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Naturalness and convention in the International System of Units☆

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ABSTRACT

In 2018 the units of the International System are expected to be redefined by fixing the numerical values of seven constants. In addition to specifying units, these definitions will implicitly specify a set of metric conventions – namely, criteria for determining equality among quantity intervals – for many kinds of quantity. For these kinds of quantity, the determination of differences and ratios will become implicitly tied to the mathematical forms of accepted fundamental laws. This overlooked consequence of the redefinition generates a conceptual tension between the need for long-lasting unit definitions and the need for testable fundamental laws. While fundamental laws will remain testable through the same methods that have been employed for their testing prior to the redefinition, certain kinds of evidence that support challenges to fundamental theory will become unavailable under the 'New SI'.

1. Introduction

In the fall of 2018, the General Conference on Weights and Measures (CGPM) is expected to redefine the units of the International System (SI) by fixing the numerical values of seven constants [1]. Four of these constants will have their numerical values fixed for the first time as part of the SI: the Planck constant (h), the elementary charge (e), the Boltzmann constant (k_B), and the Avogadro constant (N_A). The fixed numerical values of these four constants will serve to define the kilogram, ampere, kelvin and mole, respectively.[1] These definitions will follow the example of the metre,[2] which was redefined in 1983 by fixing a numerical value for the speed of light in vacuum (c).

Much discussion and debate among metrologists has accompanied the drafting of the new definitions, focusing on questions such as: which constants to fix? How should the new definitions be worded? What levels of uncertainty are acceptable for the realizations of new SI units? and: When would be the best time to introduce the new definitions [2–5]?

While these questions are undoubtedly important, this article will discuss several other questions that have received less attention in the metrological literature concerning the revision of the SI. These questions concern the very idea of fixing the numerical values of fundamental constants and the commitments that follow from adopting this idea. Specifically, this article will address the following three questions:

1. What are the implicit assumptions involved in fixing the numerical values of fundamental constants (regardless of which constants are fixed and which numerical values are chosen)?
2. How are these assumptions different from the assumptions involved in defining units through other means, such as by reference to particular artefacts or by reference to properties of specific kinds of physical systems?
3. What influence do these assumptions have on the possibility of testing fundamental theories after the new definitions are adopted?

In raising and addressing these questions, the aim of this article is not to argue against the planned revision of the SI, but to identify some of the hidden presuppositions that accompany the upcoming metric reform and clarify their consequences. One important consequence, it will be shown, is that the new definitions place a higher burden of proof on empirical challenges to fundamental theory than current definitions. This hurdle can be circumvented, but only at the cost of inconsistency with a key assumption underlying the redefinition. Hence a tension exists between the need for long-lasting unit definitions and the need for testable theoretical laws.

Part of the reason that this tension has gone unnoticed may be that it concerns an implicit change in metric conventions associated with the new unit definitions. Metric conventions are rarely discussed in the contemporary metrological literature, although historically they were of central concern for measurement experts in the natural sciences. The next section will clarify the distinction between scaling conventions and metric conventions, drawing on literature in the history and philosophy of science. Sections 3 and 4 will further clarify the nature of metric conventions and distinguish among three kinds of metric convention:

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[1] However, the seven constants are better viewed as jointly defining an entire system of units. See Section 6.

[2] The metre, along with the second and candela, will be defined based on the same constants as before the redefinition, but with an explicit-constant wording.

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token-based, type-based and law-based. Sections 5 and 6 will explore the metric conventions implied by the 'old' and 'new' SI unit definitions, respectively. Section 7 will identify a key assumption, called the naturalness assumption, underlying the shift towards law-based metric conventions. Section 8 will discuss the implications of adopting law-based metric conventions for the possibility of testing the fundamental laws of physics. Section 9 will show that the hurdles presented by law-based metric conventions to theory testing may be circumvented, but only by violating the naturalness assumption. Section 10 will present concluding remarks.

2. Scaling conventions vs. metric conventions

Reports of measurement results convey information about the objects being measured, alongside information about the way scientists choose to represent measurement results. These two kinds of information are often referred to as 'fact' and 'convention'. While a clear-cut distinction between fact and convention is difficult to maintain in general [6], in some instances they are distinguished rather clearly. When the temperature of an object is reported as being 25 °C, the unit Celsius and the zero point of the Celsius scale are conventions. They are not determined by the subject domain about which the report is intended to convey information, but by human preferences concerning e.g. the modes of presentation, communication and use of that information.

The choice of unit and zero point together constitute what may be called a 'scaling convention' for expressing measurement results on an interval scale. In the case of a ratio scale, the scaling convention consists of a choice of unit alone. More generally, a scaling convention fixes all and only the properties of a scale that are *not* preserved under permissible scale transformations, such as between Celsius and Fahrenheit or between metres and feet.[3]

> **Scaling convention:** convention that specifies the properties of a scale that are not unique under permissible scale transformations. An example is the choice of unit of mass.

Scaling conventions are clearly recognized as conventions in the metrological literature, and the choice to use one or another scaling convention is usually clearly communicated as part of scientific reports of measurement results, most commonly by specifying the units being used.

Once scaling conventions are specified, it is tempting to think that the remaining content of the report – the part that is invariant under permissible scale transformations – is a pure statement of fact that is independent of human choice, at least insofar as the measurement procedure that gave rise to the report was accurate. Several prominent physicists and philosophers of science including Ernst Mach [8], Henri Poincaré [9] and Hans Reichenbach [10] have argued otherwise. As they have noted, another kind of human choice is involved in representing measurement results, namely, the choice of *a criterion of equality among intervals* of a quantity.

Let us illustrate this claim with the same example. The representation of an object as being at 25 °C presupposes a rule for dividing the interval between 0 °C and 100 °C into equal units. Nature does not force the choice of rule upon us. Indeed, glass thermometers filled with different fluids, such as air, water, mercury and alcohol, divide the interval between the freezing and boiling points of water into equal parts in different and nonlinearly related ways [8,11]. For over seven decades, the designers of early thermometers used multiple and inconsistent criteria of equality of temperature intervals, until in the late 1840s air thermometers became accepted as marking equal increments of temperature due to their mutual comparability. This choice was partially influenced by the limitations of glass-making at the time, and was not uniquely determined by the data.[4]

The same sorts of choices are involved in the representation of any quantity measured on an interval or ratio scale. Duration is another example. Time periods that are deemed equal to one another when using the mean sidereal day as the criterion of time uniformity are deemed unequal when the hyperfine transition frequency of caesium-133 is used, and vice versa. This is because the earth's rotation is gradually slowing down relative to the frequencies obtained from caesium clocks. Here again the two criteria of equality lead to numerical results that are nonlinearly correlated, and nature does not force us to choose one criterion over another. Instead, the choice as to which process – the earth's mean rotation or the caesium-133 transition frequency – is to be deemed uniform ultimately depends on pragmatic considerations. This last point will be discussed in detail in the next section.

The choice of criterion of equality among intervals of a quantity will be called here 'metric convention'.

> **Metric convention:** convention that specifies a criterion for the equality of intervals of a quantity. An example is the choice of criterion for the equality of masses.

As metric conventions are rarely discussed in contemporary metrology, a few clarificatory comments are in order. First, scaling conventions and metric conventions are conceptually distinct categories. Neither kind of convention logically entails the other. For example, a choice of a unit of mass need not entail any particular criterion for determining whether any two masses are equal, and vice versa: a criterion for the equality of masses need not entail any particular unit of mass. The same holds true for any kind of quantity, such as temperature, length and duration.

Second, despite the logical independence of the two kinds of convention, in practice they are often specified simultaneously. The current definition of the second specifies a unit of time, and therefore a scaling convention. In addition, the current definition of the second also implicitly specifies a metric convention for time, namely that any two periods of the radiation associated with the hyperfine transition of caesium-133 under specified conditions are equal. While all SI unit definitions, by their very design, specify a scaling convention, not all current SI unit definitions specify a metric convention. For example, the current definition of the kilogram specifies the mass of the International Prototype of the Kilogram (IPK) as a unit of mass, but does not specify a criterion of equality among masses.

Third, the complete specification of a measurement scale (as long as it is interval or ratio) requires fixing *both* scaling and metric conventions. For example, fixing a timescale requires setting the zero point and the unit of time (scaling conventions) as well as a criterion for determining whether any two durations are equal (metric convention). Without scaling conventions, units are not fixed, making it impossible to assign determinate numerical values to the objects or events being measured. Without metric conventions, it is impossible to divide an interval into equal units or to produce equal copies of a unit, and therefore again impossible to assign determinate numerical values to the objects or events being measured.

Fourth, unlike scaling conventions, metric conventions are preserved across permissible scale transformations. When converting from metres to centimetres, the unit (scaling convention) changes, but lengths that were deemed equal when measured in metres remain equal when measured in centimetres. This is due to the fact that permissible transformations for ratio and interval scales are linear. Indeed, metric conventions may be preserved across different scale types, such as between Celsius (interval) and kelvin (ratio), and even across different

[3] An introductory discussion of scale types and their permissible transformations is found in [7].

[4] The choice of air thermometer shortly preceded, and to some extent spurred, the development of the concept of thermodynamic temperature as we know it today. See [11], pp. 159–219 for discussion.