DE GRUYTER OLDENBOURG Analyse & Kritik 2016; 38 (2):497–521

Original Paper

Oliver Schlaudt*

Reflective Equilibria in Metrology?

A Case Study on the Current Reform of the International System of Units

DOI: 10.1515/auk-2016-0123

Abstract: In this paper I propose to read the history of systems of units, and in particular the current reform of the *International System of Units* (SI), understood as a set of measuring norms, in the light of reflective equilibria. The idea is that the model of reflective equilibria actually applies to processes which can be empirically observed or studied. This can help us to understand the nature of normativity and to shed light on its relativity to, and dependence on, practice.

Keywords: Reflective equilibria, measurement, metrology, systems of units, reform of the SI

1 Aims and Outline of the Paper

Nelson Goodman introduced the idea of reflective equilibria with a view to justifying logical rules, but he did not seek to extend this method to other kinds of rules and norms or to flesh out his model by offering empirical evidence (cf. *section 2.1*). In this paper I propose to read the history of systems of units, and in particular the current reform of the *International System of Units* (SI), in the light of reflective equilibria. The idea is that the model of reflective equilibria actually applies to processes which can be empirically observed or studied. This can help us to understand the nature of normativity and to shed light on its relativity to—and dependence on—practice. In the study of norms and their mutual relations to practice, units of measurement are a case in point: on the one hand, as essential elements of norms of measurement, units have a normative character (*section 2.2*) while, on the other hand, they develop in lockstep with measurement technology (*section 2.3*).

***Corresponding Author: Oliver Schlaudt:** Philosophisches Seminar der Universität Heidelberg, Schulgasse 6, 69117 Heidelberg, Germany, e-mail: oliver.schlaudt@urz.uni-heidelberg.de

The current reform of the SI is easily accessible to empirical investigation because of a well documented discussion among metrologists and scientists. A large part of this discussion is documented in discussion papers, mainly published in *Metrologia*, the official scientific journal of the *Bureau international des poids et mesures (BIPM)*, and in various official reports of the same institution. The study of these texts is facilitated by a small but highly original literature on the sociology of metrology, highlighting important mechanisms and typical patterns.[1] Unlike sociological approaches, however, I am not interested in the range of social factors involved including, in particular, institutional patterns of decision making (the decision process regarding the SI runs through a complicated structure of National Metrology Institutes (NMIs) which are organized in the *Bureau international*, involving various working groups and advisory boards, first and foremost the *Comité international des poids et mesures (CIPM)*, which is elected by the *Conférence gênérale des poids et mesures (CGPM)* and acts as the scientific committee of the BIPM).[2] In applying the model of reflective equilibria, it is solely practice-related constraints which shape the new units and which are quoted as justifications for them that are of interest. My aim is thus to identify practice-related constraints in the literature on the New SI. The most important factor, of course, will be technology and precision measurement. But in the debate on the current reform, other practice-related factors besides technology crop up additionally: theory building, teaching, legislative processes, commerce and industrial production. Their study offers insights into the micro-dynamics of the evolution of norms and its dependence on practice.

In *section 2*, I provide the conceptual framework for this study, introducing in particular the idea of reflective equilibria. I briefly explain how units are defined and also highlight the reasons for the current reform of the SI as stated in the literature. In *section 3* I identify typical patterns in the debate on the New SI in order to generate an overall view of the literature. I will propose two classifications, based on the different positions and the different roles metrologists and scientists adopt in their discussion papers: they can be either 'boosters', 'brakemen' or 'heretics' with regard to the reform, while in the course of debate, especially on the principles according to which a reformed SI should be designed, they can adopt the roles of 'rule users', 'rule explicators' or 'meta-ethicists' discussing second-order

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[1] Classical texts include Kula 1986; O'Connel 1993; Mallard 1998; and Schaffer 1992–1997. My paper also owes much to the round table "Sociology of metrological knowledge" which I co-organized with Nadine de Courtenay at the *Dimensions of Measurement* conference in March 2013 at Bielefeld. Speakers were François Hochereau (Paris), Alexandre Mallard (Paris), Simon Schaffer (Cambridge, UK) and Hector Vera (Mexico City).

[2] Quinn and Kovalevsky 2005, 2311, provide an organizational scheme.

rules. Finally, in *section 4* I derive and classify the practical (epistemic and non-epistemic) constraints to which the reform of the SI is subject. It is here that it becomes possible to identify the ingredients of a reflective equilibrium, i.e. the revision of general rules in the light of practice and, *vice versa*, the revision of practice in the light of general rules. In particular I will show that the 'maturity' of a technology, as discussed by metrologists, can be understood as a criterion for the technology's 'normative force' in the sense of its capacity to influence a reflective equilibrium.

2 The Background: The Conceptual Framework and the Historical Case

2.1 Reflective Equilibria and the Justification of Norms

Nelson Goodman introduced the idea (though not the name) of reflective equilibria with a view—as we read it—to formulating a pragmatic justification of norms. He thus achieved a balance between an 'idealistic' stance on the one hand—one that regards norms as elements of an autonomous and self-sufficient discourse—and a 'positivist' approach on the other, that identifies normative and actual validity. According to Goodman, a deduction in logic is justified "by showing that it conforms to the general rules of deductive inference", and these rules are in turn justified "by their conformity with accepted deductive practice". That is:

> "A rule is amended if it yields an inference we are unwilling to accept; an inference is rejected if it violates a rule we are unwilling to amend. The process of justification is the delicate one of making mutual adjustments between rules and accepted inferences; and in the agreement lies the only justification needed for either." (Goodman 1983, 63)

The equilibrium thus exists—after a process of mutual adjustment—between general inference rules on the one hand ('top level') and particular inferences to be covered by these rules on the other ('bottom level'). The top level is formal, consisting in a systematic codification of rules. The bottom level is informal and consists in a pre-systematic but reliable (or 'mature') practice ('mature' is the term we find in the metrological literature). The idea is that the mechanism of mutual adjustment allows us to base the justification of norms on the actual validity of an underlying practice without, however, reducing ideal validity to factual validity.

Goodman introduced this idea for the case of deductive inferences and with a view to solving what he called "the new riddle of induction", i.e. justifying rules of inductive inference. But he neither sought to extend this approach to other kinds of rules beyond logic nor did he attempt to flesh out his model by offering empirical evidence, e.g. by mapping it onto historical developments of logic. The former was done by John Rawls, whose *Theory of Justice* can be read as an attempt to establish moral principles by bringing them into a reflective equilibrium with "considered (moral) judgements" (1977). It was also Rawls who coined the term 'reflective equilibria'. Susanne Hahn (2000) attempted to fill the second gap by analysing reactions to the paradoxes of set theory in terms of readjustments between normative principles and established practices of deductive reasoning. The study I propose in this paper goes in the same direction: I propose to read the history of systems of units—and in particular the current reform of the *International System of Units* (SI)—in the light of reflective equilibria.

2.2 Units of Measurement as Epistemic Norms

Units serve as common references which render measurement results comparable and communicable. Moreover, coherent systems of units make it possible to establish mathematical equations and thus to apply analytical tools from higher mathematics.[3] Units can be given in two different forms: as a material prototype or as an abstract definition linking the unit to an individual in nature (e.g. the earth) or a natural phenomenon (a chemical element, a natural constant…). Such an abstract definition must be complemented by a '*mise en pratique*' explaining how the unit can be realized in a concrete experimental setup:

Def. 1: a unit is given by: (1) a specified prototype, kept at a certain place and under specified conditions in order to allow for a certain precision;
(2) an abstract definition plus a technological mise en pratique assumed to provide a certain precision.

It should be stressed that, accordingly, units are not abstract entities to be materialized in empirical objects. As it stands, 'the' kilogram is a material individual stored in the strongroom of the BIPM near Paris, and the word 'kilogram', as figuring in the measurement rule of mass, is the proper name of this individual. What is called 'a' kilogramm (e.g. in a set of weights for a mechanical balance) is not an *instantiation* but a *copy* of 'the' kilogram to which it is linked by a so called traceability chain.

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[3] The fact that the use of equations and analytical tools depends on a coherent system of units is not well known; on this topic, cf. de Courtenay 2015.

'Systems of units' consist of a set of base units and some units of derived quantities which are established as derived units, e.g. kilometres per hour for velocity. Such a system is 'coherent' if the values of the derived units are additionally fixed in such a way that exactly the *same* relations hold between the quantities and between their measured values (meters per second for velocity, if the latter is defined by the quantity equation $v=dr/dt$, but not kilometres per hour which involves an additional numerical factor of 3.6—cf. JCGM 2012, 8). Coherent systems of units thus enable the "double interpretation" of physical equations, i.e. as relations between quantities and relations between their values, as established by James Clerk Maxwell in the 1870s.

In order to fulfil their function as a common reference, the units must be stable in time: that is, depending on the type of definition, the prototype must be kept stable in time or the abstract unit must be identically realizable at different moments – within a given precision.

As such, units are essential elements of norms governing a special practice, measurement, for all measurement results are to be expressed in 'conventionally' fixed and collectively shared units of measurement. In countries which adopted the metric system, the kilogram, for example, is not only commonly used to express weight, its use is *obligatory* in science and trade.[4] The norm is, in a general form:

Def. 2: Measuring norm Mn_i: Measurements of quantities of the kind i shall refer to unit u_i and shall be expressed as a (rational) (sub)multiple of u_i (plus an estimation of the measurement uncertainty).[5]

Since each unit unambiguously individuates a measuring norm, we can—elliptically, for sure, but without risk of confusion—call the units themselves measurement norms.

More specifically, we can call units of measurement 'epistemic' norms insofar as the practice they govern has as its aim the production of knowledge (in the case of measurement, for example, to create intersubjectivity and enable communica-

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[4] For Germany, see the *Gesetz über die Einheiten im Messwesen und die Zeitbestimmung* from 1969 and *Ausführungsverordnung zum Gesetz über die Einheiten im Messwesen und die Zeitbestimmung* from 1985, both in *Bundesgesetzblatt I*.

[5] This definition rests on what has been called the 'classical' view of measurement, i.e. measurement as the numerical determination of a ratio of quantities, as opposed to the 'representational' view which defines measurement as assigning numbers to objects according to rules (cf. Michell 1993). Whereas the latter is designed in order to allow for a formal theory of measurement and a theory of scales, the former has the advantage of being closer to experimental practice (cf. Schlaudt 2009, chapter 11).

tion). Epistemic norms join logical, aesthetic and the most familiar ethical norms. Examples of epistemic norms include all forms of standardized routines in epistemic practices, but also norms of concept formation and theory building. Norms of theory choice are often addressed in contemporary philosophy of science as ‘values’.

Knowledge is generally classified as ‘theory’ as opposed to ‘practice’ (in the sense either of applied knowledge or of ‘blind’ practice, bricolage). Note that, regardless of this ‘theoretical’ character of knowledge, epistemic norms are still ‘practical’ norms, i.e. they govern operations in space and time. In the case of measurement these operations are partly verbal, but also—and necessarily—partly non-verbal. Regarding epistemic norms as practical norms merely entails acknowledging that empirical knowledge arises from practical, norm-governed operations (intellectual or manual, logico-mathematical or experimental). In this sense the theoretical is a part of, or superposes, but in any case is not opposed to, the practical.

To speak of theory and practice might thus be misleading in the present context, and so I seek to use a less ambiguous vocabulary. We are concerned with *norms* governing *actions* or *operations*. Among the operations we can generally distinguish between *logical* and *non-logical* ones, the latter being understood as operations in space and time. We are concerned only with the latter. Of these, we can distinguish again between *symbolic (verbal, graphic, and so forth)* and *non-symbolic* ones on the one hand and between *epistemic* and *non-epistemic* ones (i.e. related or not related to knowledge production) on the other. Establishing an equilibrium on a pair of scales is an epistemic non-symbolic operation. Writing down the result is an epistemic symbolic operation. And expressing regret that the scales are imprecise is a symbolic (verbal) non-epistemic action[6]. Putting the scales back in their case is a non-symbolic and non-epistemic operation (though perhaps part of the local measurement routine). The terms ‘practical’ and ‘theoretical’ do not properly capture these distinctions because they refer ambiguously to all three of them: ‘theoretical’ can mean at once logical, symbolic, and epistemic, while ‘practical’, conversely, can mean non-logical, non-symbolic, and non-epistemic. I will thus avoid using these terms.

In the present paper we are concerned first and foremost with the non-logical and non-symbolic aspect of measurement—measurement as an empirical and material operation.[7] This aspect can be divided into epistemic and non-epistemic fac-

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[6] The emphasis here is on ‘regret’ as opposed to, say, ‘claim’.

[7] This is the reason why, in Def. 2, I adopted the classical definition of measurement. The representational view takes measurement as a purely logical operation, the ‘assignment of numbers to objects’.

tors, and both actually contribute to shaping the units: for epistemic reasons the unit of length must be stable, but it is for non-epistemic ('purely practical') reasons that we use the meter and not the light year when measuring distances on the scale of everyday life. Thus among the epistemically 'admissible' units there are still those that are more and those that are less practicable. The choice of units is shaped but not determined by epistemic questions and is thus conventional without being arbitrary. (Hence the quotation marks around 'conventionally' above.)[8]

2.3 Historical Evolution of Norms: The Case of the SI

Units of measurement also clearly evolve historically in lockstep with advancements in the measurement techniques they govern. Measurement techniques progress in terms of their scope as well as their precision within a given domain (where both features surely interconnect), and these developments make necessary revisions of the units. The reason for this is clear: measuring consists in empirically determining the numerical ratio which holds between two quantities q_1 and q_2 (according to the definition of measurement assumed in Def. 2). In a standardized measurement, a standardized unit u is chosen for q_2, i.e. q_1 is expressed as a multiple (or submultiple) of u. When the method adopted to determine the numerical ratio allows for precision p_1 (say 10^{-6}), but the material instantiation of unit u is known or suspected to vary within limits $p_2 > p_1$ (say 10^{-5}), the choice of the unit reduces the precision of the overall result and thus drops behind the experimental potentialities. It *underachieves* in a normative sense (to summarize my thesis).

A dependence of the evolution of units on technological progress has already been observed on the large scale, though it was not stated in terms of reflective equilibria (Vera 2015). This dependence can be observed in the metric system (1799) and also in the *International System of Units* (SI 1960). The SI is a (coherent) system of seven well-defined base units which many states have adopted as legal and obligatory for civil and commercial matters.[9] Some of the base units have already undergone several changes in definition in order to keep up with

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[8] I use 'convention' not in the sense of a Lewisian convention in game theory, but to designate, as in conventionalism, an element which is underdetermined by the relevant factors and which can thus be regarded as if it were settled by decision and by a choice from alternatives.

[9] In his sociological studies Hector Vera (2007a; 2007b; 2015) offers some interesting information regarding mechanisms involved in the spread of the metric system, especially for the case of Mexico. Besides purely political and institutional dimensions, Vera also highlights a number of underlying material and practical aspects such as availability of instruments and teaching. As a

the precision requirements of research and industrial production. Until 1977, the second was linked first to the mean solar day, i.e. to the rotation of the earth around its axis, then to the tropical year (or, more precisely, to the "tropical year for 1900 January 0 at twelve hours of ephemeris time"), i.e. to the movement of the earth around the sun. Since 1977, the second is realized by a caesium atomic standard and is defined as a "the duration of 9 192 631 770 periods of the radiation corresponding to the transition between the two hyperfine levels of the ground state of the caesium 133 atom" (CGPM 1967/68, Resolution 1). The metre, originally defined by an artefact, was first linked to the wavelength of a given type of radiation, similar to the second, but was then coupled to the second via the speed of light. Since 1983 the metre has thus been "the length of the path travelled by light in vacuum during a time interval of 1/299 792 458 of a second" (CGPM 1983, Resolution 1). The driving force behind these changes was an increase in precision and a more refined theoretical understanding of the underlying processes which limited the precision of the previous standards (cf. Mills et al. 2011, 3908, and Himbert 2009, 32–33).

2.4 Our Case: The New SI and Its Technological Foundations

Today, the kilogram is the last unit defined by a prototype, kept in the triple-locked strongroom of the BIPM,[10] the "*kilogramme des Archives*". It is a platinum cylinder standard created in the 1790s and was replaced in 1889 by a platinum-iridium standard, the "*International Prototype Kilogram (k)*". There are six other official working copies stored at the BIPM (the so-called "témoins", "witnesses") as well as various national prototype copies at the NMIs, which also possess standards of multiples and submultiples of the kilogram between 1 mg and 50 tons (Kovalevsky and Quinn 2004, 804; Schwitz et al. 2004, 882). Since 1889, three verifications of the standards, e.g. comparisons between k and its national copies, have been conducted. The result of this—a continuous drift between the standards which exceeds today's demands for precision—is one of the main reasons for the current revision of the SI (cf. below, *section 4.2*). The mismatch between the prototype definition of the kilogram and contemporary technology is depicted in striking terms even by a critic of the reform:

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general framework we might mention the work of Brennan et al. 2013, ch. 5, who provide a useful classification of such patterns.

[10] The three keys are in possession of the director of the BIPM, the director of the *Archives nationales*, and of the president of the CIPM. Cf. e.g. the report of the 1999 visit of the prototype in *Conférence générale des poids et mesures*, 21e session (octobre 1999), BIPM 1999, 129–30.

> “Physicists are now able to pick up and move a single atom. The required cleaning of Le Grand K [the kilogram prototype] removes trillions of atoms of platinum and iridium, and deposits trillions of atoms from the solvents and gloves used in the cleaning.” (Hill 2012)

The aim of the current reform of the SI, however, is not only to redefine the kilogram but to rethink the entire system in order to achieve a satisfying theoretical coherence within it and with contemporary physical theory. The definition of the metre is a model for the new definitions. It contains a constant of nature, the speed of light, and can thus also be restated by saying that the metre is the length such that, expressed in metres per second, the speed of light has the exact numerical value of 299 792 458. This is the so-called “explicit constant” formulation, linking the units to constants whose value is no longer experimentally established but conventionally ‘frozen’. The idea is to link all of the units encompassed by the system to constants of nature. Note that, in the process of doing so, the uncertainty that has hitherto accompanied our best empirical values of the constants is transferred to the material realizations of the units (henceforth defined in an abstract manner plus a *mise en pratique*). Efforts to link the kilogram to a fundamental constant were undertaken as early as the 1990s (Quinn 1996, 83; 2000, 94). The redefinition of the kilogram began to be more vigorously debated around 2004 (Schwitz et al. 2004; Mills et al. 2005). A corresponding “Draft Chapter 2 for SI Brochure, following redefinitions of the base units”, signed by the president of the Consultative Committee for Units (CCU), has circulated since 2010, though it was not until 2011 that the CCPM adopted a resolution “Sur l'éventuelle révision à venir du Système international d'unités, le SI”.[11]

The thesis that norms and their revisions depend on technological change can easily be confirmed for the current reform of the SI. Generally speaking, the intended reform depends on new experimental setups linking quantum effects to observable phenomena at the laboratory scale (Quantum Hall Effect, Josephson Effect, spectroscopy etc., cf. Piquemal/Jeckelmann 2009). With regard to the kilogram, two propositions for a redefinition are in competition with one another: linking the kilogram to the Avogadro constant N_A or to the Planck constant h. Both definitions entail a different *mise en pratique*, namely, the Avogadro project and the Watt balance respectively (for a description of these, cf. Stock 2011; Becker/Bettin 2011). Note that these experiments fulfil a twofold function: first, they serve as a measurement device for the respective constants of nature, N_A and h. Then, once the numerical value of one of the constants is frozen by definition, the same experimental setup serves to realize the new kilogram. Measurement devices and the technology of the *mise en pratique* are thus one and the

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[11] Comptes rendus de la 24e CGPM 2011, 2013, 212.

same thing.[12] As we will see in more detail below (*section 4.2*), this technology plays the role of the bottom level of a reflective equilibrium and, as such, is a key to understanding the emergence of the New SI. At present, the competing ways of redefining the kilogram yield incoherent values. For that reason, at end of 2014 the reform of the SI was deferred to 2018.[13]

2.5 Rough Application

Prima facie systems of units of measurement are a good candidate for reflective equilibria. The latter can be regarded as a model of dynamic mutual dependence between the practices and norms governing such systems, with normative force being ascribed to the underlying practice. The official (systems of) units—defined by abstract definitions or with reference to an artefact (e.g. the kilogram)—play the role of the (systems of) general rules (top level), while individual measurements constitute the underlying practice (bottom level). A measurement yields a valid result and can be regarded as a valid expression of a quantity (*with a certain degree of precision*) if—other material conditions being assumed met—it is carried out 'according to the rule', i.e. with a valid copy or realization of the official unit. (Note that precision of measurement, unlike validity of deductive inference, comes in degrees. That is why, unlike Goodman, we have included the precision clause in our version of the reflective equilibrium.) The historical dynamics come into play at the bottom level: New technologies and new theoretical insights allow for measurements of greater precision, finally exceeding that of the official unit. Today, measurement of mass is possible with a precision that is greater than that of the official kilogram prototype (constructed in 1889). The unit or general rule thus no longer matches the underlying practice and must be revised and readjusted to it. The current reform of the SI differs from the situation considered by Goodman in that the underlying practice has already been systemized, but the corpus of rules has to be *revised* due to this constant historical development. This is no reason, however, for not expecting to find the process of mutual adjustment described by Goodman.

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[12] Cf. Riordan, forthcoming, section 4.

[13] Sur la révision à venir du Système international d'unités, le SI, *Comptes rendus de la 25e CGPM* (2014), null, 2; Roadmap towards the redefinition of the SI in 2018, Richard/Ullrich 2014.

3 Patterns in the Discussion on the New SI among Scientists and Metrologists

The SI is a *formal* system of norms in the sense indicated by Brennan et al. (2013, 41–42) because it provides secondary rules for the modification of primary norms. In an informal system without secondary rules, Brennan et al. stress, “changing the content of primary rules will *necessarily* be a slow and tedious process. There, the only way rule change can happen is by some people beginning to accept different primary rules of conduct, and enough other people eventually coming to do likewise” (2013, 108). When there are secondary rules, the discussions preceding decisions taken according to these rules, however, might be quite long too. The people involved have to be convinced and might only slowly begin to accept the necessity of a change and the propositions made for this change. In the case of the New SI, there is a rich and well documented debate of this kind in the literature (consisting mainly of articles published in *Metrologia* between 2004 and 2010). Although I will use this literature primarily to identify various practical constraints shaping the New SI, it is helpful—and interesting in itself—to identify briefly the typical patterns that stand out in this debate. It will be useful to classify the actors according to two sets of categories, related, first, to their attitude towards the reform of the SI and, second, to the role they adopt in the debate vis-à-vis criteria and second-order norms in the construction of systems of units. These two sets of categories constitute a cross-categorization. However, I am not interested in patterns of correlations between the two sets of categories. Instead, each of them will prove useful in its own right. The first set of categories will be important when working out the ‘normative dynamics’ of the New SI and the second set will be helpful in discussing the literature.

In terms of the first issue, we find in the debate about the New SI ‘boosters’, ‘brakemen’, and, as a third category which I would like to add, ‘heretics’. These categories resemble the “adopter categories” identified by Everett M. Rogers in his classical work on the diffusion of innovations: innovators, early adopters, early majority, late majority, and laggards (Rogers 1983, 23). The boosters promote the reform as “urgently needed” and simply “logical” (Schwitz et al. 2004); they speak of a “decision whose time has come”: there is “no need to wait”, the reform should be adopted “without delay”, for there is “everything to be gained” (Mills et al. 2005). The brakemen, by contrast, hold the reform to be “not really urgent” (Becker et al. 2006, 11; Gläser et al. 2010, 420) and call for reflection: the reform “should not become an objective in itself” but rather be “based on real and practical experimental results” (Milton et al. 2006). The heretics, finally, organized on the webpage *MetrologyBytes.net*, deplore the fact that “the official committees that decide on the New SI Proposal meet behind closed doors, with observers expressly forbidden, and have refused to answer basic questions about their proposal", and declare that "many researchers feel the [official BIPM journal *Metrologia*] is strongly biased towards the New SI Proposal, and papers critical of the New SI are routinely rejected".[14] Others go further and speak of "censorship and suppression" by the BIPM. "The new SI is the culmination of decades of development by self-selecting committees in the direction of obfuscation." (Price 2012, 217–218) The rhetoric appears exaggerated, but indeed institutions tend to exclude or even discredit criticism going beyond a certain consensus.[15] Therefore there is no reason to pay less attention to this part of the literature than to the officially recognized publications.

On the second axis we can identify the participants in the debate according to the role and rhetorical strategies they adopt: there are 'rule users' who engage in the debate by putting forward arguments they simply hold to be pertinent, 'rule explicators' who try on a more abstract level to name the implicit criteria and second-order norms in the construction of systems of units (Bordé 2004; Becker et al. 2007) and, finally, 'meta-ethicists' who explicitly raise questions about these criteria, their justification and their relative importance (Milton et al. 2007, Cabiati/Bich 2009). With a view to identifying the practical constraints involved, the last two groups are the most interesting, for these metrologists are engaged, as it were, in a "sociology of themselves",[16] permitting us to pick up the relevant items directly from their texts.

4 Aims of the New SI and Dynamic Factors in Its Development

4.1 Factors Influencing the New SI

I will now identify the different constraints involved in shaping the New SI. Let me recall that the SI is a system of norms governing *practical* operations (comprising both manual and intellectual aspects) performed with the epistemic aim of knowledge production. In this sense the norms are shaped entirely by prac-

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[14] MetrologyBytes.net [27 February 2015].

[15] Foucault described similar mechanisms in 'The life of the infamous' (Foucault 1994, 237 et seqq.).

[16] Expression used by Simon Schaffer in our round table "Sociology of metrological knowledge", cf. note 1.

tical constraints, including (1) practical constraints of epistemic importance (i.e. inherently related to the aim of knowledge production) and (2) non-epistemic constraints of purely practical importance. It is tempting in a first approximation to distinguish correspondingly between ‘internal’, i.e. knowledge-related, and ‘external’, i.e. purely practical, constraints in the construction of the New SI. (We can regard the classification as provisional, for it is not necessarily *a priori* clear whether a practical constraint implied in knowledge production is or is not of inherent importance to knowledge making.) The internal factors are mainly pushing factors, since epistemic deficiencies of the SI are the main reasons for the reform. In the case of the New SI, by contrast, external factors are rather conservative constraints (mainly because of transition costs, cf. Brennan et al. 2013, section 5.3).[17]

Before going into the detail, it should be stressed that the criteria and practical constraints involved do not necessarily harmonize. Conflicts between them are to be expected, and decisions on norms can consist in trade-offs between incompatible features. (For a prototype unit, there is a conflict between stability and accessibility. In the case of the New SI, highly theoretical considerations about uniformity and coherence conflict with considerations about teaching and intuitive grasp.)

4.2 ‘Internal’ Constraints in the Construction of the New SI

The internal constraints or requirements of systems of units in general, and their specifications in relation to the New SI, can be easily extracted from the literature. They are fully acknowledged as such and explicitly quoted in debates. Surprisingly, the concepts used to denote them seem not to be fully standardized and their use remains somewhat informal, notwithstanding the remarkable preoccupations of metrologists with vocabulary (as documented in the continuing work on the *International Vocabulary of Metrology (VIM)*). A cursory glance at the current literature enables us to identify the following, partially redundant, items: (a) accuracy; stability, constancy, and durability; reproducibility, traceability, and accessibility; (b) coherence, consistency, rationality, and uniformity. The items in the first group are related directly to the role of units in measurement, i.e. to

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[17] Timmermans and Epstein only take into account such conservative and external constraints in their theory of standard-setting, which seems to me too poor to grasp the development of metrology. They write: “Depending on the process of standard-setting, standards can imply a lowest common denominator of available options, the power of the strongest party in standardization, a negotiated order among some or all stakeholders, or a confirmation of how things are already done by most parties.” (Timmermans/Epstein 2010, 79)

the reliability and precision of its results. The items in the second group are concerned with principles for the construction of systems of units out of individual units.

(1) A lack of stability is given as a key reason for pursuing the reform of the SI:

> "Measurement standards based upon material artefacts cannot provide the assurance of long-term stability and, indeed, the principal weakness of the SI in this respect is our inability to establish the long-term stability of the kilogram until such time as we will be able to define it in terms of atomic or fundamental physical constants." (Quinn/Kovalevsky 2005, 2314)

(2) Limited accessibility is a direct consequence of efforts to keep the prototype kilogram stable. Stability and accessibility thus are potentially conflicting criteria. A non-prototype-based definition of the units, however, promises in principle to solve this conflict, which is also an argument put forward in favour of the reform. The consequences of the New SI in terms of accessibility, however, have to be judged realistically:

> "For example, it is possible for quantum phenomena to provide the basis for extremely accurate and stable definitions of the base units, which are in principle accessible anywhere, but their practical application may be very limited if they can only be realized using highly complex experimentation. [… They] would lead to useful reductions in uncertainty, but provide no significant improvement in accessibility." (Milton 2007, 357)

Fig. 1. The International Prototype of the Kilogram, or: An allegory of conflicting norms. The Kilogram has to be stable (protection by the bell jars) and accessible (the grip tongs). Reproduced by permission of the BIPM. All rights reserved.

(3) Uniformity and coherence are both involved in the reform. The definitions of units gathered in the SI obviously lack uniformity: some refer to natural kinds, some to constants of nature and others even to artefacts, as is still the case for the kilogram. Authors from the conservative camp also acknowledge the “need for a general rationalization and simplification of the system” (Cabiati/Bich 2009, 458). Coherence in the technical sense explained above refers to the identity between quantity equations and numerical relations without conversion factors appearing in them, underlying the use of equations in physics. As Milton et al. (2007, 356) stress, coherence in this sense is not only a mathematical property of the SI but also a “practical” one, “to be monitored experimentally”. The difficulty of monitoring depends on the definitions adopted, so that theoretical and experimental requirements might conflict.

(4) Consistency refers to the coherence of the definitions of the units with present-day physical theory and experimental methods. Coherence in this sense is a subtle issue, brought out very clearly by Christian Bordé (co-president of the *Comité Science et métrologie de l’Académie des sciences*, Paris) who worked out three conditions for redefining units in terms of fundamental constants (2004; 2005). The first of these is related to the semantic role of fundamental constants in physical theory and is of less importance to us here. Conditions two and three are—and here it is important to quote the wording—that a “realistic and mature technology of measurement” is found and that “confidence [is] felt for the understanding and the modelization of the [underlying] phenomenon”.[18] Bordé uses both epistemic and, even more importantly, psychological vocabulary to spell out this condition (“knowledge of the whole underlying physics”, “some people still feel uncertain”, a “psychological barrier must be overcome”, we “must have complete faith”). The terms ‘realistic’ and ‘mature’ in the first condition actually belong to the same realm, since they implicitly refer to the actor's evaluation of the technology. Since we never know whether “all possible small parasitical effects have been dealt with” in the handling and theoretical understanding of a measurement technology, any decision on the definition of units is effectively a sort of bet on the future development of physics and technology.

Bordé’s analysis is of major significance for our approach as it sheds new light on the criterion of coherence or consistency with physics. Indeed the latter could have been taken as an ordinary formal criterion, like logical coherence. In Bordé’s analysis, however, the coherence criterion is in fact concerned with the question of maturity or, more precisely, with our confidence in the technology of the *mise en pratique*; i.e. it is a psychological matter. This allows us to interpret the debate to

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[18] Doubts about precisely this aspect are expressed e.g. by Khruschov 2010.

be in large part about the maturity of the new measurement techniques explored by the New SI. This strongly supports the hypothesis of a reflective equilibrium in the justification of norms, as will become clear below.

With regard to the standards of 'maturity' to be met by a new definition of the units and by the technology supporting such a definition, the main parties in the debate (identified above) adopt divergent attitudes according to which they can be ranked:

For the boosters of the reform, confidence in the future availability of new technology seems to be sufficient to support the reform. This at least can be inferred from their opponents' reactions. The brakemen, namely, criticize what they consider to be an overhasty stance, demanding that a working technology be actually at hand. Milton et al. (2007, 360) warn:

> "Basing changes to the SI on the expectation, rather than the fact, of a particular outcome for experimental results would mark a dangerous move away from it being a system that is based on a real and practical experimental basis."

One participant in a round table discussion on the New SI quotes the existing experimental infrastructure of 50 Josephson experiments, 30 quantum Hall experiments, and five watt balances as a strong argument in favour of the reform (Stock/Witt 2006, 585). Contrariwise, critics of the New SI raise questions about the reliability of the existing technologies and our theoretical understanding of the system, quoting recent advancements which cast doubt on its sufficient stability (Khrushov 2010, 588; Hill/Krushov 2013, 747). As we have seen, distrust regarding experimental designs that are too complex was similarly expressed in the debate about accuracy.

What is of interest here is the heretic's attitude. One of the critics, accusing the Committee on Units of having a "passion for quantum physics", argues in favour of a definition of the kilogram linked to the carbon atom rather than to the Planck constant—a definition which he praises for its being easily realizable in the laboratory (Hill 2012). The carbon based definition of the kilogram would make it possible to "build a simple, rough prototype in a college laboratory, or even in a kitchen sink: Simply cut a block of nearly pure carbon so that it is roughly 8.11 centimeters on a side—that's approximately one kilogram" whereas "[t]o measure Planck's constant, you need an electromechanical device called a watt balance [... which is] two stories high and requires a team of three to five experts" (Hill 2012). Hill obviously takes primitive realizability—say in a post-catastrophic situation—to be a strong point in favor of the definition he proposes. But this argument is erroneous. Why should a metric system guarantee applicability in a post-civilization scenario if its very *raison d'être* is to fit the precision requirements of our highly complex present civilization?

The heretic's 'operational fundamentalism' or 'anti-modernism' thus seems to be at odds with the characteristic normative dynamics and the shifting equilibrium between norms and practices. As we have learnt from Bordé's analysis, anchoring the units in fundamental theories cannot simply be dismissed as an irrational 'passion for theory', because the theoretical foundation has precisely the function of justifying confidence in the new technology. I think that it is this 'precarious' nature of technological progress which, on the one hand, causes the heretic's distrust and yet, on the other, characterizes the proper historical dynamics of the SI as it is revealed in the light of reflective equilibria: technological progress is robust enough to bring about a normative shift, but it is much too fast (measurement precision is said to increase by a factor of ten per decade) to prove its maturity in temporal terms of being well-established, for example. The new techniques thus are always too new and still too precarious to exert their normative force by themselves. That is why they are in need of theoretical support in order to be regarded as 'mature' and thus to develop their full normative power.

To sum up, this analysis enables us to correlate our 'adopter categories' from section 3 to different standards of maturity of technology for the *mise en pratique* of future definitions:

boosters	**brakemen**	**heretics**
confidence in future availability of technology	existence of a reliable and well-understood technology	simple and easily mastered technology

These attitudes differ only in degree, for, as Bordé's analysis has clearly shown, confidence in our present-day technology cannot be justified without limits—it is still a 'bet' on the future, as I called it above.[19] Today's technology may, and surely will, in future lay bare its previously unknown shortcomings and fall short of future requirements of precision. Nevertheless even the more hesitating among the metrologists, the brakemen, do not demand more than the bare existence of technology in the form of a well-established practice for justifying the reform of the SI, and the reform which is underway today will surely settle somewhere around

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[19] The uncertainty affects not only the *mise en pratique* but also the abstract definition, as becomes clear from the following quotation: "The objective of the proposed changes is to adopt definitions referenced to constants of nature, taken in the widest sense, so that the definitions may be based on what are *believed* to be true invariants." (Mills et al. 2011, 3907, my italics)

the middle position. I consider this to be a strong hint in favour of the model of reflective equilibria, for it shows that the justification of norms in this case relies on established practices, not less (confidence in future technology) and not more (absolute confidence in simple technology).

4.3 'External' Constraints in the Construction of the New SI

I will now briefly mention the 'external' constraints, i.e. those which are presumably not inherently linked to epistemic aspects of measurement and thus are probably not important for the justification of epistemic norms in the sense of reflective equilibria, though they may shape them in important ways. Four such constraints can be identified in the debate: everyday life, industrial production, teaching, and metrological working routines.

(1) Everyday life weighs heavy on the current reform, albeit in ambiguous ways. On the one hand, the 'mundane' world constitutes an important conservative constraint in the sense of sources of norm persistence, as discussed by Brennan et al. (2013, section 5.3). The transition costs of a change in size of the kilogram would be extremely high, for example. Hector Vera has argued that it needed a profound political revolution to establish the metric system, one which affected all aspects of the units: sizes, names, definition and decimal subdivision (Vera 2015). The director of the BIPM, Milton, emphasizes:

> "Since the SI is a practical system that is used worldwide, the reasonable scope for changing it must avoid leaving large numbers of users with obsolete implementations or significantly changed values. Changes that go beyond these limits would require consultation processes that might take decades and whose cost and complexity would be difficult to justify in view of the likely benefits." (Milton 2011, 575)

The BIPM published a *FAQs about the New SI*, the five first questions of which are aimed at reassuring the general public that the reform will affect neither the names, magnitudes and subdivisions of the units nor the choice of base quantities and coherent derived units, i.e. that the reform will effectively be 'invisible' to them.[20] Metrologists are anxious to show the harmlessness of the planned revolution:

> "For almost all practical applications of the SI by scientific and technical users, and for everyday commerce in the market place, the changes in the definitions of these four units will be of no consequence. Only for the most precise experimental measurements will the

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[20] http://www.bipm.org/en/measurement-units/new-si/faqs.html [March 2015].

> changes matter, and we believe that, in these cases, the new definitions will be more robust, more fundamental and better suited to new scientific developments." (Mills et al. 2011, 3909)

This constraint thus blocks one dimension of the units—their size—but does not directly affect the current reform.

(2) Industrial production, on the other hand, may become more aware of the SI. As a representative of one manufacturer of precision calibration instruments reports in a round table discussion on the New SI, some manufacturers have begun to realize SI units directly instead of addressing an accredited laboratory. However, "[r]edefinition of the measurement parameters without shifts in their values will have little impact on industry" (Stock/Witt 2006, 586).

(3) There is another easily overlooked external constraint which may yet be of great importance: teaching and communicating the New SI. Hector Vera stresses that pedagogues, though neglected from a science-centred point of view, are crucial to any social order (Vera 2007b). Metrologists, however, seem to be quite conscious of this and stress that "any new definition must be comprehensible to this audience [the wider community of scientists involved in using and teaching the principles of the SI] to avoid breaking the perceived link between practical measurements and the SI" (Milton et al. 2006, 356). Critics regret that they "are not aware of any proposed simple laboratory experiments that students and university professors can use to construct a rough approximation of a kilogram mass based on [the new definitions]", as it would be "of utmost importance to future generations who will use the SI" (Hill et al. 2011, 85–86; this attitude echoes, of course, the critical stance vis-à-vis advanced technology discussed above). The concerned public is quite heterogeneous and generally consists of more than just scientists: "the NMIs need to issue a document that explains the changes in layman's terms that the manufacturers can readily understand" (Stock/Witt 2006, 586). Cabiati and Bich propose definitions the understanding of which "does not require any scientific knowledge [...]. This could be appreciated in legal circles, where the units to be used in trade must be compulsorily prescribed" (Cabiati/Bich, 2009, 459–460). Some metrologists—and the heretics too—find it more "natural" (Khrushov 2010, 588) or "obvious" (Becker et al. 2007, 5) to link the mass unit to a natural mass standard such as the C14 atom rather than to a natural constant like the Planck constant *h* which is more difficult to grasp on a conceptual level and also generally involves more dimensions than the one of the unit to be defined (for example, the speed of light, used to define the meter, is of dimension LT^{-1}):

> "If the kilogram is defined by fixing the Planck constant and by addressing a photon collection, we would not have any evident mass reference; speaking of mass in terms of frequency would be difficult to understand." (Becker et al. 2006, 10)

This case is interesting because it is a case of conflicting criteria and theoretical considerations (i.e. considerations related to questions from physical theory) on the one hand and teaching requirements on the other. This conflict is highlighted in a dramatic manner by the heretics (Hill 2012), but is also recognized by proponents of the reform:

> "Further, since it is important that the basis of our measurement system be taught in schools and universities, it is preferable, as far as modern science permits, that the definitions of base units be comprehensible to students in all disciplines, a requirement that becomes increasingly difficult to achieve as science advances." (Mills et al. 2006, 228)

Educational requirements thus might influence the choice of a new definition for the kilogram.

(4) A further constraint characterizes the working routines of metrological institutions. Replacing the prototype kept at the BIPM with a unit which, in principle, can be realized "by anyone at anytime and at anyplace with the required uncertainty" (Mills et al. 2005, 75), has major consequences for the metrological institutions. Using the terms of sociologist of metrology Joseph O'Connell, we can speak of a "Calvinist reformation in metrology":

> "For one, direct contact with the [standard unit] is now available to everyone in principle, and to a growing number of laboratories in fact. Two, the organization that previously mediated contact between the highest authority and those that require contact with it has stepped aside and offers its clients a method for achieving this contact themselves. And finally, the philosophy of intrinsic standards [i.e. abstractly defined units] [...] has no provision for periodically correcting drift in the new intrinsic standards because they are thought not to drift. Noticeably absent from the metrology of intrinsic standards is the periodic sacramental redemption from error that equally mark the Catholic theology and the metrology of artefact standards. Instead, the judgement of whether the intrinsic standard is good or bad occurs only once, when it is built, and there is no recognition or provision that correction or comparison, or contact of any sort with the higher authority, will be needed again." (O'Connell 1996, 154)

Indeed the New SI would redistribute the work load to the NMIs which would acquire greater significance but would also have to engage in expensive experiments. On the other hand, the 'church', i.e. the BIPM, is far from losing its power in this "Calvinist reformation". Thus it is suggested that, "for the value of a primary standard to be recognized by metrological organizations [...] an international and independent institution such as the BIPM"—and that actually means none other than the BIPM itself—should organize the necessary comparisons between the NMIs, watch over the travelling standards circulating to this end among the latter, and make the reference values available to those NMIs not taking part in the comparison (Cabiati/Bich, 2009, 463). Institutions beyond the NMIs will be affected as well. Since in the New SI the prototype no longer defines but only realizes the unit, an uncertainty will be attributed to it which then spreads along the whole traceability chain. Some metrologists count this as a "cost" of the reform (Mills et al. 2005, 74). According to 'brakemen' Glaeser et al. (2010, 426), calibration laboratories could lose their accreditation as a result, and the quality of scientific research and commercial products risks going into decline. What actually seems to happen in a decentralized (or less centralized) metrological organization is a quite complex 'economy of uncertainty', in other words, assigning the uncertainty to a place where it can be handled best and where metrologists consider it to be less harmful in the overall process of constructing, guarding, distributing and tracing units.[21] It is interesting for us to note that, as a consequence of the reform, calibration laboratories risk losing their accreditation; that is, some measurements would no longer count as measurements with sufficient precision. This is a close approximation of the feedback effect in reflective equilibria, i.e. changing evaluations of the practice in the light of revised general rules.

All in all, the rigidity of the organization of metrology—due to institutional inertia but also to financial constraints—could be an important conservative constraint in the reform of the SI. The boosters of the reform tend to avoid mentioning these disadvantages for metrological practice, preferring to highlight the expected advantages (Mills et al. 2006, 238).

5 Conclusion

What I have sought to do in this paper is to read the history of systems of units and, in particular, the current reform of the SI in the light of reflective equilibria. I take this to be a more easily accessible case than logic or ethics for, unlike logic, the underlying practice—precision measurement—is continuously shifting and, unlike ethics, advancements can be identified unambiguously in terms of degrees of precision. We can thus easily see changes in the underlying practice and can study the ways in which the 'principles' (the units) are readjusted accordingly. The same holds true, of course, for the feedback effects of these readjustments on

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[21] For an idea of this 'economy of uncertainty', cf. Davis 2011.

measurement practice. Let me offer an overview of the peculiarities of the case of the New SI:

	Goodman's sketch	Present case-study
Field:	logic	metrology
Type of rules or norms: ('top level')	rules of inference	units as measuring norms
Type of validity:	logical validity	epistemic validity, precision measurement
Underlying practice: ('bottom level')	inferring	Measuring quantities and constructing units ('*mise en pratique*')
Status of the norms:	first codification	revision of an existing codification
Criterion for normative force:	'reliability', probably to be spelled out in terms of stability in time	'maturity' (which does not become evident in historical continuity, however, but has to be argued for theoretically)
Type of reconstruction:	hypothetical, speculative	empirical
External constraints:	not mentioned	various

In the current reform of the SI, the units (i.e. the epistemic norms in question) are readjusted in response to the demands of contemporary technology and technology-based research. More specifically, this study of what I called the internal constraints of the reform has shown that, in the debate on the New SI, technology, as a common practice of science and metrology, plays the role attributed to it in the model of reflective equilibria, i.e. it serves as a basis for the justification of norms. It is thus attributed a normative authority insofar as the practice is sufficiently established and, in the case of metrology, theoretically understood. One important outcome from this analysis is that the debate accompanying the current reform of the SI can be understood as being essentially about the 'maturity' of the new measurement technologies. On the one hand, the new technologies need to be backed up by arguments given that technology is developing rapidly (measurement precision is said to increase by a factor ten per decade) and the techniques in question are thus too new to exert any normative force by themselves. On the other hand, technological development is intertwined with theoretical insights from physics, and new theoretical developments make it possible to argue for the maturity of a measurement device which can then exert its normative power in the reflective equilibrium. This is the normative flux from the bottom to the top level. The reverse flux has also been observed, though: the established metrological practice is partially revised in the light of the new measurement principles. Some measurements risk losing their status as approved precision measurements. This effect is referred to as a 'cost' of the reform. As might have been expected when applying Goodman's model to an empirical case, additional constraining factors also became apparent alongside these classical ingredients of reflective equilibria. I have referred to them as 'external' constraints: measurement in everday life, in industrial production and in teaching, and also institutionalized metrological working routines.

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