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; 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.

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

In Section III and IV, a philosophical analysis of the case study will be given resulting in two main claims. First, the case study provides convincing evidence for the Duhemian themes of confirmation holism and theory-dependence of observation. Second, the episode, while clearly pertaining to

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

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

normal science, exhibits many of the properties that Kuhn claimed to be characteristic of scientific revolutions. Section V 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.

II. 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 which was supposed to organize the standardization of weight and length measures in France comprising renowned scientists like Joseph-Louis Lagrange, Pierre-Simon Laplace, or Nicolas de Condorcet. This eventually led to the establishment and proliferation of the decimal system. As another example, in the second half of the 19th century a similar enterprise in standardization was undertaken with respect to electrical units, this time in Great Britain, involving the best of Great Britain's physical scientists at the time including William Thomson, James Joule, and James Clerk Maxwell (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 ever increasing amount of coordination in the manufacturing process. Such coordination was only possible with properly defined standards in place.

To understand, why metrology has played such a central role in the evolution of science, a good place to start is Hasok Chang's study on the development of the concept of temperature (2004), which he has aptly called 'Inventing Temperature', presumably to underline the constructive and creative elements in the process. No trivial, straightforward path leads from the basic 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 metric and basic unit is deeply interconnected with and 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 may 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.

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, will move out of the focus. Thus, since classical physics is so well-established nowadays, metrology has become a domain of largely economic and technological interest. 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 at the interface 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, 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 and Thomson 2008, 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 x 10^{-34} when it is expressed in the unit s^{-1} m^2 kg, which is equal to J s.'[3] (CCU 2010, 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 laboratories all over the world, 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, it usually requires a mix of the most advanced experimental methods 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

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

[4] As the definitions of the base units become more abstract, the practical realizations of these definitions become increasingly independent and thus more important. 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 come close to becoming rather independent operational definitions.

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 et al 2011, 3908) The pragmatic and contextual nature of these criteria is obvious.

Most metrologists agree that the kilogram constitutes the most critical 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 Weights and Measures* in a basement on the outskirts of Paris. One of the most important limitations of such an artifact definition is that 'its long-term stability is not assured' (CGPM 2011, 1). And indeed, the mass of the prototype kilogram has long been known to be drifting with respect to a number of its official copies, the so-called companions or French 'temoigns'—while officially its mass has of course remained 1 kilogram by definition. This in turn affects the precision of several other SI base units, namely the ampere, the mole, and the candela, since their current definitions rely on the accuracy of the kilogram. Apparently, stability is an issue regarding the proposed redefinition of the kilogram as is universality.

As another example, the current definition of the ampere referring to the force between wires at a specific distance carrying a certain electric current has been criticized for being difficult to realize. In practice, electrical units are often established by means of the Josephson and quantum-Hall effects and their respective constants which in turn involve the Planck constant and the elementary charge. Thus, the proposed redefinition of the ampere seems just a natural step to align theory and practice.

Finally, the kelvin is currently defined by means of the triple point of water, more exactly of pure water of a specified isotopic composition, implying that any exact temperature measurement must be directly related to the triple point by primary methods of thermometry, i.e. essentially methods having the highest metrological qualities. As Mills et al. point out the new definition will have the advantage that the kelvin can be realized 'by a wide variety of experiments, over a wide range of different temperatures, by direct measurement of the thermodynamic temperature of any state of matter (or radiation) at equilibrium'. (Mills et al 2011, 3917) Thus, the main issues motivating the new definition of the kelvin seem to be availability and in particular applicability over a wide range of phenomena.

Since the mole as the ratio between macroscopic and microscopic units of substance seems less relevant to fundamental physics, I will not discuss it here. But to sum up the discussion on the motivation behind the revision of the SI, it seems fair to conclude that in all three cases, pragmatic and contextual considerations play an important role.

Let us finally have a closer look at how the new definitions may once be implemented by means of a remarkably complex, quasi-political process involving a legal framework and a number of international institutions. The procedure essentially dates back to the *Convention of the Metre* which was signed in 1875 in Paris by representatives of seventeen nations. The Convention established the *International Bureau of Weights and Measures* (BIPM), which 'acts in matters of world metrology, particularly concerning the demand for measurement standards of ever increasing accuracy, range and diversity, and the need to demonstrate equivalence between national measurement standards.'[5] The BIPM is supervised by the *International Committee for Weights and Measures* (CIPM), which is

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[5] http://www.bipm.org/en/convention/ (accessed 10.09.12)

made up of eighteen individuals from different member states, and shall promote world-wide uniformity in units of measurement either by direct action or by submitting draft resolutions to the *General Conference of Weights and Measures* (CGPM). The conference is attended by delegates of the governments of the currently fifty-six member states and by observers from the Associates of the CGPM, meeting in Paris usually every four years. One of the main tasks of CGPM is to 'endorse the results of new fundamental metrological determinations and various scientific resolutions of international scope.'[6] Thus, if or if not the proposal for the new SI is eventually accepted, will ultimately depend on a vote.

To put it mildly, such progress is quite odd for a fundamental science like physics. Just imagine a committee deciding by vote if Einstein's theory of relativity should be preferred to its Newtonian competitor. Of course, the existence of the voting process bears testimony to the considerable arbitrariness in the choice of definitions—an arbitrariness which is usually believed not to be present in the fundamental sciences.

III Philosophical Analysis

a) A shift from empirical to conventional and vice versa

From a methodological perspective, the most obvious consequence of the revision of the SI is that certain statements which used to be of empirical nature are turned into definitions and vice versa. As an example, consider the redefinition of the meter carried out in 1983. The original definition referred to a wavelength in the krypton spectrum: 'The meter is the length equal to 1 650 763.73 wavelengths in vacuum of the radiation corresponding to the transition between the levels $2p_{10}$ and $5d_5$ of the krypton 86 atom.' (Taylor and Thomson 2008, 57) Since then, the meter has been defined with reference to the speed of light: 'The meter is the length of the path traveled by light in vacuum during a time interval of 1/299 792 458 of a second.' (Taylor and Thomson 2008, 18)

Thus, while in the first case the value of the transition wavelength is definitional and that of the speed of light is of empirical nature, after the endorsement of the new definition it is the other way around. Since pragmatic reasons largely motivate the switch from one definition to the other, the choice is at least partly conventional, i.e. a considerable arbitrariness is involved. As David Lewis, who has provided the most elaborate and rigorous account of convention in the 20th century, has remarked: 'it is redundant to speak of an arbitrary convention' (Lewis 2002, 70). Thus, for every conventional statement there exists at least one viable alternative that could have been chosen just as well and this alternative is mutually incompatible with all other choices. When conventions are fixed, decision-making will be involved requiring a social process with criteria that are determined by the interests of the community. Usually, considerable pressure is exerted on members of a community to adopt the same conventions, as this enables and simplifies communication processes and coordinated action. All these properties, which are discussed in much detail in Lewis (2002), are mirrored in the process with which metrologists arrive at an agreement about definitions, as described in the previous section.

The arbitrariness in the choice of base units concerns the exact value of the respective constants, just as it is a matter of convention if we use foot or meter as base unit of length. A more complex

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[6] http://www.bipm.org/en/convention/cgpm/ (accessed 10.09.12)

question concerns the conventionality of the constancy of the respective quantities, e.g. of the krypton wavelength or the velocity of light. Is it for example a matter of fact that the velocity of light is constant across space and time or is it just a matter of stipulation or convention? Quite obviously, this question links up directly to the mentioned debate regarding the conventionality of space and time. Similar points can be made about all other constants that serve as references in the definitions of base units. A change of unit involving a simple factor implies a different value for the respective constant and vice versa, e.g. a change in the unit of mass requires a corresponding adjustment of the value of the Planck constant or a change in the unit of macroscopic chemical substance an adjustment of the Avogadro constant. At least in principle, one could imagine more complex functional relationships mirroring the mentioned debate about the conventional choice of the metrics for space and time. Since the empirical implications would remain the same, such conventional twists can only be ruled out by taking recourse to arguments of simplicity.

A number of issues depend on the question if a quantity is taken to be of empirical or of definitional nature. An empirical quantity has measurement errors and an infinite number of unknown further digits that must be determined experimentally. Also, the value of an empirical quantity might be different under yet unknown and untested boundary conditions. Finally, an empirical quantity can be confirmed by increasing the number of observations in varying contexts. All this is different for a definitional quantity, which has no measurement errors, of which all unspecified digits are automatically assumed to be zero and whose value by stipulation cannot be different under all possible boundary conditions. Finally, the value of definitional quantities cannot be experimentally confirmed or disconfirmed. The reason is that without a measurement standard in place, notions like measurement error or confirmation possess no meaning.

One might object that the constants used for definition were once established empirically and that therefore the constancy should remain an empirical fact. But this holds only with respect to a different measurement standard. Once the constants are themselves used for determining the standard, experience cannot prove the constancy of these quantities wrong. As an example, someone might want to define mass with reference to the gravitational acceleration g on the surface of the earth.[7] Of course, with respect to our usual choice of base units, the value of g changes with distance from the center of the earth. However, if the kilogram were defined with respect to g, its value would be constant by definition with no other standard for comparison. To preserve the empirical content of mechanics and the theory of gravity, one would have to make some rather complicated adjustment in these theories. While this is in principle possible, a definition by means of g can be ruled out for pragmatic reasons of simplicity. Note once more that the conventionality in the choice of base units directly implies a conventionality in the choice of fundamental laws. Referring to this situation Poincaré once stated about the laws of mechanics: 'Thus is explained how experiment may serve as a basis for the principles of mechanics, and yet will never invalidate them.' (1905, 105) Regarding the law of inertia, he added that 'this law, verified experimentally in some particular cases, may be extended fearlessly to the most general cases; for we know that in these general cases it can neither be confirmed nor contradicted by experiment.' (1905, 97)

Shifts between the empirical and the definitional can be observed for all the proposed four redefinitions of base units, although to different extent. According to the current SI, the following quantities are of definitional nature (Mills et al 2011, 3916): the mass of the international prototype

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[7] The example was suggested by one of the referees.

kilogram, the magnetic constant μ_0, the temperature of the triple point of water, and the molar mass of ^{12}C. By contrast, according to the new SI these will become empirical quantities while others become definitional that were previously considered empirical, namely: the Planck constant, the elementary charge, the Boltzmann constant, and the Avogadro constant. Since most of these quantities play quite fundamental roles in physics, the proposal of the new SI implies a considerable shift from the empirical to the definitional in physics and vice versa. In the following, the redefinition of the meter in terms of the velocity of light will mostly be used as an illustration as this example is the most intuitive and links up quite nicely with familiar philosophical discussions about space and time. However, the systematic points that will be argued only rely on there being a shift from the empirical to the definitional and thus apply to the other redefinitions as well.

As we had seen in the last section, the choice between the various definitions is underdetermined by objective criteria. Three reasons underscore this fact. First, there is a remarkable absence of major experimental discoveries connected with the proposal of the new SI. The factual basis remains largely the same. Second, the criteria invoked by metrologists are explicitly contextual and pragmatic. Finally, the political process required for the change to be implemented acknowledges on a procedural level a considerable arbitrariness in the choice of standards. Otherwise, there just would not be a final vote on the new definitions.[8]

This arbitrariness in the attribution of empirical or definitional status to a number of fundamental propositions in physics throws light on some familiar Duhemian themes. In particular, the case study provides evidence for confirmational holism, i.e. the claim that single statements cannot be tested in isolation. After all, the question of empirical or definitional status of certain propositions is intricately linked with the scientists' commitment to those propositions. In first approximation, a conventional definition should never be given up no matter what the evidence, while empirical quantities can be confirmed or disconfirmed by new observations. Thus, as long as the empirical or definitional status of propositions is underdetermined, as seems the case for the various candidates for definitions of the base units, it remains open which of these propositions are affected by both confirmatory or disconfirmatory evidence.

Relatedly, the case study also yields an example of a certain kind of theory dependence of observation. The arbitrariness in the choice of definitions implies that the definitional or empirical status of certain propositions cannot be derived from experience but rather results from the embedding in a larger theoretical context. For example, what one observes in certain experiments may depend on the definitions of the base units, as is shown below for the Foucault method to determine the velocity of light.

b) Related shifts

The shift in empirical-conventional status of certain elements of scientific theories is closely connected with a number of additional shifts, maybe most notably shifts in the interpretation of experiments and ontological shifts. These will be discussed in the following, while a number of related shifts will be briefly addressed in Section IV a. As an example, the change in definition of the

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[8] For an explicit acknowledgment of arbitrariness compare the draft of Chapter 2 for the new SI brochure after the revision: ‚The choice of which units to take as base units is to some extent arbitrary.' (CCU 2010, 3)

meter is discussed, from being defined in terms of the krypton wavelength to being defined in terms of the velocity of light. I will briefly point out that the situation is similar for the other redefinitions.

Remarkably, the interpretation of an experiment can change depending on the adopted definition of the meter. Consider the classic Fizeau-Foucault apparatus that Léon Foucault used in 1850 to determine the speed of light. The basic set-up consists of a light source plus a stationary and a rotating mirror. Light from the source is first reflected by the rotating mirror, then reflected back from the stationary to the rotating mirror. In the mean-time, the latter has advanced by a certain angle θ. Consequently, the deviation from the original path between light source and rotating mirror amounts to 2θ. By measuring the distance between the two mirrors, the angular velocity of the rotating mirror, and the deflection 2θ, the speed of light can be calculated.

Now, if the meter is defined in terms of the krypton wavelength, the experiment is indeed measuring the speed of light essentially with the help of a measuring stick that needs to be calibrated elsewhere (plus a clock to determine the angular velocity). On the other hand, if the meter is defined via the speed of light, then the experiment certainly cannot concern the measurement of the speed of light as this value is fixed by convention. Rather, it would serve the calibration of the measuring stick. Thus, while in both cases the experimental set-up is identical and also the experimental procedure is exactly the same, the experimenters are nevertheless seeing and doing different things depending on the larger theoretical context. One could say they are living in different worlds.

The change in definition also implies a shift in ontology. According to the definition in terms of the krypton wavelength, the velocity of light in vacuum has the status of an empirical quantity that has been measured to be constant across the range of our past experiences. From this perspective, the constancy is discovered to hold in the world as a real property of the velocity of light. By contrast, if the velocity of light is held constant by convention, it appears less obvious to consider it a *natural* constant belonging to the furniture of the world. After all, the status of the constancy has changed from an empirical law discovered to hold true of the world to something more resembling a law of the mind as it holds by stipulation. This change in ontological status has conceptual ramifications for the relation between space and time. Most importantly, as long as the constancy of c is held to be an empirical fact, space and time remain conceptually much more independent compared with the situation when the constancy is considered a definition or tautology. For example, in the first case the ratio between the units of space and time can change with respect to the velocity of light, in the second it cannot.

The following objection might be brought forward against this change in ontological status. Even if the velocity of light is currently fixed by convention, its constancy was once discovered as an experimental fact and somehow remains to be one. However, this view just neglects what we have argued for. Once the unit of length is defined via the velocity of light, this velocity cannot be considered an empirical constant anymore, since the notion of empirical constant makes sense only with respect to some other definition of the unit of length which has been officially abandoned. Similarly, once the velocity of light is considered a constant by definition, it cannot anymore be claimed to be discoverable or confirmable. Discovery and confirmation is only possible with respect to some other independent definition of unit of length, which again has been officially given up.

Analogous points hold for the other redefinitions even though the various constants are of quite distinct character. While the velocity of light is the property of a physical entity, namely electromagnetic radiation, the Planck constant denotes the unit of quantification of the rather abstract concept of physical action. The Boltzmann constant relates two kinds of energy, namely mechanical and thermodynamic, where the latter is ontologically reducible to the former in the context of statistical mechanics. Finally, the Avogadro constant links the mole, a macroscopic unit of substance, to its microscopic counterpart, the number of atoms or molecules.

Notwithstanding the different character of these constants, the epistemic shifts described for the redefinition of the meter occur for all of them. Experiments must be interpreted either as measuring a constant or as calibrating a measuring instrument—for example in case of the Watt Balance, one of the experiments carried out in the recent efforts to redefine the kilogram. If the kilogram is defined by means of the Planck constant then this experiment can only serve calibration purposes. Otherwise, the value of the Planck constant is measured. Even for the Avogadro constant a similar argument can be given, although our intuitions about the conventional nature of this constant are much more pronounced than, say, in the case of the Planck constant or the velocity of light. According to the current definition of mole referring to the number of atoms in twelve grams of pure carbon-12, the Avogadro constant is an empirical quantity with measurement error. The mole remains a somewhat independent macroscopic concept of substance, the identity of which with the microscopic concept in terms of number of atoms amounts in principle to an empirical hypothesis. After the redefinition, the constant will become definitional, at the same time the macroscopic unit of substance is reduced by definition to the microscopic. Thus, even in the case of the Avogadro constant, a redefinition—if interpreted literally—has ontological ramifications.

c) Carnapian versus Quinean holism

In his influential *Dynamics of Reason*, Michael Friedman discusses two versions of confirmational holism (2001, Ch. II), one relying on the empirical-conventional distinction, the other rejecting it. The former has its roots in Kantian epistemology and stands broadly in the tradition of logical positivism with Hans Reichenbach (1965) and Rudolf Carnap (1937) being the most notable proponents. By contrast, the latter was put forward by one of the fiercest critics of logical positivism, Willard Van Orman Quine (1951). In the following, I will examine to what extent the case study can shed light on the distinction, in particular which viewpoint better fits scientific practice.

The first variety of holism in the tradition of logical positivism originates in a distinction pointed out by Hans Reichenbach[9] between two different meanings of Kant's *synthetic a priori*: first, in the sense of a priori conditions for the possibility of experience ('Bedingungen der Möglichkeit von Erfahrung') and second, as unrevisable.[10] In light of the revolutions in physics at the turn from the 19th to the 20th century, the second sense seemed in outright contradiction with the actual development of science, 'refuted by experience' (Reichenbach 1965, 5). Indeed, many of the examples Kant had provided for unrevisable synthetic statements were overturned at that time, e.g. Euclidean geometry by the development of non-Euclidean alternatives. However, Reichenbach saw a role for the first sense of the synthetic a priori—a viewpoint that was surely influenced by Poincaré's conventionalism and Duhemian holism. In more recent times, Michael Friedman has revived Reichenbach's viewpoint by advocating a revisable or 'relativized' a priori in science (2001, 2002).

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[9] For an excellent overview of Reichenbach's position, see Padovani (2008).

[10] „constituting the concept of an object" vs. „necessarily true" or „true for all times" (Reichenbach 1965, 48)

Essentially, the relativized a priori denotes the conventional part in scientific theories in contrast with the empirical statements which are formulated on its basis. Reichenbach distinguished 'axioms of coordination' (Zuordnungsaxiome) and 'axioms of connection' (Verknüpfungsaxiome). The former coordinate the relation between experience and a theoretical representation of that experience. The latter are the empirical laws which are formulated on the conceptual basis introduced by the axioms of coordination. Reichenbach explicitly considers the axioms of coordination to be contingent and eventually determined by convenience.

According to Friedman, the most mature version of this first kind of holism was formulated by Rudolf Carnap in the context of his philosophy of language (1937). For Carnap, standards of correctness or validity are relative to a specific choice of linguistic framework. Questions of validity cannot be addressed without a linguistic framework in place. To ask about the truth of the rules constituting a linguistic framework amounts to a category mistake.[11] The rules are thus constitutive of experience, they are a priori suppositions. But they are conventional in the sense that a certain arbitrariness is involved in their formulation. Applied to the case study of the new SI, it turns out meaningless to ask about the truth of the constancy of a quantity that is used for the definition of units. The correctness of quantitative statements can only be evaluated with respect to a definition.

In view that Thomas Kuhn is often seen as one of the philosophers responsible for the eventual demise of logical positivism, it is remarkable that Kuhn's view on scientific progress owes much to Carnap's approach—as is also stressed by Friedman (2001, 41-43). Kuhn's distinction between normal and revolutionary periods in science constitutes an informal counterpart to Carnap's conception of linguistic frameworks. A Kuhnian paradigm, which is unrevisable in periods of normal science, provides the conceptual framework, on the basis of which the empirical content of a scientific theory can be extended and refined.

The more radical holism of the 20th century is due to Quine's attack on the analytic-synthetic distinction (1951), which—if successful—would obviously undermine the empirical-conventional distinction as well. Despite Quine's qualms with defining analyticity, he does not deny that some conceptual distinction can be construed between the definitional and the empirical, between linguistic and factual statements. What Quine denies is that this distinction is epistemically relevant for classifying statements about the world. All knowledge supposedly is of the same kind, all propositions are hypotheses of equal epistemic status. However, Quine does allow for a gradient denoting a quantitative measure for how likely a proposition is given up in the case of recalcitrant experience but this gradient marks no qualitative distinction between different types of statements (1951, 43). Quine thus denies the value of a distinction between definitions and empirical propositions, between questions of meaning and questions of fact, between the formulation of a linguistic framework and how statements are formulated within such a framework.

At first sight, the case study appears to support Quinean holism. After all, metrologists move back and forth between definitions and empirical statements as if there were no distinction between them. On the other hand, they explicitly designate propositions as being definitional. So, contrary to Quine, some value must lie in identifying certain statements as definitional and others as empirical, even if the distinction is made on pragmatic grounds. There just is no full arbitrariness. For example, the distinction has to be carefully observed by all those doing high-precision experimental work,

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[11] 'To the conventionalist, the very idea of truth by convention is as incongruous as that of meaningful nonsense.' (Ben-Menahem 2006, 1) Speaking of truth contradicts the arbitrariness of conventional choice.

because in these realms different choices of definition can make a difference. Also, epistemic status has ontological ramifications that can become relevant in the case of recalcitrant evidence, as we had seen in Section III b. Quine's holism therefore is at odds with scientific practice.[12] However, the case study does show considerable flexibility—but not arbitrariness—in ascribing conventional and empirical status to various parts of scientific theories. While Carnap and Kuhn provide an adequate framework for an analysis of the case study, this flexibility is not sufficiently accounted for in their approaches.

IV Comparison with Kuhn's Theory of Scientific Revolution

a) Characteristics of scientific revolutions

Repeatedly, Kuhn has likened the conversion experience in scientific revolutions to the holistic switches in perception familiar from Gestalt psychology.[13] In these Gestalt switches, even though the same stimuli continue to act on the senses, the mental perception switches back and forth between different interpretations. Classic examples are the Necker cube, the Rubin vase, or the rabbit-duck illusion. In the last, the perception switches back and forth between rabbit and duck. Kuhn claims this to be analogous to the changes in world view during scientific revolutions: 'What were ducks in the scientist's world before the revolution are rabbits afterwards.' (1996, 111)

The Gestalt switch metaphor seems suitable also for what is going on during a redefinition of concepts as in the revision of the SI. While in principle the observations and largely also the scientific descriptions of these observations remain the same, just as the lines in the rabbit-duck illusion remain the same, there is a fundamental change in the interpretation of what is going on. Namely, certain propositions are first held to be empirical statements and then definitions and vice versa. That this implies changes in perception analogous to Gestalt switches was already pointed out in the last section, for example when discussing the interpretation of the Fizeau-Foucault experiment.

In the following, I will approach the issue a little more systematically and briefly outline how a lot of the characteristics that Kuhn postulates for scientific revolutions are actually realized in the revision of the SI, even though one would not naturally consider the episode a scientific revolution. Unfortunately, in the *Structure of Scientific Revolution* (from here on abbreviated as *Structure*) it remains somewhat vague what is actually required for a scientific revolution. The narrative style in the *Structure* has many advantages, but conciseness is better found in the work of the later Kuhn. In his article "What are Scientific Revolutions?", Kuhn draws up a list of three criteria, which he claims to be characteristic of scientific revolutions (1987, 28-32): (i) revolutionary changes are 'somehow holistic', (ii) they involve meaning change, and (iii) there is a central change of model, metaphor, or analogy. Let me address these in turn and show that all of them are to a certain extent present in the revision of the SI.

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[12] For related criticism of Quine's positition on holism and underdetermination, see Pietsch (2011).

[13] Kuhn draws the comparison already in the *Structure of Scientific Revolution* (1996, Ch. X). In later work, Kuhn refined the use of the analogy in restricting it to the experience of individuals, both historians and scientists. With respect to scientific communities, by contrast, the late Kuhn considers the analogy ‚damaging', mainly because it blanks out the microprocesses occurring during an extended revolutionary period. (Kuhn 1989, 86-89; see also Hoyningen-Huene 1993, 205)

(i) The crucial property of holistic changes is that they cannot be made piece-meal or step by step, but rather have to be made all at once. Otherwise one would be faced with incoherence and contradictions in the transition process. In the Gestalt switch analogy, either all lines must be interpreted as depicting a duck or as depicting a rabbit. There just is no meaningful intermediary state in which one part of the drawing could be interpreted as duck and the other as rabbit. Kuhn contrasts the holistic changes in scientific revolutions with the cumulative changes characteristic of normal science. In the latter, one revises or adds stepwise, for example single law-like generalizations, resulting in a slow but steady accretion of scientific knowledge.

The redefinitions in the case study indeed seem to constitute a process that cannot be made stepwise. For example, one cannot change the empirical-conventional status of the constancy of the velocity of light without at the same time changing the status of another proposition suitable for establishing a base unit of length, e.g. of the krypton wavelength. There must always exist at least one definition because otherwise all statements involving spatial quantities would become meaningless. On the other hand, there cannot exist two independent definitions at the same time as this would lead to contradictions, for example if both the velocity of light and the krypton wavelength are considered without measurement error and with all further digits fixed to zero in the Fizeau-Foucault experiment. Thus, one cannot change the empirical-conventional nature of one proposition without changing the nature of another proposition. This change in status has a number of technical implications which must be adjusted in turn as already pointed out in Section III a, regarding measurement errors, the value of further digits etc. Furthermore, a change in the status of fundamental quantities usually has conceptual ramifications. For example, the change in status of the velocity of light has crucial consequences for the relationship between space and time, which must be taken into account simultaneously with the change in definition. Analogous points can be made for the other redefinitions. Obviously then, the revision of the SI constitutes in many ways a holistic switch.

(ii) Meaning changes are also central to Kuhn's perspective on scientific revolutions. A typical example concerns the change in the notion of mass from Newtonian mechanics to Einstein's theory of relativity. Although the same term figures in both theories, it refers to quite distinct concepts. More specifically, Kuhn understands by meaning changes a revision 'in the way words and phrases attach to nature, [a change] in the way their referents are determined' (1987, 29). Since cumulative changes can also imply meaning changes in this sense, for example when a new property of an entity is discovered, the notion needs to be framed more restrictively. Kuhn suggests that revolutionary changes in concepts alter, 'massively, the set of objects or situations to which those terms attach' (1987, 29-30).

A straightforward example of a meaning change in the revision of the SI was given in Section III b concerning the velocity of light. I argued there that the constancy in one instance constitutes a fact about the empirical world, in the other it is rather a law of thought that holds by stipulation. In a way then, this constitutes the most extreme case of a change in referents that one can imagine. At first, the value of the velocity of light is measurable as an actual property of a physical entity, and then, once it is used for definition, it ceases to be measurable at all, as any measurement is turned into a calibration, and thus has no referent in direct experiences anymore. Furthermore, all sorts of conceptual ramifications concerning the nature of space and time are connected with this change in status. These are difficult to list completely but they contribute to the holistic meaning change of a cluster of concepts involving space, time, velocity, etc. during the revision of the SI.

(iii) Finally, a change in model, metaphor, or analogy can also be observed. Notably, constants like the velocity of light or the Planck constant are construed in quite distinct ways depending on the various definitions. In one case, they can be considered to be modeled on natural laws referring to universal empirical facts. In the other case, they are modeled on definitional quantities, supposedly making explicit formerly unrecognized tautologies in the relation between physical quantities. In the case of a definitional relation, logical necessity is presupposed, while in the case of an empirical relation, we are dealing with physical necessity. Some of the implications were already discussed in Section III a. Physical necessity implies that the value of the constant is approximate, can be falsified and be dealt with in an error discussion. In the case of logical necessity, the value of the constant is determined by definition, cannot be falsified and is exact. Maybe most interesting are the ontological consequences. Definitional constants imply a reductionist attitude with respect to the concepts they link: for example, if the Boltzmann constant is taken to be definitional then thermodynamic energy just is mechanical energy, or if the Avogadro constant is taken to be definitional then the macroscopic notion of substance is reduced to the microscopic.

Thus, all the criteria given in Kuhn (1987) seem to be fulfilled at least to a certain extent in the revision of the SI. Going back to the *Structure* and the *Postscript*, various other statements that Kuhn makes about scientific revolutions fit the case study as well. Remarkably, Kuhn claims in the *Postscript* that a change in empirical-conventional status, i.e. the main mechanism we identified in the revision of the SI, is one central element of what happens during revolutions: "Laws are often corrigible piecemeal, but definitions, being tautologies, are not. […] I currently suspect that all revolutions involve, among other things, the abandonment of generalizations the force of which had previously been in some part that of tautologies." (1996, 183-4)

In the *Structure*, Kuhn discusses scientific revolutions in terms of a number of shifts in perspective that change the way how a scientist confronts the world, all of which are somewhat analogous to Gestalt shifts. These include shifts in ontology, shifts in meaning, explanatory shifts, problem shifts, and shifts in accepted solutions. All these shifts somehow imply a change in world view, i.e. that scientists 'see new and different things when looking with familiar instruments in places they have looked before' (1996, 111). Very literally, such a change in world view occurs, when experiments like the Fizeau-Foucault determination of the velocity of light or the watt balance to measure the Planck constant of Section III b are suddenly interpreted in different ways.

A shift in ontology regarding the nature of fundamental constants was also pointed out in Section III b. Certainly, shifts in ontology imply a change in meaning of related scientific concepts, but also explanatory shifts. For example, the constancy of the velocity of light requires different explanations depending on its empirical-definitional nature. Problem shifts are somewhat less pronounced in the case study, but nevertheless certain problems cease to exist with a new definition, while other new ones arise. For example, if the meter is defined via the velocity of light or the kilogram via the Planck constant, then determining the error as well as further digits of these constants cease to be legitimate problems. Also, it is not anymore a valid research question if these constants might change under yet unknown boundary conditions. Of course, as the definition is changed, problems of the described nature arise for a different constant that was previously used for the definition.

Finally, the social dimension is an important element in Kuhn's account of scientific revolutions, emphasizing in particular the crucial role of the scientific community in theory choice: 'As in political revolutions, so in paradigm choice, there is no standard higher than the assent of the relevant community.' (1996, 94) In later work, Kuhn developed a more refined view, while insisting that in principle he had not changed his mind (1973, 321). Essentially, Kuhn claims that the criteria for theory choice include objective as well as subjective, shared as well as individual criteria—ranging from the social context to dominant world views to individual experiences of certain scientists (1973, 325). Arguably, the remarks about the social aspects of scientific revolutions combined with the analogy to political revolutions concern the most controversial part of Kuhn's account of scientific revolutions. Nevertheless, these social aspects are very pronounced in the case study of the new SI: e.g. in the considerable correlation between revisions of the metric system and major social changes like the French revolution, and in the whole procedure how changes in the SI are implemented, namely by a voting process. In metrology, the explicit assent of the community is indeed the ultimate criterion.

b) Incommensurability

Kuhn's incommensurability thesis makes a claim about the mutual relationship between different paradigms treating an overlapping range of phenomena. The notion has been notoriously difficult to explicate and Kuhn more or less struggled during his whole life to formulate an explicit account of what incommensurability amounts to. This should not surprise us much, since it is a rich term that is supposed to account for a considerable variety of historical situations as well as theoretical claims regarding comparability, communicability, and translatability.

Maybe the most prominent element in Kuhn's account of incommensurability concerns the idea of fundamental meaning change in scientific theories, implying that it is 'impossible to define all the terms of one theory in the vocabulary of the other' (1983, 34) or equivalently, that there is no neutral language into which two theories can be translated 'without residue or loss' (1983, 36). A different language or different description of the phenomena can only be learned by what Kuhn calls interpretation, i.e. by directly observing the use of scientific terms, how they are attached to the world by the relevant community. For Kuhn, interpretation is completely distinct from translation. (Kuhn 1983, cf. also Hoyningen-Huene 1993, 213-214)

It can be argued that different versions of the SI are incommensurable in this way, since no complete translation seems possible in the sense given by Kuhn. Kuhn identifies two crucial features (1983, 38). First, a translation should not alter the meanings of words and phrases. In particular, it should not change the way referents are determined. Second, a translation should only replace words and phrases in the original with other words and phrases, in particular it should not require 'glosses and translators' prefaces' (ibid.). Now, redefinitions change the referents in important ways. This essentially results from the discussed meaning changes, e.g. in the case of the speed of light. While both views refer to a similar entity, this entity has different features, for example with respect to constancy. It is the change in ontology, which leads to the failure of translation. One could of course resort to a metalevel and explain the conventional-empirical shift with its large number of implications for the use of the term and of interrelated concepts, but this is what Kuhn wants to exclude with his condition that no translators' prefaces should be employed.

Incommensurability and the related discussion of criteria for theory choice constitute central theses in Kuhn's argument against the conception that science is advancing towards a clearly identifiable 'permanent fixed scientific truth' (1996, 173). This claim also fits well with the case study, as it seems widely acknowledged by metrologists that the choice between different versions of the SI is not a matter of truth, since some arbitrariness will always remain. Truth just is the wrong concept to discuss these changes.

c) Résumé

We have seen that a lot of the characteristics that Kuhn invoked for scientific revolutions are realized to some extent in the case study, even though most physicists and presumably also philosophers of science would classify the revision of the SI as an episode in normal science. In the next Section V, I will try to resolve this tension by arguing that the holistic aspects of physical theories as evidenced so clearly in the case study constitute a germ of future revolutions within normal science.

But let me first make a number of comments in what respects the case study differs from Kuhn's picture of scientific revolutions. Maybe most importantly, there are no major discoveries or theoretical innovations motivating the proposed revision of the SI. Thus, there are no anomalies, no crisis, while at least in the *Structure*, Kuhn claims crisis to be a prerequisite of scientific revolution (1996, 92), although already in the *Postscript* he holds the more nuanced view that nothing in his account of scientific revolutions hinges on this (1996, 181).

The second difference concerns the extent to which the characteristics of scientific revolutions are manifest in the considered episode. While most of them are present in principle, are qualitatively there, the standard examples of scientific revolutions like the Copernican, the Chemical, or the Darwinian Revolutions are much more pronounced. We are thus dealing very much with a tamed revolution, a revolution without tooth and claw. While 'real' revolution are complex and messy, in the revision of the SI, the changes in terms of conventional-empirical status can be made explicit at least in first approximation if abstracting from some more minor conceptual ramifications.

A related difference concerns the question, if the episode is perceived as a scientific revolution by the relevant communities. This seems not the case. Certainly, physicists would not consider it a scientific revolution. First, it has virtually no impact on their daily work. Instead, the revision of the SI has been explicitly conceived in a way to have as little practical implications as possible. Second, the new definition will almost certainly not be taken as definite. Rather, physicists will continue to ask questions that are officially prohibited. Even if the meter is defined via the velocity of light, physicists will continue to measure the velocity of light in various contexts and consider the possibility that it might have different values under extreme circumstances, e.g. in the early universe. Thereby, physicists implicitly acknowledge an arbitrariness in the choice of definitions.

Although metrologists might be inclined to consider the redefinitions as being of revolutionary importance, they will certainly not think of them as paralleling in any way the more familiar scientific revolutions from the history of science. This is not only a question of scale. It owes much more to an acknowledgment of the mentioned arbitrariness. The psychology is different compared with 'real' scientific revolutions, where most members of the community believe that the new theory is somehow a better approximation of the truth. But truth is just the wrong criterion to discuss changes in the SI. Finally, the revision of the SI is lacking the chaos and turmoil that usually accompanies both political and scientific revolutions.

V Conclusion

The moral to be drawn from the case study is certainly not that we are dealing with a scientific revolution that almost everyone fails to recognize. To the contrary, the revision of the SI should be classified as normal science, largely due to the reasons given in Section IV c. The more subtle moral is that there is a revolutionary germ in normal science. It consists in the considerable underdetermination regarding the empirical-conventional status of various propositions or, equivalently, in the underdetermination of commitment to these propositions, implying confirmation holism. Since, as was shown, changes in empirical-conventional status have a lot in common with scientific revolutions, one could say that at least in some cases where holism is present in a scientific theory, several paradigms coexist within this theory—thus preserving a certain flexibility, which may become especially important in the case of recalcitrant experience, of anomalies, and of crisis. Then, these paradigms will be developed in different ways resulting in a transition period with different schools and eventually leading to the establishment of a new paradigm.

As the case study shows, the distinctions between normal science and revolutionary periods as well as between an empirical and a conventional part in scientific theories remain essential tools for analyzing scientific progress. The actual developments however turn out much more complex than suggested by these simple dichotomies. Kuhn himself has pointed out that revolutions can be of different scale and need not always involve large changes of worldview (1996, 49). Another aspect was stressed by Peter Galison (1997) that various communities with different preferences and interests contribute to scientific progress, for example theoretical physicists, experimental physicists and engineers. What is a revolutionary development for one community can constitute complete normal science for another. Now, the case study of the new SI points to a further complication, namely that there is considerable flexibility within normal science even from the perspective of a single community. Most writers in the Kuhnian tradition have focused on what a paradigm fixes and less on what it leaves undetermined. Kuhn has rightly emphasized the dogmatic nature of paradigms, since a constant questioning of the foundations would certainly be harmful to scientific progress. But the flexibility of paradigms regarding the attribution of empirical and conventional status is also important, to adequately integrate new evidence and thus sustain continuous scientific progress within normal science.

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