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METROLOGY AND VARIETIES OF MAKING IN SYNTHETIC BIOLOGY

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INTRODUCTION

In *The Logic of Modern Physics*, P.W. Bridgman proposes an understanding of metrological concepts based on the operations necessary to produce measures. A metrological concept (such as length) has meaning because and *only* because there exists a 'set of operations by which [the measure] is determined'[1] (such as laying measuring rods end to end or using the reflection of a laser). The concept and the operations are one and the same; a change in operations results in a change in concept (thus, rod-length and laser-length are not the same thing). This perspective shares much with J.L. Austin's view on certain linguistic acts[2]; simply stated, measurement operations are performative of measurement concepts. In this volume, Martin Kusch examines Wittgenstein's views on measurement to similar effect[3]—acts of measurement define and sustain concepts of measurement. As a result, Kusch argues, communitarian epistemology and the sociology of knowledge are useful traditions with which to examine metrology. Here, I use a case study from synthetic biology to demonstrate that metrological practices make more than just concepts. They also define fields, their members and their objects.

Bridgman's operationalism[4] examines how acts and concepts of measurement come into being together. My study demonstrates that the consolidation of a field, the making of uniform objects, and the normalization of metrological practices are different facets of a single phenomenon: the making of a metrological community. Using communitarian epistemology and original empirical research, I establish two points. First, to understand metrology is to understand a metrological community. Second, to understand that community is to understand how its practitioners, their work and their objects are ordered. Thus: to understand metrology in synthetic biology is to understand a community dedicated to proper engineering; to understand that community is to understand an engineering-based ordering of the collective, its objects and its participants' acts.

The study

The empirical material I present here is the result of an eighteen-month ethnographic investigation of a synthetic biology laboratory in the United States. During that time, I worked alongside the unit's researchers and interacted formally and informally with them. I carried out interviews with individuals from my host lab and its partner lab, which shared space, equipment and some personnel with my own. I also studied other laboratories at seven different institutions in the United States through short-term ethnographic research and in-depth qualitative interviews. In total, I carried out 24 such interviews. Moreover, I attended events central to synthetic biology, including: the Fifth and Sixth International Meetings on Synthetic Biology; research networks meetings such as those for the US Synthetic Biology Engineering Research Centre; and the yearly undergraduate International Genetically Engineered Machine competition.

SYNTHETIC BIOLOGY AND ENGINEERING: CONSOLIDATING THE FIELD

I begin by describing the relationship between synthetic biology and engineering. Synthetic biology is an unsettled, heterogeneous field.[5] At present, it is not characterized by any single identity, nor does it have definitive practices, concepts and goals[6] – in many ways it is 'all things to all people'.[7] Those who self-identify as synthetic biologists come from a range of disciplines and employ a variety of ideas and methods to achieve a diversity of aims. Nonetheless, factions exist within this community that display greater coherence. The most prominent of these, and the one I explore here, wants to make synthetic biology into an 'authentic' engineering field: to consolidate the community around a shared set of engineering principles, practices, aims and expectations.

Members of the engineering contingent have published a number of review articles in which their broad mission – the consolidation of the field using an engineering mould – is expressly articulated. For instance, Endy argues that the basic target of the field is to 'make the engineering of biology easier'.[8] Similarly, Heinemann and Panke claim that synthetic biology is about 'putting engineering into biology'.[9] My interviewees expressed similar views.

For many of those I interviewed, engineering (as target and as practice) is vital to the identity of synthetic biology. Karen[10] is a principal investigator and dedicated champion of synthetic biology. Her laboratory's research aims at advancing the engineering capacities of synthetic biology. Some of the research seeks to produce so-called foundational technologies – tools to facilitate future work along engineering lines. When I asked her to describe synthetic biology, she replied:

> … I, first of all go back to how we defined it ten years ago. Which was a group of computer scientists and bioengineers, asking a simple question, which was, "how can we make biology easier and more predictable to engineer?" And that was the basis for forming synthetic biology. As far as I am concerned, end of story.

As do the authors I mention above, Karen describes synthetic biology as an engineering field with engineering goals and an engineering pedigree. For her, engineering is so vital to the identity of the field that she reduces all of synthetic biology to its engineering target (' … end of story … '). Karen also explained the importance of 'authentic' engineering as a mechanism for differentiating the field from the already-existent genetic engineering. Setting and securing synthetic biology's identity depends upon establishing such a boundary[11] – a border defined by engineering.

Members of synthetic biology's engineering contingent routinely portray genetic engineering as not authentically engineering, unlike their own field. Gary, another principal investigator, argues that the field will practice and produce as do disciplines like civil, electrical and mechanical engineering. His laboratory makes basic tools and techniques for synthetic biology: mechanisms that enable the rapid assembly of small segments of DNA and reduce the unpredictability of functional constructs, and conceptual tools that make the design of biological technologies easier to carry out. He has argued in publications that synthetic biology will replace the craftwork of genetic engineering with the systematic rigour of established engineering. When interviewed, he made this same point:

> So I think, there's that idea of putting the engineering back into genetic engineering which is, you know, turning it into something very formal, theoretical, having a theoretical frame for how to do it. I think, that is a very real aim of the field.

Gary's view that synthetic biologists must follow a particular type of conceptual scheme and carry out specific forms of practice is shared by those who sponsor the engineering view of the field. It is also the primary method by which practitioners draw boundaries between their work and that of genetic engineering.

Barry, whose work on mechanisms for failure prevention in biological technologies is based in great part on systems and control engineering, also articulated a sharp distinction between synthetic biology and genetic engineering. For him, the latter has too little engineering:

> They call it genetic engineering, but for example, they are not necessarily engineers doing that, they are a scientist … [synthetic biology] is bringing a lot of engineering to the table of

> what we can do with biological circuits. Just the word "circuit", is an engineering concept, it is not something they are going to actually use in traditional biology.

Science and engineering are distinguished by an important boundary, Barry argues. To justifiably lay claim to the identity of 'synthetic biologist', a practitioner must position herself on the appropriate side of that boundary. Michael, a postgraduate student at my host laboratory, expressed a similar view. The transition from genetic engineering to synthetic biology, he states, involves moving away from science. Though the field begins 'with people just doing something based on science 100%', Michael says, practitioners will with time 'know more and more engineering principles', which will enable proper engineering practice and through it, the making of a proper engineering field.

The engineering ideal also serves as a normative guidepost for individuals within the community. Practitioners must position themselves and behave in ways that satisfy engineering expectations; valid members of the community are those who demonstrate engineering praxis and ethos. Robert, a principal investigator who loudly advocates the engineering vision, argues that what 'distinguishes synthetic biology from the broader field of biotechnology … is that it does a better job of recognising what a great engineer is all about'. That is, synthetic biology employs normative criteria common to traditional engineering. Important here is the production of enabling technologies, Robert says:

> A great engineer doesn't just deliver a technology that solves a particular application … a great engineer will develop tools that make the solving of all problems of that similar category, the same category, easier … a great engineer will deliver the application, but actually, will make it easier to deliver on all sorts of applications in the future.

For Robert, the quality of a practitioner in synthetic biology depends upon her willingness and ability to advance the field *as an engineering discipline*. For him, as for others in the engineering contingent, this involves delivering foundational technologies. Crucially, individuals' behaviour and membership is to be evaluated following an engineering ideal. Practitioners are rewarded and sanctioning according to engineering norms.

In summary, synthetic biology is to be proper engineering and its practitioners are to be proper engineers. The field's boundaries are set according to conceptions of engineering. Its members' behaviour is to be evaluated according to engineering norms. The field and its members' practices are to be ordered in an engineering fashion.

SYNTHETIC BIOLOGICAL PARTS: MAKING OBJECTS UNIFORM

For advocates of the engineering ideal, making synthetic biology an authentic discipline of engineering involves nothing more than enabling authentic engineering practice: Heinemann and Panke argue the two are 'synonymous'.[12] This latter goal demands a series of so-called foundational technologies: tools that can 'make the design and construction of engineered biological systems easier'.[13] Of these, the making of modules for construction – synthetic biological parts – has received considerable attention.[14] Such modules are to be the nuts and bolts of synthetic biological artefacts. They are to be physically and functionally uniform and their use is to be routinized.[15] Importantly, the objects are to satisfy an engineering order.

Because being engineering means *doing as* engineering, the making of standardized parts is involved in the setting of boundaries and the demarcation of synthetic biology as something other than genetic engineering. Juliet, a renowned principal investigator, oversees a range of projects all aiming to deliver new, engineering-focused tools and techniques, including foundational technologies. When asked about the identity of synthetic biology, she replied:

> So, to me, that specific sort of, focus on the application of engineering principles, and the development of sort of, foundational tools, is something that really sets synthetic biology apart …

For her, the making of enabling technologies defines the field. A similar, but more specific argument was made by Andrew, another prominent synthetic biologist. More than others quoted here, he pursues the making of products for commercial ends. To his chagrin, his research is often classed as genetic engineering despite his own self-identification with synthetic biology. During the interview, he argued vehemently for his place in synthetic biology by emphasizing the importance of and his commitment to standardized parts. He said:

> … genetic engineers or the molecular biologists, I think, don't think about modular parts and standardised parts, and assembly of parts … I think the mindset is different. And so, it is about the engineering, for me.

Andrew points to how practice distinguishes fields and establishes disciplinary identities. In so far as engineers practice differently from scientists[16], the making of uniform parts serves to set boundaries between what synthetic biology hopes to be and what it sees genetic engineering as being right now. Being engineering is *doing as* engineering and *having as* engineering: producing and having access to standardized parts.

Crucially, parts are to be characterized. According to their advocates, synthetic biological parts are to display '"plug-and-play" compatibility'.[17] That is, parts are to feature reproducible and robust functionality – predictable utility. Enabling such performance demands making parts of a kind uniform and producing reliable descriptions of each kind. Parts must be rendered physically and functionally standard and then characterized using shared descriptors. Without achieving both aims, users would be unable to choose appropriate parts for specific needs, nor could they expect predictable, reliable performance: parts would not be uniform. Fulfilling these two goals still presents sizable difficulties. Rose, a doctoral student at Karen's laboratory, argues:

> … as much as people in the field like to talk about, parts are characterised and they are going to be standard, and so we can share them, and you'll know how it works because I measured it, and then you'll know how it's going to work in your system. One of the difficulties is that, that type information that those quantitative descriptions, that just doesn't exist for most parts. And even if it does exist for a part, more often than not, the way that it was quantitatively described or characterised, would not be applicable to how you're going to use the part.

Parts are not sufficiently standardized, nor are the methods for satisfactory quantitative characterization yet in place. Frank, a principal investigator whose laboratory works on tools for measuring, modelling and analyzing living systems, concurs: 'everyone in synthetic biology agrees that we are not characterizing things well enough'. Data sheets reporting the behaviour of individual parts do not exist for all parts. Attempts to produce a central database for such information (or even the parts themselves) have not succeeded as hoped. Last, methods for developing quantitative measures – metrological practices – have not been adequately normalized.

An example of parts characterization in synthetic biology may serve to illustrate the relationship between characterization, quantification and metrology. Research at the BIOFAB, a synthetic biology centre in California, has attempted to standardize and characterize transcriptional promoters[18]. Promoters are genetic sequences that trigger and drive the transcription and translation of other sequences. In a sense, they are parts that operate as on/off switches. The BIOFAB's characterization of commonly-used promoters employed fluorescent reporters in order to measure the intensity with which different promoters drive transcription and translation. Promoters were paired with a gene that triggers the making of a fluorescent protein. 'Stronger' promoters cause more of the protein to be produced; thus, by measuring the fluorescent intensity of a colony of organisms transformed to carry the promoter-fluorescence construct, researchers can infer the strength of each promoter. A quantitative measurement of fluorescence helps practitioners characterize promoters according to each part's strength. *Quantification* of fluorescence, a practice in *measurement*, supports a particular (and here the preferred) type of *characterization*. Moreover, these three practices contribute to the ordering of parts: such-and-such a promoter is stronger than another.

In summary, the objects of synthetic biology are to be made uniform as objects *of proper engineering*. Their design, construction, evaluation and use are to be ordered in an engineering fashion. A crucial aspect of this is quantitative characterization – a practice that requires normalized engineering metrology.

BRINGING MEASUREMENT TO LIFE: NORMALIZING METROLOGY

Rose and Frank's frustration with missing metrology is shared by many in synthetic biology. For these researchers, making uniforms parts and consolidating the field as one in engineering demand normalizing metrology: developing standard measurement operations and making their use routine.

Recall that constructing synthetic biology's engineering identity involves distinguishing it from efforts such as genetic engineering. Karen, quoted above, argues that such research in biotechnology has been 'a little non-quantitative and a little bit *ad hoc*'. For her, the two flaws must be resolved together: enabling systematic design and construction requires quantitative measurement. Frank makes a similar point:

> I don't think it is so hard to build something, it's hard to build something that you know works or, again, because we probably just have such bad assays. And we don't even know so much what we are trying to measure.

Making technological artefacts is to be a defining feature of the field as one in engineering. Importantly, it is a pursuit that demands shared metrology. To do what it wants to do and be what it wants to be, the field must come together in measurement.

My interviewees presented a number of reasons for the current lack of metrological capacity in synthetic biology. For instance, Frank pointed to the recalcitrant and unpredictable character of living nature. More importantly, practitioners discussed the absence of metrological standards. Andrew, quoted above, says:

> So, say you do fluorescent measurement on this machine, you go to the next machine that is sitting right beside it, it could be very different. You could go to your colleague, a few cities away, and do the measurement, even more different, right?

Metrological contingency is a serious challenge to synthetic biology, particularly when there are no set ways of carrying out particular measurements. Juliet says:

> … people all sort of, have their favourite way of, you know, measuring something. You know, and maybe they don't have the exact same sort of, measuring devices in their laboratory, right? Meaning, some people might have a very nice, sort of, right, flow cytometer that allows them to do multi-colour analysis … Other people might only have like, a luminometer, right, or something to do beta-gal ... So that can make it hard, right, to sort

> of, standardize measurement, so require the people to measure things in a specific way. It is also the case that, even sometimes, the set-up of these instruments is different because you set them up in different ways, and you set gains and all this other stuff in different ways, right?

Local variations in equipment, preferred methods, requirements and aims result in a lack of metrological consistency. Measuring a basic characteristic of a synthetic biological part, such as the activity of a transcriptional promoter, can be done in a number of ways, each of which requires a different set of procedures and instruments. At present, no single method has a definitive lead over the rest, much less is any the established method for the field. Lack of consensus is the problem.

The need for metrological consensus came up repeatedly, often as a crucial hurdle for the field. Karen made this point when I asked about synthetic biology's metrological capacity:

> We can measure lots of things. I mean, we can measure single molecule levels in cells. We are really good at measurement … So, ways to measure things are always, that's a big part of technology right now. So, that's a very rapidly moving area, there will be no worries there. The question is, do we actually need all those measurements?

Karen argues that the capacity for precise and useful measurements exists, but there is too much variety in methodology. She identifies a fundamental problem: too much is measured because there is a lack of agreement about what to measure. Not enough attention is paid to what kinds of measuring are necessary, which are not so, and which needed kinds are currently unavailable. Advancing the field as one in engineering demands communal answers to these queries.[19] The problem is not one in technical capacity, but one in collective agreement.

Unfortunately, collective agreement – consensus about what and how to measure – is lacking. Nick, a postdoctoral researcher at my host laboratory, argued that agreement is both absent and necessary. He said:

> … in terms of standardization of measurement, it's a shambles, I would say, right now. There needs, there definitely could be more standardization … And it is going to require, you know, organization, because it is a lot harder. You know, it's a lot harder to be strict about how you measure things, the way you measure it. A lot of biologists, I think their tendency is to just get it done and not worry about, you know, how, somebody else can be able to compare my numbers, you know, five years down the road.

Nick points to the lack of metrological consensus and the importance of communal organization in order to enable agreement. Conventional practice in biology, he argues, does not encourage (much less demand) the type of metrological consistency that is common to established engineering disciplines. Simply stated, metrology is to play an important role is establishing synthetic biology as a field in engineering and one distinct from biological sciences. Its disciplinary character and metrology are entwined.

Other interviewees pointed to important structural difficulties that lead to metrological inconsistency and a lack of work to remedy this fault. Gary, Frank and Andrew all suggested that the field lacks practitioners willing to perform metrological research because such work is undervalued by the broader scientific community. Frank argued that without 'a link between high quality characterization of parts and getting a paper published in *Nature*, the field may not care as much'. He asks, 'where do you publish datasheets? How do you get academic credit for making datasheets?'. Simply stated, it is unlikely that practitioners will carry out difficult work that goes unrewarded or does not lead to professional advancement. Lucy, a doctoral researcher at Karen's laboratory, argued similarly. Parts characterization and measurement are vital to the development of synthetic biology, but achievements in this domain are 'not a good Ph.D. thesis anymore'. The research is not encouraged or admired. Thus a structural feature of the field – metrological research is not regarded highly or rewarded well – discourages important, necessary work.

A second structural challenge is important. At present, no central facilities exist to construct, characterize and validate parts. Whenever a component is borrowed, the borrowing laboratory must repeat key measurements anew. The alternative, argues Frank, is to 'rely on what some other lab may have said, which may or may not be reliable'. Metrological inconsistency and the lack of broadly respected providers means that one laboratory cannot trust the parts or measures produced by another. The objects intended to be the nuts and bolts of biological engineering cannot be used as are nuts and bolts in mechanical engineering. Rose, the doctoral student quoted above, says that 'something that is fairly frustrating is that, you often have to characterise everything yourself, at this point'. Central facilities and shared providers will not resolve all of these issues instantly. 'There will always be trial-and-error', Lucy argues, but 'it would be great to … start with something that's a little better understood'. Put otherwise, it would be great to practice as do established engineering disciplines: with no lack of 'trial-and-error'[20] but with much material and metrological consistency. Frank, Rose and Lucy are noting a lack of trust in the reliability of measurements and the performance of parts. Again, these problems have everything to do with lack of communal agreement. While technical challenges exist to making parts and measures uniform, the greater challenge is to do with consensus.

In summary, metrological practices are both necessary and currently unsatisfactory in synthetic biology. The key problem is the lack of metrological consensus in the community: measurement needs to be normalized and coordinated collectively.

MAKING MEASURES, MAKING THINGS, MAKING FIELDS

The three preceding sections have established three claims, respectively. Synthetic biology intends to consolidate itself as a field of engineering. It intends to produce uniformly engineered objects. It intends to normalize practices of engineering metrology. These three aims are facets of a broader process: the making of a metrological community.

Martin Kusch, in his comprehensive presentation of and argument for communitarian epistemology, writes:

> To understand knowledge is to understand epistemic communities; and to understand epistemic communities is to understand their social and political structures.[21]

My argument here follows directly from this claim. *To understand metrology is to understand metrological communities.* This is the case both because metrology, like knowledge, exists only in and through social collectives, and because metrology in turn serves to order the community, its objects and its practices.

Consensus and community in measurement

The sociology of knowledge and communitarian epistemology stress that knowledge is a collective good. Knowledge presupposes the existence of 'a plural, communal subject, a "we"'.[22] It is because any such 'we' exists that knowledge claims can be established, justified, and transmitted; it is because any such 'we' exists that correct and incorrect uses of knowledge claims can be distinguished; and it is because such 'we's' exist that there can be multiple, incompatible, and internally-consistent bodies of knowledge. So too is the case with metrology. In his contribution to this volume, Kusch makes this point in advocating 'metrological relativism'.[23] The validity of metrological systems is established through social consensus; any single act of measurement is correct in so far as it meets collective approval (or put otherwise, avoids sanctioning by community members); and different collectives can give rise to incompatible, internally-consistent metrologies. Thus communities – and specifically, agreement within a community – enable particular systems of measurement to exist and persist.

Consider synthetic biology. This group's desire to consolidate the field around a shared set of engineering principles, practices, aims and expectations characterizes the type of metrological work these researchers seek to enable: *engineering* metrology. Were this community seeking a different disciplinary end, its metrological ambitions, concepts, practices, instrumentation, and norms would be correspondingly different. So too would be what measurements are considered valid, how they are validated, and when consensus is reached or missed.

I submit that metrological consensus can also work to bring a community into being. Thus while metrologies are the result of social agreement and are shaped by the conventions of each collective, as Kusch agues, they can also contribute to bringing such communities into existence. Most broadly, this is the case because of synthetic biology's unsettled and heterogeneous character at present. If metrological consensus can be accomplished, it will serve as an act (ideally, one of several) in unifying disparate practices and practitioners. However, there exist more nuanced reasons for the potential of metrological consensus to help consolidate the field. Recall that synthetic biology is to *be* engineering by *doing as* engineering. Heinemann and Panke write that 'to be successful as an engineering discipline, synthetic biology will need to repeat the corresponding developments of its sister engineering disciplines'.[24] One such 'development' is the production of metrological tools and techniques of the kind 'widely used in the electrical, mechanical, structural and other engineering disciplines'.[25] My interviewees repeatedly identified quantitative measurement and characterization of objects as necessary capacities for making synthetic biology into a field of engineering. They also emphasized that a lack of metrological consensus is the key problem facing efforts to establish engineering measurement in synthetic biology. Without a standardized and broadly accepted system of measurement – without normalized metrology – necessary advances in this craft will not come to pass. Without this craft, attempts to establish synthetic biology as an engineering discipline will not progress.

At present, there exists no metrological consensus in the field. Should such agreement come to pass, it will assist in the making of field that remains still in-the-making. Metrological consensus will help bootstrap the discipline into being, order that discipline once it exists, validate its status as engineering, and sustain that status over time. It will not do this determinatively, nor will it do it alone, but such consensus will assuredly help the process along. The interviewees suggested a plethora of ways in which this is to happen. Bringing systematic, quantitative procedures to synthetic biology will help make rigid the boundary between this field of 'proper' engineering and existing ventures in genetic 'engineering'. Quantification of the field will advance its similarity to established engineering disciplines. Shared metrological practices – consensus – will help unify the field's currently heterogeneous population along engineering lines. This same consensus will help mould members by sanctioning individual deviation from the engineering ideal. Put otherwise, metrological consensus will act to establish, validate, order and sustain a community. *Making measures and making the field are tied together.*

Making measurable objects

Making sense of metrology is making sense of communities. All communities have their objects: some because they produce them, all because they have shared conventions about how to make sense of entities and phenomena. Kusch argues that there exists no knowledge of natural things 'without knowledge about communally instituted taxonomies, standards, and exemplars'.[26] In looking out my office window, I make sense of this object facing me through a classificatory system specific to my community. Because I am familiar with my community's kinds, have exemplars for each, and can be corrected by others when I stray from shared beliefs, I can make sense of the object as a 'tree'. Absent my community or if I should belong to another, the object would fall under different taxonomies, and I would make sense of it in a correspondingly different way. It is in this sense that communities have their objects. Our knowledge – a collective good particular to a community – makes objects intelligible. Importantly, Kusch tells us, this knowledge is not a detached description of things out there; beliefs 'shape their referents'.[27] Our empirical beliefs 'concern both what is and what ought to be', and thus they 'fit the world only because they also form the world'.[28] Communities engage their objects in ways particular to the beliefs that render those objects intelligible. So too is the case with measurement and metrological communities, which render, order, and validate objects.

Synthetic biology hopes to be in the business of designing and fabricating technologically-functional biological artefacts. Doing so involves planning and producing material entities, as well as rendering such entities intelligible in particular ways. That is, the field's objects must be *made* in the ordinary sense and in the sense of being placed within an ontological order.[29] Metrology plays a role in both.

Above, I presented practitioners' views that quantitative measurement is a key capacity for enabling synthetic biology to produce functionally uniform and operationally reliable parts *in an engineering fashion*. The researchers made similar claims regarding the technological products those parts are intended to underpin. *In engineering*: designing material technologies involves quantitative specifications of form; producing technologies involves ensuring that those specifications are met as accurately as is necessary; and evaluating produced technologies demands quantitative tests of performance. These activities all involve measurement. Moreover, the very material constitution of objects will be shaped by engineering metrology. After all, the objects to be measured must be made physically capable of being measured in the first place (say, by incorporating reporter genes). Thus, communal expectations of measurability affect both the manner in which objects are to be made and the form those objects are to take.

Measurement is also involved in rendering objects intelligible as objects of 'proper' engineering. Things are intelligible to us in particular ways because of our communally-instituted beliefs. Synthetic biologists view biological things as objects of engineering: usable substrate for an enterprise in technological design and construction.[30] They are engineering and 'engineerable' objects. To bring engineering metrology to bear upon biological entities is to understand these as measurable objects. Most basically, because they are subject to the concepts and practices of a particular metrology: they can and are to be measured. More significantly, their intelligibility is structured according to quantifiable parameters of design, construction and performance. Objects can and are to be understood by way of quantitative datasheets.

Enabling intelligibility is the core, but not sole, manner in which metrological communities order their objects. Advocates of engineering in synthetic biology seek to make 'well characterized parts'.[31] Characterization involves quantitative measurement of parts' performance and will produce datasheets. Practitioners will use these to order parts according to function and behaviour: such-and-such part does X function at a rate of Y. What is measured and how it is measured will be employed to organize functional components, as happens in established engineering fields. Doing so produces pragmatic taxonomies designed to enable the design and production of technologically-functional artefacts.

Last, objects are to be evaluated following metrological norms. Their validity as 'proper' objects of engineering follows from their measurability. Inferior parts are those not yet or incapable of being given quantitative characterization. Satisfactory, usable parts are those with sufficient quantitative characterization. Proper engineering produces objects that can be understood and evaluated using systematic quantitative metrology. Thus to be proper objects, synthetic biological technologies must fit this requirement.

Following Kusch, metrological beliefs and practices concern both what is and what ought to be. Synthetic biological objects are to be quantifiable entities of engineering. Their shape, the ways in which they are made, how they are to be understood, ordered, used and evaluated all reflect the metrological particularities of this community. *Making measures and making objects are tied together.*

CONCLUSIONS: MEASURING AND MAKING

Those I studied define the boundaries of synthetic biology, as well as inclusion and exclusion in the field, following a conception of engineering. For them, the field is to be consolidated following an engineering order. The objects of synthetic biology are to be made uniform as engineered and as *of* engineering. Their form and ontology are to follow an engineering order. Measurement in synthetic biology is to be normalized – homogenized and made routine – according to an engineering mould. The goal is ordering measuring practices as do established fields of engineering. All three things – field, objects and practices – are to be structured and validated as facets of 'proper' engineering.

Importantly, each variety of structuring and validation is entangled with the other two. Success in engineering metrology will allow objects to be validated as properly of engineering. Success in producing proper objects of engineering will validate the field as one authentically in engineering. Measuring contributes to the making of things, which in turn helps establish the field. Normalizing metrology, making objects uniform, and consolidating the field are different facets of a single enterprise: the making of a metrological community.

This provides us with a compelling communitarian elaboration to the ideas with which this article began – arguments from P.W. Brigman's operationalism. Bridgman proposes an understanding of metrological concepts based on the operations necessary to arrive at a measure.[32] Shared measurement operations bring a shared concept into being. My work with synthetic biologists shows that metrological consensus – collective agreement about what and how to measure – also brings into existence a metrological community. This 'we' brings with it a communal identity, expectations of its participants, and an ontological order. Making measures creates the metrological concept, but it also helps define the field, its members and its objects.

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[3] M. Kusch, '"A Branch of Human Natural History": Wittgenstein's Reflections on Metrology', this volume.
[4] Bridgman's work has received increased attention recently, and deserves further examination and use from fields such as science and technology studies and current history and philosophy of science. See for example: H. Chang, *Inventing Temperature: Measurement and Scientific Progress* (Oxford: Oxford University Press, 2004); H. Chang, 'Operationalism', *The Stanford Encyclopaedia of Philosophy* (Fall 2009), at http://plato.stanford.edu/archives/fall2009/entries/operationalism/ [accessed 31 March 2014].

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[8] D. Endy, 'Foundations for Engineering Biology', *Nature*, 438:24 (2005), p. 452. See also D. Endy, 'Synthetic Biology: Can We Make Biology Easy to Engineer?', *Industrial Biotechnology*, 4:4 (2008), pp. 340-351.
[9] M. Heinemann and S. Panke, 'Synthetic Biology: Putting Engineering into Biology', *Bioinformatics*, 22:22 (2006), pp. 2790-2799.
[10] To maintain anonymity and ensure confidentiality, I use pseudonyms for all of my interviewees.
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