Fundamental Constants - The Ultimate Metric

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***Abstract* — The proposed changes to the SI are generating considerable debate and discussion not just in metrology but also in the field of fundamental constants. This is an excellent time to reflect on general topics involving fundamental constants, units and the SI. In particular, it is useful to prepare for some of the obvious questions that will be forthcoming from the general public.**

***Index Terms* —Measurement standards, measurement units, fundamental constants, physics, metrology.**

I. Introduction

In the last few years there has been a renewed effort to modify the international system of units, the SI, such that it is based on exactly fixed values of several fundamental constants [1]-[3]. While much of the effort has been focused on selecting a particular set of fundamental constants [2]-[3], refining our knowledge of their present values [4]-[5] and developing the official wording [6], we sometimes lose sight of the broader picture.

What are units and why do they keep changing? What are fundamental constants and why do we believe fundamental constants are really 'fundamental'? How long will this new SI last before it must be redefined again? Are we somehow artificially constraining future physics developments by these changes to the SI? Do we really gain anything by making this change to our measurement system? These are some of the simple questions that can be difficult to answer in a simple and often nonscientific fashion.

II. What are Units?

To the layman a unit is simply the standard against which other measurements of the same measurand are compared. But to a metrologist a system of units is expected to have certain characteristics. First they must be accessible - if you can't access a unit it isn't of much use. Second they must be stable in time and space so that measurements may be interpreted with minimum uncertainty. Units must be consistent with other units and it is convenient, if not essential, that all measurements use the same system of units. They also must be practical, coherent and span all physical measurement. Ideally, units should be unique but it turns out that this is not absolutely required.

The International System of Units, the SI, is designed around these characteristics to satisfy the world's measurement needs. Yet the SI has continually evolved as our breadth of measurement expands and as we have required more and more stable units.

The SI of the 1890's consisted of four base units, the kilogram, metre, second and kelvin and the other SI units were derived from combinations to these base units. These four base units were all realized with physical artifacts.

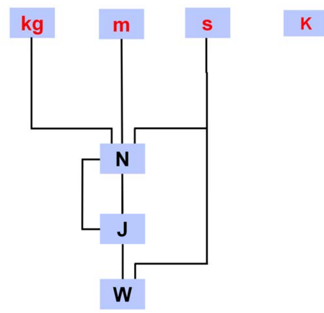

Figure 1. Schematic diagram of the original SI with its four base units each based on physical artifacts.

In the 1900's the electrical quantities, then luminous intensity and finally the quantity of matter were included. As well, the definitions and realizations of the now seven base units have been changed and refined to achieve the best stability.

During this evolution the characteristics of the base units have become blurred. They still form the set of units from which all derived units depend but they are not truly independent, they are not the ultimate in stability that we can achieve and some other things called fundamental constants have entered into the SI.

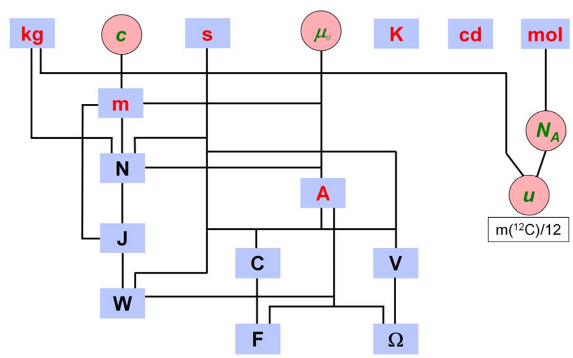

Figure 2. Schematic diagram of the present SI showing the seven base units in red, some derived units in black and the relationship to four fundamental constants, ***c*** the speed of light, $\boldsymbol{\mu_0}$ the permeability of free space, ***u*** the atomic mass unit and N_A the Avogadro constant.

In 1990 the electrical community adopted exact, conventional values for the Josephson and quantum Hall effects. This was done to improve reproducibility and internal consistency within the electrical quantities but it also dramatically improved worldwide accessibility at the highest precision. In the 22 years since its implementation this activity has been extremely successful, even though it is not strictly implementing the SI.

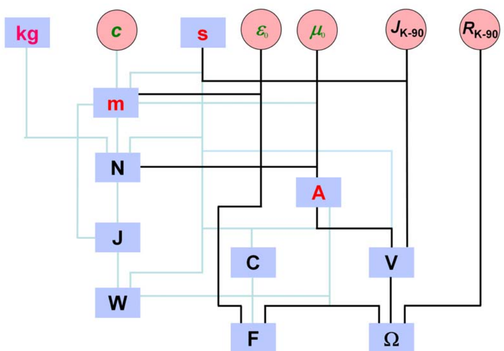

Figure 3. Schematic diagram of the present SI illustrating the use of the conventional values of J_{K-90} and R_{K-90}, along with the Josephson and quantum Hall effects, to realize conventional voltage and resistance units.

III. What are Fundamental Constants?

A. Fundamental Constants in Physics

This is perhaps the most difficult question to answer simply. Consulting the CODATA recommended values of the fundamental physical constants: 2010 [5] will certainly provide a long list of fundamental constants, but it does little to clearly explain why those have been chosen as opposed to other possibilities. Further, there is no simple list of parameters or characteristics that the fundamental constants share. To appreciate what fundamental constants are we must go back to the foundations of physics.

Physics is man's attempt to describe all physical activity of matter and energy in terms of equations that relate their properties. There are about 10^{57} atoms in our solar system and equations for everything would be overwhelming and we thus strive for single descriptions that can be applicable a broad range of situations. The most broadly applicable of these equations are loosely known as the laws of physics and some believe that if physics were complete we would only have one grand theory that includes the final and minimal set of the fundamental laws of physics.

This pursuit of reducing the numbers of things to consider is not just a practical imperative and not just a modeling strategy but is also a path to a deeper understanding of the universe. In the same way that we have attempted to make our equations broadly applicable we also have attempted to make the properties broadly applicable and scalable. So instead of describing the motion, of say a particular baseball, we model the baseball's property, which in this case would include its mass, in units of kilograms. Thus the same equations of motion become applicable to any size ball (or any object) through the scaling of its properties in terms of our units of that property.

But we can also reduce the number of properties to just those that are independent. So the baseball could be modeled as a combination of elementary particles and the baseball's mass could be modeled as the sum of the elementary particles' masses. Fortunately, much of the known universe is made up of things (including particles, space and energy) that are the same and whose properties are not only indistinguishable from each other but also observed or assumed to be invariant in space and time. For example, electrons all have the same charge, hydrogen atoms have the same emission spectra and photons all travel at the same speed in vacuum. So in general fundamental constants are invariant properties of atoms, elementary particles or space, as well as the coupling between energies originating from different types of force.

B. Are Fundamental Constants Really 'Fundamental'

As you browse through the CODATA recommended values of the fundamental physical constants you may notice that there are values of h and $h/2$ or values of the relative atomic masses of the electron, proton, neutron and deuterium and you may wonder if one is more fundamental than another. The simple answer is we don't really know and so we list the most likely ones that are most widely used. As an example, the argument of $h/2$, sometimes called the quantum of angular momentum, being more fundamental than h, the quantum of action, has strong adherents for both sides and it continues to be argued vigorously.

This question of the hierarchy of fundamental constants is further complicated by the duality found in nature. We often find ourselves asking questions such as:

- are waves more fundamental than particles?
- are the properties of vacuum more fundamental than the properties of an elementary particle?
- is mass more fundamental than charge?

The true answer of which constant is more fundamental may only be found when we get a lot closer to that 'final and minimal set' of the fundamental laws of physics that I mentioned earlier. At the present moment these arguments are speculative and philosophical and in the mean time we can only treat the constants as equally fundamental.

III. The Evolution of Our Understanding

It may be surprising but most of the advances in physics, even the most profound, are incremental in their application. As an example consider relativity. Newton's laws of motion were not abandoned once relativity was accepted. Instead Newton's laws are retained and are still used with high accuracy but with the realization that relativity may have to be included in some situations. Similar situations occur with quantum mechanics, QED, QCD and the standard model.

This incremental application of new physics gives us some confidence about how future discoveries in physics could impact fundamental constants and our system of units.

IV. The New SI

The redefinition of the SI involves exactly fixing the values of five fundamental constants namely, ***c*** the speed of light in vacuum, ***e*** the elementary charge, ***h*** the Planck constant, ***k*** the Boltzmann constant and $\boldsymbol{N_A}$ the Avogadro constant. This is a profound change not just in the philosophy of the SI but also in the direct manner in which we acknowledge that fundamental constants are nature's units and our ultimate metric.

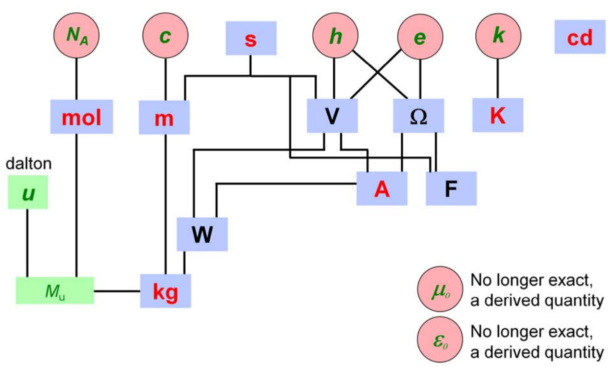

Figure 4. Schematic diagram of the 'new SI' illustrating some of the relationships between the five fundamental constants, the seven base units and some other derived units and fundamental constants.

Official wording of unit definitions and other details about the 'new SI' can be found on the BIPM website [6]-[7].

V. How long will this new SI last?

Historically, even minor changes to individual units in the SI have happened on a time scale of 20 or more years. This has as much to do with the time constant of administrative change as it does with improvements to metrology. Major changes to the SI have had even longer time periods. There should be no need to ever simply change the fixed values of the five fundamental constants so long as they remain fundamental constants. Even with major advances in physics it seems more likely that they will be incorporated as additional components with other fundamental constants rather than actually changing the existing laws of physics. Although it is impossible to be sure, I expect that these five fixed values will be the basis of the SI for the next 75 years, perhaps much more.

VI. Constraining Physics?

Some people have worried that by exactly fixing the values of these five fundamental constants we are somehow restricting the way physics can develop. For example, if a correction to the Josephson or quantum Hall effect were found there would be an impact on disseminated values of voltage or resistance. While this impact could require a modification to the mise en pratique it would not require a change of the fixed values of ***h*** or ***e***. These proposed changes to the SI are only affecting our measurement system but not the laws of physics. In fact, the only constraint that fixing the values of these five constants can have is to complicate the testing of their invariance in time. By definition this could not be measurable in the new SI but it would be observable as some law of physics being violated.

VI. Conclusion

The proposed changes to the SI promise to improve our measurement system, make it more internally consistent and give it an invariant basis that should continue far into the future.

Acknowledgement

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