How a ‘Drive to Make’ Shapes Synthetic Biology

Citation for published version:
Schyfter Camacho, P 2013, 'How a ‘Drive to Make’ Shapes Synthetic Biology', *Studies in History and Philosophy of Science Part C: Studies in History and Philosophy of Biological and Biomedical Sciences*. https://doi.org/10.1016/j.shpsc.2013.05.010

Digital Object Identifier (DOI):
10.1016/j.shpsc.2013.05.010

Link:
Link to publication record in Edinburgh Research Explorer

Document Version:
Peer reviewed version

Published In:
Studies in History and Philosophy of Science Part C: Studies in History and Philosophy of Biological and Biomedical Sciences

How a ‘drive to make’ shapes synthetic biology

Pablo Schyfter

Abstract

A commitment to ‘making’—creating or producing things—can shape scientific and technological fields in important ways. This article demonstrates this by exploring synthetic biology, a field committed to making use of advanced techniques from molecular biology in order to *make* with living matter (and for some, to *engineer* living matter). I describe and analyse how this field’s ‘drive to make’ shapes its organisational, methodological, epistemological, and ontological character. Synthetic biologists’ ambition to make helps determine how their field demarcates itself, sets appropriate methods and practices, construes the purpose and character of knowledge, and views the things of the living world. Using empirical data from extensive ethnographic and interview-based research, I discuss the importance of seemingly simple and unimportant commitments—in this case, a focus on the making of things rather than the production of knowledge claims. I conclude by examining the ramifications of this line of research for studies of science and technology.

Keywords: synthetic biology; making; boundary-work; methodology; epistemology; ontology

How a 'drive to make' shapes synthetic biology

1. Introduction

This article examines how a commitment to 'making'—that is, creating or producing—bears upon the character of a field in science and engineering. I argue that something seemingly straightforward—namely, that certain fields are in the business of *making things*—has important implications for how scientific and technological ventures demarcate themselves, define accepted practices, produce knowledge, and construe the nature of the things with which they engage. That is, my research shows that a 'drive to make' can shape the organisational, methodological, epistemological and ontological facets of a field.

I employ the term 'making' in its ordinary sense. That is, I understand making to be broadly synonymous with creating, constructing, building and producing; it is the putting together, bringing-into-material-existence of something. The plainness of this definition does little to convey the richness of its consequences for science and technology. Fields seeking to construct things differ in significant ways from those intent on other ends, such as developing knowledge claims and furthering understanding. All scientific and technological fields engage in making things and in producing knowledge, but not all fields have as their end-goal the production of artefacts or the making of knowledge claims. Distinctions in end-goals matter.

A 'drive to make' can help account for the presence of specific practitioners, the goals set by them, the practices undertaken, and all manner of topics of clear interest to scholars of science and technology. Making pervades such things as practice, discourse, norms and expectations. Moreover, particular varieties of making shape fields in correspondingly particular ways. As such, this article explores both how a broad commitment to making—a 'drive to make'—shapes a scientific and technological field, as well as how one particular style of making—an engineering-based configuration of practice—has particular implications for the same field.

My study focuses on synthetic biology, a loose conglomerate of researchers engaged in developing new tools and techniques for intervening in—and *making with*—the stuff of the living world. I examine how a 'drive to make' shapes synthetic biology in four arenas. First, making has *organisational* implications. As a number of studies have argued, constructing with biological things is a defining characteristic of synthetic biology (Calvert, 2007; O'Malley et al., 2007; Keller, 2009; O'Malley, 2009). As I demonstrate, making—in act and as ideal—serves to unify what is still a very heterogeneous and disconnected group of researchers (Lentzos et al., 2008). That is, a 'drive to make' is crucial to acts of boundary setting and field delimitation (Gieryn, 1983). Second, making has *methodological* consequences. While the field may be committed to making in a broad sense, the way in which that making is to be carried out is a matter of serious, ongoing debate. A particularly vocal contingent of practitioners seek to make as do 'real' engineers, and set down their methodologies accordingly (e.g Endy, 2005). Methods of making become implicated in setting down how to practice and who to be; particular methodologies (such as those of engineering) produce particular fields. Third, making moulds the field's *epistemological* character. Synthetic biology's drive to make influences what type of knowledge is to be produced, of what use that knowledge is, and how construction and knowing relate to one another. Again, particular varieties of making define this relationship differently. Last, the field’s commitment to making is *ontologically* significant. This is the case for all styles of practice in the field, but appears most clearly for the contingent invested in the engineering-based vision of synthetic biology. For these, the things of living nature are constituted as ontologically equivalent to the inanimate materials employed by existing engineering fields: as usable substrate at the disposal of technology-making ventures.

My argument draws on extensive empirical research on synthetic biology. For 18 months in 2010 and 2011, I worked as a postdoctoral researcher at a synthetic biology laboratory in the United States. I conducted an extended ethnographic study of this research group and its partner lab, which shared space, instruments, supplies and some personnel with ours. As a member of the laboratory, I presented at weekly lab meetings, interacted closely with fellow lab members, and had access to all facilities pertaining to the group’s work. I also conducted 24 in-depth qualitative interviews with synthetic biologists. These included fellow lab members as well as principal investigators, postdoctoral researchers and doctoral students at other institutions in the United States. Furthermore, I conducted short ethnographic visits to 7 additional laboratories, also in the United States. Some of these visits consisted of no more than one day, while others extended over the course of several weeks. Last, I attended events associated with synthetic biology, including: one-day symposia; large conferences such as The Fifth International Meeting on Synthetic Biology (SB 5.0); meetings of research networks such as the Synthetic Biology Engineering Research Center (SynBERC); and the yearly International Genetically Engineered Machine undergraduate competition (iGEM).

As an emerging field, synthetic biology is made up of various factions whose goals and practices differ from each other in key ways. As such, I chose research locations and interview participants based on the most viable criterion: self-identification with synthetic biology. I did not prefer one type of synthetic biology research over others. Although I often draw attention to the field’s engineering-focused contingent, my research encompassed all manner of practitioners. Similarly, my argument applies to all of synthetic biology. Making is not the exclusive purview of one contingent. My examination of engineering-driven practitioners demonstrates how a particular form of making shapes the field in a particular way. Importantly then, my use of the term ‘making’ must not be understood as synonymous with the term ‘engineering’. The latter is one specific variety of making, but not the sole one at work in synthetic biology.

The question of ‘making’ was never a direct query put to the interviewees, but the topic appeared consistently and in a significant manner across my enquiries. Moreover, it was prominent during my ethnographic investigation, and it is a key facet of the field’s discourse. In pursuing the topic, I have found that examining and understanding synthetic biology demands a concern for ‘making’ and its implications. Here I identify and examine some of these, with a view to establishing the importance of this basic, but defining quality of certain fields in science and engineering.

2. Making a field

Synthetic biology is a field under construction. At present, those who self-identify with ‘the field’ of synthetic biology constitute a diversity of practitioners. Biologists, chemists, computer scientists, and all manner of engineers are some of the immigrants to synthetic biology; with them they bring different practices, tools, aims, and epistemic and ontological commitments. This pluralism does not yet exist within a common framing—‘the field’ lacks a unifying identity. As a result, the term ‘synthetic biology’ itself is employed without consistency by those who self-identify with 'the field.' Similarly, observers and analysts of the field, such as me, define and sort out the field differently (e.g. Calvert, 2010; Mackenzie, 2010). Work that may go unquestioned as synthetic biology in some quarters will often meet with scepticism in others. In many regards, the field is a 'fragmented' one (see Schyfter and Calvert, forthcoming).

Despite the multifariousness that is characteristic of synthetic biology (but perhaps also as a response to it) efforts to consolidate the field exist. Many of these draw on the drive to make as an axis around which the field can unify. 'Making' plays a crucial role in synthetic biologists' boundary-work—in simplest terms, the practice of constructing social borders around particular activities in order to distinguish them from others (Gieryn, 1983 and 1995). My study suggests that different factions within the field, irrespective of divergent backgrounds, aims, and practices, all employ making as a characteristic that distinguishes synthetic biology from other research areas. Divisions internal to the field concern to what ends that making is put, and what form the process should take. Making itself is a shared commitment—a basis for establishing the boundaries of synthetic biology.

Those I observed and with whom I conducted interviews routinely commented on the importance of making, and building synthetic biological constructs was often characterised as a defining aspect of the field. More than just practice or method, making is set down as an imperative. Michael[1] is a doctoral student at my host laboratory. His work encompasses both computational simulation and analysis, and so-called 'wet-work'—laboratory bench-work with biological materials. Michael and a postdoctoral colleague currently seek to design and fabricate a counter—a genetic construct capable of retaining a record of previous events. Counters are in effect genetic memory devices. It is hoped that such devices will help researchers track cell lineages across generations and enable the production of more sophisticated constructs resembling electronic circuitry[2]. When asked how his work with counters fits into the broader field of synthetic biology, Michael responded:

> Some people want to build a house, some people want a bridge, some people want to build, you know, a swimming pool or whatever, right? It is the same in synthetic biology. You know, some people want to build oscillators, some people want to build a counter, some people want to build an edge-detector.

For Michael, synthetic biologists follow a drive to make. Though the products he mentions—counters (Friedland et al., 2009), oscillators, and edge-detectors (Tabor, et al., 2009)—differ, each was the result of a venture in constructing an artefact. It is the act of making that is of importance to Michael. Although his computational work demanded a great deal of effort, he consistently portrayed it as a step toward the real end-goal—*making the counter*.

A colleague of Michael's, also a doctoral student at my host lab, expressed a similar understanding of synthetic biology. Natalie had difficulty defining the identity of her field, but ultimately settled on the act of making as its distinguishing feature. She stated that

---

[1] In order to ensure anonymity and confidentiality, I have given each interview participant an alias.

[2] Much of synthetic biology has focused on constructing biological analogues to electronic devices. For instance: oscillators (Elowitz & Liebler, 2000; McMillen et al., 2002; Strickler et al., 2008), logic gates (Lerderman et al., 2006; Rinaudo et al., 2007), and switches (Gardner et al., 2000; Atkinson et al., 2003; Lipshtat et al., 2006)

synthetic biology should be understood "as a method, or you can think of it as like making, just making a system that hasn't been seen." Synthetic biology is both a method of making, and the broader exercise in constructing novel biological systems. In either case, construction is at the heart of the enterprise. Natalie's research focuses on building mechanisms for cell-cell communication: tools for transmitting 'messages' from one cell to another (Chen and Weiss, 2005). Her artefacts are different in kind from those Michael produces, but the two researchers share a drive to make. For her, as for many synthetic biologists, the specific character of a given construct matters less than does the act of building itself. Importantly, the *method* of making is also a subservient question to the general work of making. Although studying in an engineering-focused laboratory, Natalie is suspicious of the engineering vision within synthetic biology. She argues that researchers "don't know enough about biology to have it be perfect, like a piece of steel can be made perfect. We don't know what the rules are." Engineering practices as can be found in established engineering may not work in the realm of living things, but the particularities of making matter less than does making itself, which is key to the field.

As with all forms of boundary-work, making shapes the field's identity both through inclusion and exclusion. Frank is the principal investigator of a lab involved in both systems and synthetic biology. These two fields display a number of similarities, and distinguishing between them can be problematic (Church, 2005; Smolke and Silver, 2011). In his attempt to draw a clear delineation between the two, Frank described systems biology as an attempt to map the components and describe the dynamics of naturally-occurring biological systems, whereas synthetic biology is:

> … trying to really take those sorts of, biological modules and use them as tools to build novel, or different, or tuned biological cells, that show different biological behaviour.

Thus, Frank distinguishes between systems and synthetic biology by referencing the latter's drive to make. While both are interested in the internal goings-on of living systems, Frank argues, systems biology does not engage in construction of novel living things, much less technological objects. A postdoctoral researcher at my host lab, who styles himself a systems biologist, made a similar distinction between the two fields. Jake said:

> In synthetic biology you typically go, you start with something, you start more from scratch, I mean, usually it's never completely from scratch, you typically steal proteins and genes from other systems, but you start with something simple and then you construct as a forward engineering.

Like Frank, Jake references the drive to make (as well as acts of making) as that which demarcates the boundaries of synthetic biology. He contrasts synthetic biology's "forward engineering" with the "reverse engineering" of systems biology. His use of the term 'engineering,' as became evident later in the interview, had to do less with engineering as a particular set of practices and more with the general acts of intentionally designing and fabricating things (that is, the general act of making). Jake argued that while systems biology seeks to decipher the underlying processes of naturally-occurring entities, synthetic biology works to construct novel systems. Where the former aims to pinpoint entities and interactions, the latter hopes to build. Jake's own research fits this distinction perfectly; he examines the actions involved in the infection and destruction of cells by bacteriophage lambda—naturally-occurring phenomena. In his estimation, his efforts involve analysis, not construction, and therefore fall outside synthetic biology. This sentiment was one often expressed by those not involved in construction but located in research groups labelled to be working in synthetic biology. Both Frank and Jake noted their uneasiness in belonging to a synthetic biology research network, because their interests lie with knowledge-production, not the making of things.

The drive to make, as a useful axis around which diverse practitioners strive to consolidate their work, serves to establish synthetic biology's identity: to be a synthetic biologist is to make. This basic proposition is prevalent and important to understanding the field, and was often mobilised at my host lab to signal belonging or the lack thereof. As I noted above, Michael's work entails both computational research and 'wet-work' at the lab bench. During my time with the research group, he transitioned from a phase of computational studies and simulations of biological systems to a phase of material construction. The other lab members light-heartedly joked during one of our weekly meetings that Michael was finally doing 'real' synthetic biology. He was finally making. In a similar vein, Robert, our laboratory's principal investigator, dismissed a certain branch of work as outside the remit of synthetic biology because "they're never going to *make* anything." I was criticised and dismissed as outside the 'real' group of the laboratory, because I did not pick up a pipette and carry out some genetic transformations. Robert and the rest of the group saw that act—the making of a novel biological system—as a necessary one for truly belonging in a synthetic biology lab.

Making also features in the institutional set-up of the field. The principal research network for synthetic biology in the United States is the Synthetic Biology Engineering Research Center (SynBERC). Research supported by SynBERC is institutionally structured in a variety of ways, but a key feature is the use of so-called 'testbeds'—specific functional end-products. Foundational research—say, the building of basic component for construction or the development of necessary instrumentation—is intended to serve the making of several technological artefacts, such as a 'tumor-killing bacterium' and a 'microbial chemical factory.' (SynBERC, 2013) Making structures the institutional organisation of SynBERC.

The boundaries that define scientific and technological fields are contingent products of social practice, a "consequence of rhetorical games of inclusion and exclusion" (Gieryn, 1995: 406). Synthetic biologists construe their field as one geared toward construction. Even the title of field reflects this commitment: 'synthetic' as that which must be made, which does not exist but for human artifice. Making is set as a defining characteristic of the field, and used to distinguish it from similar enterprises in molecular biology. The field's internal divisions come not from divergent commitments to making, but rather from different uses to which that making is put and competing methods by which it is carried out. Paradoxically, making becomes both what defines synthetic biology's boundaries and a ground for internal contests.

3. Methods of making

Making may serve as a broad umbrella under which to force divergent practitioners, but disagreements exist concerning how that making is to proceed. The heterogeneity found by observers of synthetic biology can be examined productively as a condition resulting from divergent methods of making. Given the importance of construction to synthetic biology's identity, differences in practice are tied to differences in the precise character of that identity. If synthetic biology is a field that makes, how that making is done bears seriously upon what synthetic biology is. Thus making serves as a ground for contesting identities by way of methodologies.

One of the most salient methodological debates in synthetic biology concerns practitioners' different commitments to so-called 'authentic' or 'real' engineering practice. While making is an expected part of synthetic biological research, making *as a 'real' engineer* is not. At present, those who attempt to produce technological objects with a biological substrate using the conventions and practices of established engineering form one contingent of a broader field. They hope to define 'standard' synthetic biology practice and through that practice, the field's identity. Thus, methodology becomes both a mechanism for internal boundary-work, as well as its consequence (Gieryn, 1983 and 1995).

Because the engineering contingent tends to be the most vocal in advocating for synthetic biology (e.g. Endy and Arkin, 1999; Specter, 2009), and because talk of erecting a 'true' field of biological engineering is a compelling narrative, these practitioners have received a considerable amount of attention from observers of the field. Given this context, it is crucial to keep in mind that the matter is very much a contested one (Kwok, 2010). Making as a 'real' engineer does is less a methodological reality than it is one potential approach to building with biology (Finlay, 2013). I see its importance in how advocates use the engineering vision to define what the field should be by way of how it should make. Consider Barry, a postdoctoral scholar deeply invested in the engineering project. He states:

> You look at the difference in chemical engineering and chemistry, what does chemical engineering bring to the table? It brings a whole methodology for how to think about chemical processing. And so I think that is what synthetic biology is trying to do for genetic engineering.

Methodology defines how a discipline carries out its work, but for Barry and his fellow engineering devotees it also shapes synthetic biology's identity. Making *in a particular way* contributes to a specific understanding of the field's purpose, place and potential.
The engineering project is often cast as enabling the 'rational design' of biology (Finlay, 2013). In fact, the concept of 'rational design' is often employed interchangeably with 'engineering.'[3] Essentially, the term designates the systematic, rigorous and predictable planning of synthetic biological constructs—it specifies a particular type of methodology. This 'rational design' is intended to be 'decoupled' from the process of fabrication (Endy, 2005; Mackenzie, 2010), just as engineering design and factory-floor fabrication are complementary facets in the making of technological things. As I view the matter, design and fabrication are interrelated sets of practices which in a united and non-linear way serve acts of making. Making is neither design nor fabrication. It encompasses both. The synthetic biologists I interviewed expressed similar views, placing emphasis both on design and on fabrication.

Sam, a principal investigator and leading voice in the engineering contingent, describes 'rational design' as "the rational composition of exogenous objects to create a desired effect, to specification." That is, 'rational design' entails predictive planning of functionality as well as methodical construction. Jake, a postdoctoral researcher quoted earlier, associates 'rational

[3] The term is often used in the titles of many publications stemming from synthetic biology laboratories. For instance: Ajo-Franklin, 2007; Prather and Martin, 2008; Armstrong et al., 2009; Fletcher et al., 2012.

design' with the skill necessary to go through the act of making "on a more engineering… you know, well thought-out fashion." In clearly similar terms, Rose describes it as follows:

> And it means that you're not just, as I said, you know, kind of, what I was saying before, you're not just slapping parts together and hoping that it works. That there is some, you know, conscious, you know, some thought that goes into what you're building.

According to this description, synthetic biology brings with it an improve type of making: thought-out design driven by predictive rules, and systematic fabrication that extends past 'messy' and erratic genetic modifications. Those who champion 'rational design,' as does Rose, view existing genetic engineering as *ad-hoc* craftwork—"just slapping parts together and hoping it works"—and celebrate the goal of engineering-based synthetic biology—construed as well thought-out, systematic making. Methodical construction is portrayed not simply as reliable, and therefore preferable, methodology; it is also a trait that marks synthetic biology as different from, and superior to previous attempts at building with biology. For Rose and those whose understanding of the field is similar, 'authentic' synthetic biology rests upon making that follows a specific mould; methods of making shape practices, identities and boundaries.

So-called 'engineering principles' are styled as necessary tools and tenets for bringing this vision of synthetic biology into being (Andrianantoandro et al., 2006; Endy, 2005; Heinemman and Panke, 2006). Such principles include the production of modular building components (Hartwell et al., 1999; Lucks et al., 2008; Sauro, 2008); standardisation of such components (Arkin, 2008; Canton et al., 2008); abstraction of complexity (Endy, 2005); quantification of performance (De Lorenzo and Danchin, 2008); and the 'decoupling' mentioned above. The goal in making use of these principles is to model synthetic biology after an engineering ideal—to be an engineering field by practicing like an engineering field. That is, identity by way of method. Daniel, a control engineer and synthetic biologist working at my host lab, argued that the design process of synthetic biology must be made to look "like the engineering processes that are used for design in other [engineering] disciplines."

Consider as an example of such methodology the making of 'standardised' component parts like so-called BioBricks™. These 'parts' are genetic sequences framed by specified ends. Ideally, defining standard ends should enable two 'parts' to be fused together easily, successfully and in a functionally predictable manner. Single 'parts' can be combined into larger 'devices' with specified functionality, just as combining isolated parts can yield a working engine in an automobile. The techniques used to combine BioBricks™ are not new; they are those of existing molecular biology technologies. The novelty is to be found in the attempt to define common, standard ends and in the work to rally a community around their use. Thus, 'engineering principles' like standardisation concern the character and practice of the field.

Standardisation is only one practice supported by the engineering contingent. Barry, a postdoctoral researcher quoted earlier, works on techniques for improved reliability and failure-prevention in synthetic biology. His aim is to enable greater control over constructs and to lessen the functional uncertainty that currently plagues many projects in the field. To achieve these ends, Barry develops mechanisms that shut down malfunctioning organisms (through programmed death) and backup constructs that reinforce correct behaviour. His work places emphasis on control and reliability. Sarah, another postdoctoral researcher, views synthetic biology much as does Barry: as defined by engineering methodology. Her laboratory develops tools and techniques for rapidly assembling genetic elements: joining small genetic sequences in order to produce large constructs. Sarah views such tools as necessary instruments for enabling systematic engineering, and believes that systematic engineering is what sets synthetic biology apart. She says:

> But the thing that distinguishes the field as we know it now from, I guess, what we have been doing previously as molecular biologists, is that there is this idea that we need to start thinking of what we do in a little different way. And start applying *principles of engineering* to biology. (my emphasis)

For Sarah, making *as an engineer* distinguishes what the synthetic biologist does from earlier interventions with molecular biology (such as genetic engineering). She holds that never before has engineering truly been applied to biology, a common view among practitioners in the engineering contingent. She also views developing basic engineering tools and 'foundational technologies' as necessary research. As do others invested in the engineering vision, she considers it crucial to provide the instrumental infrastructure needed to make that vision come into being.

If making defines synthetic biology, different methods of making are avenues leading to alternate identities. The group examined here—those committed to a 'real' engineering practice—is the most vocal in its aims, as well as the one with the most clearly delineated standards of practice. The success of engineering-based practices like standardisation and functional decomposition is uncertain. Work in synthetic biology is less rational design than it is 'kludge': "a workaround solution that is *k*lumsy, *l*ame, *u*gly, *d*umb, but *g*ood *e*nough" (O'Malley, 2009: 382). It mirrors *actual* engineering practice (see e.g. Vincenti, 1990) rather than matching an *idealised* representation of engineering. As I write this, engineering-based practices matter to acts of making in synthetic biology, but they are equally important (arguably, more important) in the contest to define the identity of the field. Within the scope of this paper, engineering-based practices (both in use and in rhetoric) also demonstrate that commitments to making can shape scientific and technological fields in particular and meaningful ways.

Gieryn's boundary-work has been extensively used to discuss disputes over the demarcation of science from non-science (1983). If synthetic biology comes to be defined by engineering methodology, then boundaries that distinguish between engineering making and non-engineering making will serve to delineate between synthetic biology and non-synthetic biology, respectively. Boundaries (and consequently, identities) will follow methods.

4. Making and knowing

I have established that making is central to all of synthetic biology. I have also demonstrated that particular methodologies of construction carry correspondingly particular implications for the field. So too do the *ends* to which making is put. The question of end-goals drives my entire argument, but is all-important when considering epistemological issues relevant to synthetic biology's drive to make.

A number of authors have sought to examine the relationship between the construction of things in synthetic biology and the production of knowledge claims about living nature (O'Malley et al., 2007; Keller, 2009; O'Malley, 2009). This work has conceptualised making and knowing in the field either in terms of an oppositional relationships—the two are fundamentally distinct—or by subsuming one under the other—making *is* knowing, or *vice versa*. I propose to examine the relationship as taking two forms: 'making to know' and 'knowing to make.' Each of these relationships is characterised by different end-goals, types of construction and epistemic species. They are also practiced to different extents and valued differently by the varying methodological factions in the field. My analysis is greatly indebted to, although is not a direct application of, Vincenti's work in the epistemology of engineering (1990). As with the previous section, I focus on the engineering contingent in synthetic biology not because its members are representative of the field taken as a whole, but because it enables a study of how specific varieties of making shape fields.

My use of work from the epistemology of engineering necessitates a preliminary word on engineering knowledge. Among those committed to engineering-based synthetic biology, there is a perceived divide between knowing and making. Those I interviewed expressed strong views on the distinction between these two. Natalie, from my host lab, argued:

> An engineer, I think, I see a lot of engineers that want to make something, so it's not necessarily, you know, I guess, not necessarily an application, but I would say they want to make a tool or they want to make an application. But it isn't so much that they're trying to reveal something about an underlying system. So I would say that that's the main difference that I see.

She drew a strong delineation between those aiming 'to know' and those working 'to build,' presenting these two as fundamentally different practices. This separation was common among those I interviewed. Liz, a principal investigator with training in chemical engineering, vehemently argued a comparable point. Although she is somewhat hesitant about the potential of a uniquely engineering-driven approach to synthetic biology, she nonetheless expects the field to take a final form much like chemical engineering. When I asked about engineering and knowledge, she said:

> I think engineering, that most people who choose engineering and most people who think about what engineering is at its core, would argue that, what makes it different from science is the applied focus. And if you accept that, and say, this is why I'm an engineer and why I'm not a scientist, then at some point all the things we do are driven towards applications.

For these individuals, engineers seek to make, whereas scientists (here mostly biologists) try to understand. This was a characterisation I encountered repeatedly during my research, and while simplistic, it articulates a crucial point at the heart of my argument: making *things* and making *knowledge* are not equivalent end-goals. This statement may be simple, but I find it is often overlooked in studies of science and technology.

The critical literature on engineering emphasises this point. Walter Vincenti's excellent epistemological work begins with a recognition that engineering is driven by an imperative to make, rather than an epistemic aim (1990). Similarly, Louis Bucciarelli draws attention to engineering practice as centred on the production of specific artefacts (1994). Nonetheless, both authors also discuss the key role played by epistemic practices in engineering. Vincenti in particular argues that engineering knowledge is a unique epistemological species—a particular kind of knowledge not reducible to scientific knowledge. Broadly, their work provides my argument with several crucial observations about knowledge. First, knowing and making are neither fundamentally distinct nor reducible to the other. Second, *types* of knowing and knowledge differ in science and engineering fields. Synthetic biology amply demonstrates both the interwoven nature of making and knowing, and the differences between knowledge claims geared to construction and understanding.

The first of my two knowing-making relationships is 'making to know.' This term refers to the practice of using synthetic biological constructs to derive an understanding of naturally-occurring phenomena. 'Making to know' is characterised by an epistemic end-goal, the construction of model systems, and a variety of knowledge geared toward scientific understanding. Frank, a principal investigator quoted earlier, conducts research into the behaviour of protein scaffolds. His concern is understanding natural phenomena. He notes:

> So, certainly, in synthetic biology, we are creating genetic variation and, presumably, functional variation. So I think that, you know, inherently, that allows us to probe questions about evolution or to, at least evolution approaches to ask about what's important about, you know, achieving certain functions.

Franks acknowledges the potential of his work for applications, but ultimately pursues his research for epistemic end-goals. Acts of 'making to know' closely resemble existing work in molecular biology. After all, modifying natural entities in order to study them has been and continues to be a routine part of life sciences research. As Keller argues with reference to the synthesis of life, studying and intervening are never very far removed in science (2002 and 2009). As a result, those who practice this variety of work and their research can easily be marginalised in synthetic biology. This is certainly the case with Frank, for whom (as I noted earlier) the label of synthetic biologist is often an uncomfortable one.

Rose, whose work has led to the production of biological memory devices, argues that her synthetic systems can be instruments for understanding. She says:

> So people are, and I think of myself as one of these people, building things that can be used, to know. Like, they're *building to know*. So, you know, for example, you would build a circuit, but you're not just going to build a circuit, you're going to use the circuit to study some biological phenomenon, it's not just to see if the circuit works. (my emphasis)

Although her memory devices have utilitarian ends, they can also serve as models of the natural and spaces for experimentation. 'Making to know' serves epistemic ends. Roosth, in a discussion of making and knowing in synthetic biology, goes further. She suggests that in synthetic biology, "people now *build biotic things in order to understand the things that they themselves are making*" (2013: 168, emphasis original). This argument differs from my own, but still places the act of making at the heart of synthetic biology's epistemic practices.

'Knowing to make' refers to acts of knowledge production intended to enable the making of a technological thing. 'Knowing to make' is characterised by a utilitarian end-goal, the making of technologically-functional artefacts, and a type of knowledge geared toward design and fabrication. Following Vincenti, I hold this species of knowledge to differ significantly from knowledge aimed at advancing scientific understanding (1982 and 1990). The drive to make technological things results in different epistemic conventions, including different techniques, standards and uses[4]. Barry, a postdoctoral researcher cited earlier, is heavily invested in the engineering-based view of synthetic biology. He argues:

> So, I think, there's a lot of confusion there between biology and what we are trying to do in synthetic biology. Because I think the biologists are seeking out to understand what are the natural functions, whereas, we are saying, no, it can do whatever you want it to do, as long as it all fits together, and we build a new regulatory network and the inputs lead to the outputs which we predicted.

To those seeking a functional end-product, the intricacies of a living system, its behaviour and its 'true' nature are irrelevant in and of themselves. Only that which bears upon the successful working of the intended technology—that which is involved in securing a given output from given inputs—is of concern[5]. A good piece of knowledge here is considerably different from a good piece of knowledge in the previous relationship. Vincenti writes that knowledge in this type of practice "is judged in the end on the basis of whether it helps to achieve a successful design" (1990: 207) rather than its ability to resolve gaps in understanding. David Bloor, writing about the development of knowledge in aeronautics in the early 20th century, similarly points to the contentious debate between those who judged knowledge on its 'applicability' and those who judged it on its physical 'truth.' Concerning the former, Bloor writes:

> Neither rigour nor purity were central concerns, nor was it their primary goal to test the physical truth of their assumptions. They tested their conclusions for utility rather than their assumptions for truth (2011, p. 244)

In short, functional success prevails. 'Knowing to make' involves developing the foundational knowledge to foster proficiency in the making of functional technologies. Many engineering-driven synthetic biologists speak of 'making biology easier to engineer' (Endy, 2005). 'Knowing to make' is the epistemic facet of this venture.

Framing knowledge practices as mechanisms for enabling 'real' engineering, as do proponents of the engineering vision, has important implications. Knowledge-making practices differ, as I have explored in detail elsewhere (Schyfter, 2013). What comes to count as good knowledge also differs, since the standard becomes function, rather than explanation. Even judgements about what constitutes a valid epistemic venture change, as I suggested in the previous section. Knowledge that enables 'foundational technologies,' often dismissed as 'mere' methodology, is crucial to fields committed to delivering functional technologies. Efforts to develop quantitative measurement tools (key epistemic instruments in engineering) will be valued in a way that a knowledge-oriented variety of synthetic biology might not do. Knowledge-making for the engineering contingent is shaped by their particular variety of the drive to make.

5. Making things

[4] Vincenti writes: "As in many aspects of engineering knowledge, in engineering science the purpose of design is determinative." (1990, p. 135) Simply stated, engineering knowledge is motivated and shaped by the design ends of the project.

[5] There also exist plainly pragmatic concerns about how much knowledge to develop. Vincenti notes: "In some problems overall results may be all the engineering, and to go into detail would be a waste of time and money…" (1990, p. 130)

The preceding sections have addressed how making is immanent in organisational, methodological and epistemic facets of synthetic biology. The field's drive to make also has *ontological* implications. Practitioners' commitment to building shapes not only what they do and what they expect of their field, but also how they understand the things upon which they work—the stuff of the living world. Although of relevance to all of synthetic biology, the ontological implications of the 'drive to make' are most evident when examining the contingent of practitioners aiming to practice 'real' engineering. As such, I explore this group before turning back to ontological issues relevant to the entire field.

My research shows that aiming to engineering with the stuff of biology implies a particular ontology of living things. Namely, the biological world is construed as material for making, rendered intelligible as 'substrate' for construction[6]. During my interview with Robert, a prominent synthetic biologist and head of my host lab, he discussed what characteristics make the field unique. First in his view is the 'real' engineering to be practiced. Importantly, he also discussed the type of stuff employed in this 'real' engineering:

> So, for example, all the starting materials that we work with come via this evolutionary process.

Here, the 'material' used to make things is the entirety of living nature. It is in this basic sense that the biological world becomes intelligible as 'substrate.' During our interview, Rose sought to impress upon me her enthusiasm about synthetic biology's potential by saying:

> And nature is so incredibly varied and complex, that it really just provides us with a plethora of parts, and mechanisms. You know, the world is our oyster, right? So, there's a lot of stuff out, and I don't even think we've really begun to tap into, tap too deeply into the resources that are kind of, like, at our disposal.

Her comment is instructive in various ways, but two points are particularly important. First, the living world is "oyster" for the taking, a reserve of things to be employed. As Rose states, biology is "at our disposal." Second, this world is ontologically constituted as already amenable to engineering practice. It is not simply material; it is "parts" and "mechanisms." Others make reference to the "toolkit of life" (Fischer et al., 2011). Mary is a doctoral student working to decipher the basic mechanisms of cell growth and spatial orientation. She hopes to understand how single-cell organisms 'polarise'—basically, determine their front and back. Her view of the biological world is comparable to that of Robert and Rose—living things are sources of usable functions. Organisms are to be harvested for capacities that we find useful[7]. She says:

> So, if you collect, if you have of people like me, trying to take one function and figure out what can do that function, and you collect that over time, then maybe you can come up with sort of, this book that says, later on, some synthetic biologists is like,

---

[6] Mackenzie has discussed the relationship between 'design' and the character of 'biological substance' in synthetic biology (2010). His argument extends beyond the ontological question addressed here, but he engages with it in a compelling and useful manner.
[7] For instance, certain cells are capable of photosynthesis. Some applications of biotechnology may benefit from that capacity, so using a cellular 'chassis' that is photovoltaic may enhance the functionality of that particular construct.

> well, in this system that I am trying to build, like I am trying to build this biological device, and I want it to polarise and then move and then do something. And they can go through this book and say, well, first we must figure out what we need to polarise.

Mary conceives of cataloguing natural entities by what functions they may enable in synthetic constructs. Not a taxonomy by physiology or phylogeny, but one by technologically-usable capacities. This type of categorisation mirrors standard practice in many engineering fields, which produce voluminous catalogues of parts to be employed in building technologies. In essence, this is the goal Mary sees for synthetic biology. As with other practitioners I encountered, she renders the living world as material at the ready for engineering.

In effect, the ontology given to living things makes them indistinguishable from substrates used to carry out established engineering. In this regard, the ontological aspect of the drive to make helps establish an engineering-based identity for the field. Certain practitioners want their field to be indistinct from existing engineering disciplines; one way to achieve this goal is through the materials for making. In effect, objects are recruited into acts of boundary-work. The effort of defining the field along particular lines of practice and identity is extended to include the things with which the field works. Sam, who strenuously advocates for the engineering approach, makes this case explicitly in saying:

> You know, we took a little piece of flint we found on the ground and we banged it against a rock until it was sharp, and then they used it to cut something, right. So we found a little bacteria, we found one lying around on the ground, we chipped away at its genome, and chipped away and then tried to use it… What's the difference between the rock and the bacterium? Well, the level of complexity, the degree of difficulty, the incredible array of knowledge and other technologies you used to create it.

In this account, stone and bacteria become equal materials: flint and genome are both things to "chip away at" until a working technology is produced. The level of complexity may differ, but as Sam later made clear, he believes complexity is no obstacle to systematic engineering with biology:

> So, the problem with cells are, we may be able to catalogue everything that's inside of them, one day, we don't do that now. We understand that there is nothing magic to them. That they are nothing but a bunch of atoms that are sitting together. And that those atoms interact through standard physical laws.

Any suggestion that living things may differ in kind from the inanimate materials employed in conventional engineering fields is "idiotic" according to Sam—simply a surrender to what is ultimately fully tractable using physical laws and engineering principles. Repeatedly during our interview, he dismissed—verbally or with animated hand-waving—arguments that the biological may demand new ways of doing things (particularly, of making). The living works as does the inanimate. It is no different. As a result, synthetic biology can be engineering just as much as can established varieties of engineering.

The matter of ontology and making is seen most easily by way of synthetic biology's engineering contingent. However, it is not limited to this group. The field as an entirety embraces particular understandings of the living world more readily than do 'traditional' life sciences. Mechanical heuristics and metaphors pervade synthetic biology, so that even those who are not committed to practicing 'real' engineering often engage with living things as if they were technological. For example, terms such as 'parts' and 'devices' are used routinely when speaking of genetic elements and constructs. The use of mechanical heuristics is of course not something new, as other pieces in this special issue demonstrate, but the role played by them in synthetic biology is different. Here, such metaphors and perspectives serve a broader 'drive to make' by rendering the stuff of biology as inherently amenable to our practices of building.

6. What making does

In introducing his volume on engineering knowledge, Walter Vincenti takes note of the following:

> For engineers, in contrast to scientists, knowledge is not an end in itself or the central objective of their profession. Rather, it is… a means to a utilitarian end—actually, several ends. Engineering can, in fact, defined in terms of these ends. (Vincenti, 1990, p. 6)

Vincenti's argument can be summarised with one straightforward claim: ends matter. Ends shape fields. Synthetic biologists, I contend and have argued, share a 'drive to make.' Their field must be understood as shaped by that end in a variety of ways.

It has been my intent here to demonstrate that a field's drive to make can shape it in meaningful ways—ways that deserve consideration in studies of science and engineering. The difference between an imperative to produce things and one to develop knowledge claims is significant. While admittedly limited in its reach, the present argument has established that a commitment to construction moulds synthetic biology in four broad respects.

First, *The drive to make has organisational implications*. Those invested in synthetic biology employ the aim and practice of 'making' to demarcate the boundaries of the field, and to draw distinctions with comparable fields, such as systems biology. To be a synthetic biologist is to aim at making things. The 'drive to make' is a crucial component of the field's identity.

Second, *the drive to make has methodological implications*. Despite a uniform commitment to making, synthetic biologists contest various methodologies. My research demonstrates that disputes over methodology are most significant in their role as proxies for debates concerning identity. For those practitioners hoping to make synthetic biology a 'real' engineering field, methodology is a critical ground for contesting this identity.

Third, *the drive to make has epistemological implications*. The importance placed upon making defines the epistemic practices of synthetic biology. In one regard, making leads to knowledge-production through intervention in and material reconstruction of the natural. In a second regard, knowledge claims are defined by their use in the making of technologically-functional artefacts. The resultant knowledge serves artefact design. These epistemic distinctions are tied to methodological and identity contests ongoing in the field.

Fourth, *the drive to make has ontological implications*. When making in synthetic biology is framed as an engineering venture, it has the implication of rendering biological things ontologically equivalent to the inanimate materials employed in designing and constructing conventional technological artefacts. More broadly, the field embraced the types of mechanical heuristics explored in this special issue. In this general sense, viewing the living world as susceptible to our practices of making helps satisfy synthetic biology's drive to make.

Crucially, these implications shape synthetic biology in such a way as to render it different from fields whose principal aim is not the making of things, but rather the furthering of understanding through knowledge claims. If synthetic biology sought to accomplish the latter, my observations of the field would have reflected that difference. Synthetic biology would be organisationally, methodologically, epistemologically and ontologically different. Moreover, the case of the engineering contingent demonstrates that different varieties of the drive to make can shape the field in different ways. Making as does an engineer will produce one field of synthetic biology; making as is done in another type of artifice will deliver a different field.

Basic commitments—such as the 'drive to make' in synthetic biology—demand further attention and scrutiny from those who study science and technology. These are often so 'obvious' that they escape attention. However, I find nothing self-evident about a field's desire to make things. Instead, I see a space for further refining our comprehension of science, technology and engineering. My four-part analysis demonstrates that simple founding premises—'this is a field geared toward the making of things'—can have diverse and important results. Many of these are beyond the scope of the present argument, which is limited by the usual constraints of space. Among these are scientific and technological fields' narratives of promise, the role of other social entities like legal institutions, considerations of value, and the relevance and influence of industry. I am unable to address these and others, but they should be components of further study into the place and role of making, as well as the significance of end-goals.

Moreover, I find it important to recognise and examine the unique facets of fields whose goal is the making of things, rather than the production of knowledge[8]. Doing so in no way diminishes the importance of material practices in scientific undertakings[9], nor does it overlook the role played by knowledge in making-centred ventures. It simply commits us to acknowledge that fields reflect that which they hope to accomplish. It forces us to acknowledge that *ends matter*.

Within the context of this special issue's other pieces, a drive to make helps account for the use of mechanical metaphors, and (as I discussed earlier) will underlie particular ontological commitments that draw the biological and the technological together. The use of such metaphors is not limited to fields seeking to engineer with living things, but within such fields statements about 'parts,' 'devices,' 'circuits' and 'chassis' may be more than heuristic tools (see e.g. Lewens 2000 and 2004). For those invested in the engineering vision, they are used just as they might be by mechanical and electrical engineers, because the field is to be (and is *to make*) just like other engineering disciplines.

---

[8] The advent of dedicated engineering studies (Downey 2009) will in all likelihood produce an extensive literature of making-centred fields. However, wider scholarship on science and technology may benefit from thinking about 'making.'

[9] See e.g. Pickering, 1984; Pinch, 1985; Shapin and Schaffer, 1985; Rheinberger, 1997; Collins 2001.

During our conversation, Sam sought to impress upon me how much the drive to make set synthetic biology apart from fields seeking to study the natural world. He conveyed the following anecdote:

> I had a student who was trained as an undergraduate in microbiology, who did a rotation in my group. And he was just stunned at the end of the rotation, he did a great job and he worked really hard. At the end of the day, he was talking to me and he said, 'I don't get it, you guys are just trying to make stuff.' Yeah, our goal is, we have this specific target in mind, we're trying to make it, if we aren't making a lot of it we want to understand why we're not making a lot of it, but it's very directed, we have an end goal. And he says, 'You're not trying to uncover any novel biological phenomena.' The last thing I want is novel biological phenomena! I want predictability. I want things to behave in the way they have been described to behave. And he, quite frankly, just didn't see how that was valuable.

The gap in understanding between student and advisor suggests two simple, but crucially important, lessons: *ends matter* and *making matters*.

References

Ajo-Franklin, C.M., Drubin, D.A., Eskin, J.A., Gee, E., Landgraf, D., Phillips, I., & Silver, P.A. (2007). Rational design of memory in eukaryotic cells. *Genes & Development*, 21, 2271-2276.

Andrianantoandro, E., Basu, S., Karig, D.K., & Weiss, R. (2006). Synthetic biology: New engineering rules for an emerging discipline. *Molecular Systems Biology*, 2.

Arkin, A. (2008). Setting the standard in synthetic biology. *Nature Biotechnology*, 26(7), 771-774.

Armstrong, C.T., Boyle, A.M., Bromley, E.H.C., Mahmoud, Z.N., Smith, L., Thomson, A.R., & Woolfson, D.N. (2009). Rational design of peptide-based building blocks for nanoscience and synthetic biology. *Faraday Discussions*, 143, 305-317.

Atkinson, M.R., Savageau, M.A., Myers, J.T., & Ninfa, A.J. (2003). Development of genetic circuitry exhibiting toggle switch or oscillatory behavior in *Escherichia coli*. *Cell*, 113(5), 597-607.

Bachelard, G. (1984). *The new scientific spirit*. Boston: Beacon Press.

Bloor, D. (2011). *The enigma of the aerofoil*. Chicago, IL: University of Chicago Press.

Bucciarelli, L.L. (1994). *Designing engineers*. Cambridge, MA: The MIT Press.

Calvert, J. (2010). Synthetic biology: Constructing nature?. *The Sociological Review*, 58, 95-112.

Canton, B., Labno, A., & Endy, D. (2008). Refinement and standardization of synthetic biological parts and devices. *Nature Biotechnology*, 26(7), 787-793.

Chen, M.T., & Weiss, R. (2005). Artificial cell-cell communication in yeast *Saccharomyces cerevisiae* using signaling elements from *Arabidopsis thaliana*. *Nature Biotechnology*, 23, 1551-1555.

Church, G.M. (2005). From systems biology to synthetic biology. *Molecular Systems Biology*, 1.

Collins, H.M. (2001). Tacit knowledge, trust, and the q of sapphire. *Social Studies of Science*, 31(1), 71-85.

De Lorenzo, V., & Danchin, A. (2008). Synthetic biology: Discovering new worlds and new words. *EMBO Reports*, 9, 822-827.

Downey, G. (2009). What is engineering studies for? Dominant practices and scalable scholarship. *Engineering Studies*, 1(1), 55-76.

Elowitz, M., & Leibler, S. (2000). A synthetic oscillator network of transcriptional regulators. *Nature*, 403, 335–338.

Endy, D. (2005). Foundations for engineering biology. *Nature*, 438(24), 449-453.

Endy, D., & Arkin, A. (1999). *A standard parts list for biological circuitry*. Berkeley, CA: Defense Advanced Research Projects Agency White Paper.

Finlay, S.C. (2013). Engineering biology? Exploring rhetoric, practice, constraints and collaborations within a synthetic biology research centre. *Engineereing Studies*. (Available at doi:10.1080/19378629.2013.763811)

Fischer, M.A. et al. (2011). De novo designed proteins from a library of artificial sequences function in Escherichia coli and enable cell growth. *PLoS One*, 6(1), e15364.

Fletcher, J.M., et al. (2012). A basic set of de novo coiled-coil peptide oligomers for rational protein design and synthetic biology. *ACS Synthetic Biology.*

Friedland, A.E., et al. (2009). Synthetic gene networks that count. *Science*, 324(5931), 1199-1202.

Gardner, T.S., Cantor, C.R., & Collins, J.J. (2000). Construction of a genetic toggle switch in Escherichia coli. *Nature*, 403(6767), 339-342.

Gieryn, T.F. (1983). Boundary work and the demarcation of science from non-science: Strains and interests in professional ideologies of scientists. *American Sociological Review*, 48(6): 781-795.

Gieryn, T.F. (1995). Boundaries in science. In S. Jasonoff, G.E. Markle, J.C. Peterson, & T. Pinch (Eds.), *Handbook of Science and Technology Studies* (pp. 393-443). London: Sage.

Hartwell, L.H., Hopfield, J.J., Leibler, S., & Murray, A.W. (1999). From molecular to modular cell biology. *Nature*, 402, C47-C52.

Heinemann, M., & Panke, S. (2006). Synthetic biology: Putting engineering into biology. *Bioinformatics*, 22(22), 2790-2799.

Keller, E.F. (2002). *Making sense of life*. Cambridge, MA: Harvard University Press.

Keller, E.F. (2009). Knowing as making, making as knowing: The many lives of synthetic biology. *Biological Theory*, 4(4), 333-339.

Kwok, R. (2010). Five hard truths for synthetic biology. *Nature*, 463, 288-290.

Lederman, H., Macdonald, J., Stefanovic, D., Stojanovic, M.N. (2006). Deoxyribozyme-based three-input logic gates and construction of a molecular full adder. *Biochemistry*, 45(4), 1194-1199.

Lentzos, F., Bennett, G., Boeke, J., Endy, D., Rabinow, P. (2008). Roundtable on synthetic biology. *BioSocieties*, 3, 311–323.

Lewens, T. (2000). Function talk and the artifact model. *Studies in History and Philosophy of Science, Part C*, 31(1), 95-111.

Lewens, T. (2004). *Organisms and artifacts*. Cambridge, MA: The MIT Press.

Lipshtat, A., Loinger, A., Balaban, N.Q., & Biham, O. (2006). Genetic toggle switch without cooperative binding. *Physical Review Letters*, 96(18), 188101.

Lucks, J., Qi, L., Whitaker, W.R., & Arkin, A. (2008). Towards scalable parts families for predictable design of biological circuits. *Current Opinion in Microbiology*, 11(6), 567-573.

Mackenzie, A. (2010). Design in synthetic biology. *BioSocieties*, 5, 180-198.

McMillen, D., et al. (2002). Synchronizing genetic relaxation oscillators by intercell signalling. *Proceedings of the National Academies of Science*, 99(2), 679-684.

Morange, M. (2009). Synthetic biology: A bridge between functional and evolutionary biology. *Biological Theory*, 4(4), 368-377.

O'Malley, M.A. (2009). Making knowledge in synthetic biology: Design meets kludge. *Biological Theory*, 4(4), 378-389.

O'Malley, M.A., Powell, A., Davies, J.F., & Calvert, J. (2007). Knowledge-making distinctions in synthetic biology. *BioEssays*, 30(1), 57-65.

Pickering, A. (1984). *Constructing quarks*. Chicago: University of Chicago Press.

Pinch, T. (1985). Towards an analysis of scientific observation: The externality and evidential significance of observational reports in physics. *Social Studies of Science*, 15(1), 3-36.

Prather, K.L.J., & Martin, C.H. (2008). De novo biosynthetic pathways: rational design of microbial chemical factories. *Current Opinion in Biotechnology*, 19(5), 468–474.

Rheinberger, H.J. (1997). *Toward a history of epistemic things*. Stanford, CA: Stanford University Press.

Rinaudo, K., Bleris, L., Maddamsetti, R., Subramanian, S., Weiss, R., & Benenson, Y. (2007). A universal RNAi-based logic evaluator that operates in mammalian cells. *Nature Biotechnology*, 25, 795-801.

Roosth, S. (2013). Biobricks and crocheted coral: dispatches from the life science in the age of fabrication. *Science in Context*, 26(1), 153-171.

Sauro, H.M. (2008). Modularity defined. *Molecular Systems Biology*, 4, 166.

Schyfter, P. (2012). Technological biology? Things and kinds in synthetic biology. *Biology & Philosophy*, 27(1), 29-48.

Schyfter, P. (2013). Propellers and promoters: Emerging engineering knowledge in aeronautics and synthetic biology. *Engineering Studies*, (Available at doi: 10.1080/19378629.2012.762651)

Shapin, S., & Schaffer, S. (1985). *Leviathan and the air-pump.* Trenton, NJ: Princeton Univeristy Press.

Smolke, C.D., & Silver, P.A. (2011). Informing biological design by integration of systems and synthetic biology. *Cell*, 144(6), 855-859.

Specter, M. (2009). A life of its own. *The New Yorker*, 28 September.

Strickler, J., et al. (2008) A fast, robust and tunable synthetic gene oscillator. *Nature*, 456, 516-519.

Synthetic Biology Engineering Research Center. (2013). Testbeds. http://www.synberc.org/testbeds/. (Accessed on 21 February, 2013)

Tabor, J., et al. (2009). A synthetic genetic edge detection program. *Cell*, 137(7), 1272-1281.

Vincenti, W.G. (1982). Control-volume analysis: A difference in thinking between engineering and physics. *Technology and Culture*, 23(2), 145-174.

Vincenti, W.G. (1990). *What engineers know and how they know it.* Baltimore: The Johns Hopkins University Press.