an experimental way in which we can discriminate between two contending theories of a varying fine structure constant, α. (In the first, α varies because of a varying e, in the second because of a varying c.)

I will be largely agreeing with Michael Duff's arguments that there are no fundamental units of nature. I suggest, however, that considering these arguments with a slight pragmatic, practical or operationalist viewpoint brings us to conclude that there is just one fundamental constant of nature. One measure of the world is necessary in order to inject meaning into our system of measurement and to connect our experimental results to scientific theory. In making this argument, I will be taking inspiration from the ideals that brought about the kilogram in the 1790s.

Lavoisier, Borda, Couloub, Monge, Condorcet, Laplace and Lagrange (amongst others) believed the kilogram to be "not in any way arbitrary" and "taken from nature". The kilogram had been defined as a litre of ice-cold, pressureless, pure water. There were many components to what these natural philosophers meant when they called this unit “natural”. Amongst them, was the idea that it was necessary to perform a fresh experiment to generate the kilogram: the experiment was the first of an operation that could generate the kilogram again and again; it would not change over time because it relied solely on natural law. I will be arguing that we need something along these lines—we need to point to something in the physical world—in order to get our measurement systems off the ground. Theoretically, we need only do this once.

My argument requires taking a particular interpretation of the act of setting physical constants to 1. I will be using expressions such as c=1 as identities in order to generate further units. At the very least, I hope to bring philosophical attention to this peculiar procedure and to show that different attitudes exist to it within the field of theoretical physics. My argument that there is only one fundamental unit of nature rests on the sense I give to “fundamental”. It is in distinguishing and critiquing the very many meanings we can attribute to this word in this setting where the value of this work hopefully lies.