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**THE GENESIS OF SYNTHETIC BIOLOGY: INNOVATION,
INTERDISCIPLINARITY AND THE IGEN STUDENT COMPETITION**

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ABSTRACT

Synthetic biology involves using interchangeable DNA sequences to genetically engineer organisms in new ways. In this paper I use the annual International Genetically Engineered Machines (IGEM) undergraduate student competition at MIT as a case study to examine ways in which synthetic biologists, several of whom were originally pioneers in software and computing, have attempted to establish this field. In particular, they have emphasised open source science and technology, the ‘private collective’ innovation model and interdisciplinary team-working. The registry of standard biological parts (‘BioBricks’), featured in the competition and maintained by MIT, is a good example of this open source approach to science. BioBricks are freely and publicly accessible, allowing research to develop quickly, and at relatively low cost. Notably, one student team used BioBricks in their project to engineer e-coli to recognise arsenic, which could be used for low-cost water testing in countries like Bangladesh, where many wells are arsenic polluted. At the same time, there are concerns about some aspects of the development of such tools and their potential for bioterrorism. Interviews with key scientists and engineers who established the competition and students who have taken part form the basis of the dataset.

INTRODUCTION

It has been said that we are living in the century of biology. Synthetic biology is emerging as the exemplar of this brave new world where the DNA of simple organisms, such as bacteria and yeast, can be engineered to perform new functions with potential applications across many sectors including pharmaceuticals, energy and computing. Researchers have identified at least two approaches to synthetic biology (O'Malley, et al., 2007). The most high profile is in synthetic genomics and exemplified by Craig Venter and his team's development of the first synthetic chromosome with the ultimate aim of developing a sustainable form of hydrogen. The second is based on BioBricks, standard biological parts that can be linked and inserted into the genomes of organisms, originally invented and then further developed by Tom Knight and his colleagues at MIT. This paper is focused on the latter, and examines the genesis of the BioBrick approach to synthetic biology.

In this paper I argue that the BioBricks represents a unique way to build a new field of scientific enquiry, which emerges from Knight's background as a computer engineer, who only late in his career turned to biology, and his experience as a teacher and student at MIT. It is based on the idea of using student competitions to establish and grow a science. Knight along with Randy Rettberg and Drew Endy developed the International Genetically Engineered Machines Competition (IGEM), in which undergraduate students work in interdisciplinary teams over the course of a summer using BioBricks to build biological machines with a faculty supervisor. The students are from a variety of backgrounds, biology, engineering, and bioinformatics contributing their own expertise to building the machine, and teaching each other, and their faculty advisors, relevant aspects of their disciplines to progress the development

of the machine as the whole. At the end of the summer, students develop a wide range of applications, some serious (cancer stickybots – bacteria that recognize colon cancer cells stick to them and commit suicide) and some whimsical (knocking out the metabolic path that make e. coli smell like faeces and inserting new ones that make the bacteria smell like bananas and mint), but throughout the competition and the IGEM Jamboree, the student conference at which work is presented, there is a sense of play and humour. In the course of their work, students develop new BioBricks, such as sequences for cell death, light recognition, and pattern formation, which are then uploaded to the Registry of Standard Biological Parts ('the Registry') at MIT, an open source database that is made available to other students and researchers; an anti-patent approach is another unique feature of BioBricks. Once students complete IGEM, many go on to do masters degrees and doctorates in the field. As a whole the field is very young; most of its key scientists are under the age of 45. Knight and his colleagues made a conscious decision to develop the field from the bottom up because the BioBricks approach was seen to be so unconventional and interdisciplinary blending biology and engineering that it would be difficult to get established scholars involved. It has been successful; the IGEM competition has grown rapidly as has the Registry, and the first generation of students that attended IGEM as undergraduates are completing their doctorates and entering academe having used the Registry in their research.

The BioBricks model is interesting as well in the ways in which it has addressed social engagement, which it has attempted to blend with the rest of the scientific agenda, though not always very successfully, in IGEM and in the conferences the

BioBricks Foundation sponsors, such as SB 1.0-4.0, involving social scientists and NGOs voicing concern.

The purpose of this paper is to explore critically the model of knowledge generation used in BioBricks, looking in particular at its genesis in biological computing, the private-collective (or open source) innovation model, interdisciplinarity and engagement with social concerns particularly around biosafety but also increasingly of corporate control. It is likely that whereas once BioBricks, IGEM and the Registry were inextricably intertwined, that they are increasingly becoming disaggregated as synthetic biology as a field grows and more investment is made available both from public and private sources. The BioBricks model of growing the field of synthetic biology breaks down traditional boundaries of research and teaching, biology and engineering, open and closed source knowledge, and the nature of disciplinary knowledge and expertise, and synthetic biology itself erodes the distinction between life and machine (see also Fujimura, 2005). As it does so it raises concerns for social movement organisations about regulation and the sanctity of life, which the BioBricks community has attempted to deal with by advocating self governance. So far this has been a successful strategy, but the true test of this will be when the first BioBrick products are ready to be produced because it is likely to be some time yet before they are made available.

TOM KNIGHT AND THE INVENTION OF BIOBRICKS

Knight has spent most of his life at MIT. He began working there at the age of 14 as a high school student, when he secured a job as an electrical engineer in the artificial intelligence lab. Much of his career was spent as an electrical engineer, where he

designed and built lisp, or Knight, machines, which were the first single use computers and paved the way for the commercialisation of laser printers, Windows operating systems and the computer mouse. He also worked on Arapnet (the precursor to the internet), interfaces and designed the 'packets' data transfer system, which is the basis for information transfer in the internet. As an electrical engineer, he believed Moore's Law, the idea that computer power grows exponentially, had its limits and that the atomic scale was fast being reached in silicon chip-based computer circuit designs. In the early 1990s, increasingly bored by traditional computer engineering and dissatisfied with its limits, he read Harold Morowitz's work, a physicist who later became a biologist, who worked on mollicutes, which are a type of very small organism that only contain a billion atoms. Knight reflected "Morowitz's work laid out, in words I could understand as an engineer, an agenda that seemed so exciting I had to go with it. Here's a class of organisms so simple that maybe we can understand everything there is to know about them" (Knight quoted in Morton, 2005). But as a computer engineer he was ultimately imagining a time when computers would move from physical to biological systems. A key moment came when he realised that a teaspoon of programmable bacteria could have a million times more memory than the world's largest computers, and potentially more speed than many billions of processors. As Knight says 'There is one megabyte of information in something the size of a cell. But not only that, it divides, which no other engineering system does, so you end up with an Intel processor along with the factory that makes them.' (Tom Knight, interview)

Underpinning this is the idea held by those at the artificial intelligence lab at MIT for some time that machine intelligence will only come from millions of small computers

that are interlinked, rather than from one large computer. This is analogous to the workings of the neural networks that comprise the brain.

To begin the switch, Knight began taking biology classes in 1993, while simultaneously teaching electrical engineering and talking with the MIT Artificial Intelligence Lab funders, the Defence Advanced Research Project Agency (DARPA), about biological information-processing systems. In 1995 he received funding from DARPA to begin building a molecular biology lab in the artificial intelligence department. The next year he began experiments, and as an engineer was increasingly frustrated with the lack of standardization in biology, saying that ‘biologists talk about having “good hands” in the lab, and everyone does experiments in different ways. When you put two pieces of DNA together you need a standard way of doing this’ (Tom Knight, interview). Knight likens this stage of the engineering of biology to the point of the industrial revolution in 1864 when screw threads were standardised, allowing for mass production of goods.

In 1999 Knight invented BioBricks, a standard for DNA, with identical restriction enzyme structures, allowing DNA strands to be ‘snapped’ together and assembled similar to children’s Lego blocks. BioBricks are the electrical engineering of biology, working in analogous ways to key components in that field, logic gates, switches and clocks, which are interchangeable. The ‘current’ is the rate at which RNA polymerase, the molecule that transcribes DNA into mRNA, moves along the DNA strand. Knight developed the first six BioBricks, and uploaded them to the Registry in 2001.

Drew Endy came to MIT as a new recruit in 2002, with a background in civil engineering he began studying molecular biology as part of his PhD, which was a computer model of a virus that infects *E. coli*; he was looking at processes that occur as the virus infects the bacteria. To test the model, he rearranged the virus' DNA so that proteins would be synthesised in a different order, then used the model to try to predict what would happen when the virus encountered *E. coli*. But in the lab the virus and *E. coli* would behave unpredictably, which he found frustrating. Following his PhD he went to work for a research institute in Berkeley where he was encouraged to take a traditional biological approach and “go back and understand a whole bunch more about the science of the organism in order to model it better...which is a fine and valid traditional path’ (Endy cited in Morton, 2005). Instead he decided to ‘build new biological systems – systems that are easier to understand because we made them that way.’

Developments of the technology allowing both the reading and writing (synthesis) of DNA sequences, partly as a result of the human genome project, were becoming possible by 2000, at which point the capacity of machines to read DNA was doubling every 18 months. Such “Carlson curves” predicted that by 2010 lab worker would be able to write and synthesise sequences for two human genomes each day (Morton, 2005).

Endy foresaw the beginning of an era where biology is no longer exclusively studied by examining natural systems, and looked for responses to his notion that ‘we should rebuild the natural biological systems we most care about and domesticate their

genomes', his only 'coherent' response to this request was said to be from Tom Knight at MIT.

IGEM

Knight's next innovation was to develop the Registry and the BioBrick approach to synthetic biology via undergraduate student projects and competitions, first at MIT in the January term then as part of a 10 week project in the summer. Knight brought Randy Rettberg from Sun Microsystems to MIT who, along with Knight and Endy, developed IGEM. IGEM was developed based on the model of Lynn Conway's 1978 MIT course on very-large scale integration (VLSI), which Knight attended. Conway, a computer scientist from XEROX and Carver Mead from Caltech had developed a method for decoupling silicon chip design from manufacturing, which was an important innovation at the time as it allowed designers to map circuits without having to manufacture them. Chip design and manufacture had previously been restricted to major corporations that had foundries. Students for the first time were not only able to learn VLSI, they were able to design circuits and have them built. Upon designing circuits they sent their plans via Arapnet to a chip foundry in California, which sent the chips back a month later. Out of this pedagogic model emerged student projects that enabled the cellular telephone, palmtop computers and games consoles (reference).

Knight and Endy based their Independent Activities Period class at MIT in January on the earlier VLSI course. Students were to design DNA circuits, sequences coding for certain proteins, and sites for proteins to bind and therefore turn genes on or off. Their sequences would then be emailed to Blue Heron, a gene synthesis company in

Seattle, and the DNA would be mailed to MIT and inserted into E. Coli. DARPA funded the synthesis, as it had funded the chip production for Conway decades before.

The first MIT synthetic biology competition started in 2004 with the question ‘Can simple biological systems be built from standard interchangeable parts and operated in living cells?’ BioBricks were made available to students from the Registry, and students were encouraged to develop their own and upload them to the Registry. In 2004 there were 5 teams from US universities, in 2005 the first International Genetically Engineered Machines Competition (IGEM) had 13 teams from 4 countries, in 2006, there were 37 teams from 15 countries, and in 2007 there were 54 teams and hundreds of competitors from all over the world. Among the projects already mentioned, students have also developed bacteria engineered to recognize light and respond to form pictures, and an arsenic biosensor in which bacteria have been engineered to change colour in the presence of arsenic, which could be extremely valuable for developing countries like Bangladesh where wells have high rates of natural arsenic contamination.

A NEW SCIENCE DEVELOPED THROUGH UNDERGRADUATE WORK

IGEM has been the basis for developing the BioBrick approach to synthetic biology, destabilising traditional notions of expertise and learning. In 2007 Endy was quoted as saying ‘One of the most amazing things about the jamboree this year was how much I was able to learn’. Also Craig Venter, who is not a part of IGEM but who is critical of pedagogical traditions in biology said ‘The way biology is normally taught, it comes across as pretty dismal – you memorise lots of facts than then you regurgitate

them...[IGEM] approaches things from a problem-solving and design perspective.

That I think is a huge leap forward'. (Endy and Venter cited in Trivedi, 2007)

IGEM also challenges traditional notions of expertise, as the students work in interdisciplinary teams teaching each other what they need to know to build the machine.

'That was the startling thing for me out of IGEM, when we suddenly have 3 biologists and 3 engineers in the same room, undergrads, and I didn't realise the difference the different schooling had on our ways of thinking, our ways of approaching problems. It was really revealing to me, I had never really considered it before. It was kind of like, we were all at the same university, we've all gone through the same educational system, just because that gentleman's studying natural science shouldn't mean he should be any less intelligent or think in any other way than I do. And because he is an engineer he thinks about problems from a very different perspective. But the great thing about IGEM was that by the end of the summer we'd both traded almost methods, to the point where we had both approaches.' (Interview, IGEM Student)

Students also teach their faculty as well as the other way around. Tito Jankowski a member of a team from Brown said 'Synthetic biology is new to the faculty; they didn't grow up with it. Collectively our team knows a lot more than our advisers.'

Faculty members agree, Gary Wessel, his advisor reflected 'We are a different generation, and we were trained to compartmentalise our education to the point where we excluded anything that wasn't specifically in our domain.' (cited in Trivedi, 2007)

Randy Rettberg, the current director of IGEM, describes his conceptualisation of building the BioBricks approach along with his pedagogical philosophy as:

'What I'm trying to do is put back some courage into the undergraduates the idea that they should trust themselves. And then, I'm trying to teach the instructors that if you do that you'll learn from them. It has really happened that, as a result of doing IGEM, the instructors themselves have learned absolutely critical things. In the end, after about 2 months, the students can outdo the instructors. The students have 500 parts [from the Registry], as

opposed to the instructor's one or two, and the students are saying "what shall we put together"? The students now can do what I as a professor can't do. Boy that was weird! I'm starting to have a fair number of professors who started saying "could you send me some of the parts you sent out to the IGEM teams for my lab?" So, it's starting to move to that next step.' (Randy Rettberg, interview).

As the BioBricks approach to synthetic biology develops, and as students begin to move through from undergraduate to graduate and finally to research positions, the links between IGEM, the Registry, and the BioBricks community become increasingly disaggregated.

'If we'd have had this conversation a year ago, the registry, synthetic biology and IGEM were so tightly inter-wrapped that it was very difficult to explain to someone that didn't have any knowledge of it, the differences. They're self-reliant and they encompass each other. What has happened I think, in the last year, very slightly, and it's still very much part and parcel, is that they've pulled away a little bit. The registry is the registry in its own right, it has labs using it, I'm using it now for example to do my PhD, and I have nothing to do with IGEM, in that respect. There are grad students at MIT, people all over the world now are starting to use BioBricks. Even indirectly. We're distributing fluorescent proteins for example. [Recipients] don't really get the fact that they're BioBricks, they just know that they've got fluorescent proteins with restriction sites on the end. And that's part of the idea of the society that we want to promote; we've got tools to give people and they can start to get around to that way of thinking and see the power of it, then we'll hopefully grow a community here.' (Interview, IGEM student)

BREAKING DOWN DOMAINS IN SCIENCE AND TECHNOLOGY

The breaking down of domains that the BioBricks approach represents evokes research on the importance of boundary work in science, between disciplines and types of expert knowledge (Gieryn, 1999; Jasanoff, 1990; Thrift, 1996). This literature drew originally from Foucault who focused on spatial aspects of knowledge boundaries, which were important in the formation of academic disciplines. 'Once knowledge can be analysed in terms of religion, domain, implantation, displacement, transposition, one is able to capture the process by which knowledge functions as a form of power and disseminates the effects of power.' (Foucault, 1980: 69) For

Foucault, then, knowledge, which carries with it power, is not only spatial but also social and historical. The concept of discourse, what is thought said or acted upon in any historical period, provides an analytical tool to assess what is seen as knowledge its attendant power dynamics, which can be applied to any field of knowledge including those in science. For example, madness could only be seen as divinely or diabolically inspired in the Middle Ages, and it could only be seen as a medical problem in the late twentieth century. Actors, scientists and others must operate within the discursive reality of the epoch in which they find themselves. Foucault sees boundary creation in the genesis of science ‘What was striking in the epistemological mutations and transformations of the seventeenth century is to see how the spatialization of knowledge was one of the factors in the constitution of knowledge as science’ (Foucault, 1984: 254).

The creation of boundaries is part of a social dynamic:

“The spatializing descriptions of discursive realities gives on to the analysis of related effects of power...[T]he formation of discourses and the genealogy of knowledge need to be analysed, not in terms of types of consciousness, modes of perception and forms of ideology, but in terms of tactics and strategies of power...deployed through...demarcations, control of territories and organizations of domains.” (Foucault, 1980: 70-1; 77)

Bourdieu’s concept of a force field usefully theorises a space where social contests take place involving definitions of science.

“What is at stake is in fact the power to impose the definition of science (i.e. the delimitation of the field of problems, methods and theories that may be regarded as scientific)...The definition of what is at stake in the scientific struggle is thus one of the issues at stake in the social struggle.” (Bourdieu, 1975: 23-4)

Kuhn’s structure of scientific revolutions (1962) though written before Gieryn, Foucault and Bourdieu, anticipates many of these points, as well as Latour, in

focusing on ideas that are thinkable, and intellectual strategies that are available in particular historical epochs, while stressing their social rootedness and attendant social contests, and is applicable to the way Knight and others developed the BioBrick approach to synthetic biology. For Kuhn, a goal of science is to construct models, or paradigms, that will account for as much empirical data as possible. As paradigms are pushed, anomalies, cases that do not fit with the model, appear. Some within a group of scientists will see that there is a problem, or crisis, and pursue what Kuhn called revolutionary science, which is the exploration of alternatives to taken-for-granted assumptions. The new paradigm appears beset by anomalies due to its lack of development, and most of the traditional scientific community will reject the new paradigm until there is enough evidence to support it. For a paradigm to be accepted 'First, the new candidate must seem to resolve some outstanding and generally recognized problem that can be met in no other way. Second the new paradigm must promise to preserve a relatively large part of the concrete problem solving activity that has accrued to science through its predecessors' (Kuhn, 1962: 168). This is apparent in the discourse of synthetic biologists. In the words of a Caltech engineering professor 'what I cannot create I cannot understand'. This is the approach that Drew Endy and Tom Knight take to synthetic biology, which traditional biology has not been able to resolve: that of building a living organism from scratch in order to understand it, so by applying engineering principles to biology, they both draw on the two disciplines while creating the new field of synthetic biology. It should be noted that building organisms from scratch by snapping together BioBricks is a distinctive approach to synthetic biology; others such as Jay Keasling take existing organisms, and rework metabolic pathways to produce specific products such

as arteseminin or biofuels; and Craig Venter's synthetic genomics approach is to build wholly new, but minimal, genomes designed to do specific things.

Paul Rabinow has characterised the views BioBricks synthetic biologists as:

'Everything that came before in biology was interesting and things were learnt, but it was not yet engineering, and not yet therefore able to achieve the kind of control over biological processes that this new discipline was able to achieve. The big question here of course is whether or not living systems are analogically close enough to the electronics industry, or indeed to the vision of nineteenth-century engineering and the standardized screw, to be directly applicable. Can the basic biological, evolutionary, non-linear aspects of living systems be engineered out?' (Rabinow in Lentzos, et al., 2008: 315)

PRIVATE-COLLECTIVE INNOVATION MODEL

Underlying the BioBricks approach is a tension between two models of innovation, the 'private investment' model based on returns to the innovator from private goods and protection of intellectual property, and the 'collective action' model, which refers to the collaboration of innovators in order to produce public good (von Hippel and von Krogh, 2003). Practices in open source software, on which the BioBricks approach is based have a history that stretches back to the 1960s and 1970s.

Scientists and engineers working in the public and private sector would often share, modify and build upon software and share it among colleagues, and Arapnet allowed developers to share code more widely and cheaply. This communal approach to 'hacker' culture, originally a positive term referring to talented programmers, was predominant at the Artificial Intelligence laboratory at MIT in the 60s and 70s (Levy, 1984).

MIT in the 1980s licensed some of the code written by its hackers to a commercial firm, which then restricted access to the 'source code' of the software, effectively a

key that allows a hacker to use and modify a software program, to its own personnel when many of the MIT hackers had been involved in writing it. Richard Stallman, one of faculty in the Artificial Intelligence lab, was troubled by this as well as the trend towards proprietary software packages that could not be modified. ‘Stallman viewed these practices as morally wrong impingements upon the rights of software users to freely learn and create.’ (von Hippel and von Krogh, 2003: 210) As a result, in 1985 he established the Free Software Foundation, which aimed to establish a legal means to retain free access to software created by hackers, which was protected by copyright law. Those who wrote software and wanted to protect free access to it could use their copyright to provide licences and guarantee rights to future users. The licence Stallman developed is the General Public Licence, sometimes called ‘copyleft’, a wordplay on copyright. It allows those who have a copy of the software rights to use it for free, examine its source code, change it, and distribute original or modified versions without cost.

Tom Knight is a product of this history at MIT, and iGEM and the Registry of Standard Biological Parts are based on the same open source approach to knowledge that was developed for software. The BioBricks Foundation has created a public licence allowing BioBricks to be protected as freely available genetic parts. This is based on the ‘private-collective innovation model’, which combines aspects of private investment with collective action (von Hippel and von Krogh, 2003). Developers invest their own time and resources to develop a product, either a BioBrick or software code, and while they could claim rights over what they produce, they instead upload it to a common source and provide it to the public for free, which results in

new knowledge essentially being provided at no cost. This raises the question of why developers should provide their intellectual products for free.

The goal of open source in the case of the Registry is to give away information on low level material, parts, while focusing on the creation and enforcement of intellectual property rights on complex products. In computer terms, Intel might patent its processor, but not the widely used and fundamental circuitry that is used throughout the computer industry, which is used in the processor. This practice of patenting high level material and making low level material freely available occurs in parts of the computer industry, but not in the pharmaceutical and biotechnology industries, which tend to patent more vigorously and then hold on to patents so the intellectual property (IP) cannot be used by others. This is understandable when it costs \$1 billion to develop and market a drug and companies need to recoup their investment. Jay Keasling, a synthetic biologist from Berkeley who received a grant for \$43 million from the Gates Foundation to develop a low cost way to produce artemisinin, an anti-malarial, from yeast, and is also part of the BioBrick Foundation, has argued that ‘if you’re going to develop drugs for the developing world you cannot afford to pay those royalties. And so we say: “Look, nobody’s really going to make any serious money off of these small components. The money is in the big applications. So let’s make a lot of small components and have them available as open source to everyone.” People can still patent the big applications – a lot of integrated components – but let’s at least have the components available as open source so everybody gets equal access, and that will further the field of engineering biology.’ (Keasling cited in Zimmer, 2007)

In this case, users of BioBricks, who are also the innovators, freely reveal DNA sequences. There is no commercial market for BioBricks as they are available to anyone. Innovators gain through widespread open dissemination as sequences are made available through the Registry, which is publicly accessible on the worldwide web. The innovators are mostly students who are not commercial rivals. The synthetic biology community is still fairly small, and many people know each other's work. Personal enjoyment and learning are motivating forces for those involved as well as the sense of well-being that comes from being part of a collective endeavour. The students also have a relatively high degree of personal autonomy and control over their creations. However there is also a tension around free riding; benefitting from public access to BioBricks, without contributing to the Registry. What is important here for the proponents of open source approaches is the embedding of hacker cultural expectations in students, which may work as long as the synthetic biology community is small and people know each other. Axelrod (1984) found that in testing this kind of dynamic through a prisoner's dilemma the reward for cooperation is higher than defection where there is no fixed end-point, which is why he suggests that where people see themselves as part of a project that is connected with a long term cooperative community endeavour that such endeavours are more likely to be successful.

Problems with associated with the private-collective model have already begun to arise with student participants in IGEM, as one informant said:

'The open source thing is a wonderful principle, but in practice it doesn't always work, and IGEM has shown that. There were labs this summer that weren't prepared to share their stuff. You get the other attitude which is, "we're happy to take but we're not willing to give"; we saw that at a few schools. "Isn't this a wonderful resource, we'll use these", completely blind to the fact that when they turn round and say, "No, this is our IP, we're patenting

this, we're going to do this, and are not prepared to put it in the Registry.” That raises all kinds of questions about the open source nature and whether it's sustainable and whether it will work. Because, at this early stage, it's all well and good but will it be able to remain like that? People will ultimately try and make money; people will ultimately try and patent ideas.’ (Interview, IGEM Student)

REGULATING SYNTHETIC BIOLOGY

The freedom that open source engenders is something that concerns some about synthetic biology. Researchers at SUNY Stony Brook created a polio virus synthetically in 2002, and those at the Centre for Disease Control synthesised the Spanish flu in 2005. Currently synthetic biology is self-governing, Blue Heron and other companies check for known pathogenic sequences, however a Guardian journalist in 2007 was able to obtain a sequence from a known pathogen from a gene synthesis company, so clearly these mechanisms are not fail safe (reference). Though it is possible, many synthetic biologists think the risk of bioterror is low. As one scientist interviewed for this research said ‘if I wanted to kill a lot of people there are much easier ways to do it; I'd probably just poison the water supply rather than use synthetic biology’ (Synthetic Biologist Interview). Jay Keasling similarly said ‘If I wanted to do evil and harm, I probably wouldn't choose biology to do it. It's damn complicated. Anyone sophisticated enough to know how to use these biological components that we're making freely available would have been able to do it anyway, to some extent.’ It is also why synthetic biologists have focused on self regulation, by engaging with such issues within the community. According to Keasling ‘If we choose to regulate the industry, we have to be willing to pay the price for that, which means there won't be cheap antimalarial drugs developed and there won't be potential biofuels developed and other drugs for other diseases and cleaning up the environment and all the things that come from this area.’ (Keasling cited in Zimmer,

2007) That said synthetic biologists are well aware of potential dangers from misuse of the technology. As Drew Endy told one group of graduating IGEMers ‘Imagine when the next biological attack happens...we’ll have one in the future eventually using a BioBrick. The most important thing to be prepared for, when that happens, I think is to make sure that our countries do not re-militarise biology, because we can’t afford that for reasons that are obvious. There’s so much you can do that’s harmful.’ (Endy, 2007)

Endy describes his reasons for engaging with regulatory, biosafety and public attitudes aspects of the technology as

‘my interest in biosecurity issues, my interest in the ownership, sharing and innovation framework, and my interest in the community and its organization all have to do with the practical limitations I’ve encountered to do the work that I think is important. I’d like to say there’s some noble instinct...but in practice I’m driven to go talk to ...many... people because, if I don’t the things I’m trying to do will never become possible. They’ll just be dead in the ground. So the issues of human practice occupy my time, and perhaps even the majority of my time, simply because they are the greatest limiting factors.’ (Endy, 2008: 321-2)

Paul Rabinow (2008) has critiqued the notion that benign self regulation by synthetic biologists, along the lines of the so-called Asilomar conference on rDNA in 1975 is possible today. He suggests that there are several ways in which life is now different from the 1970s. The main difference has been globalisation and growth of science, with many thousands of world-class scientists. Second the internet has allowed production and dissemination of scientific and technological knowledge, which is not restricted to a select few. Third, we live in a security environment that goes beyond safety (Rabinow in Lentzos, et al., 2008: 320). Fourth, as Gaymon Bennett points out, industry is involved in funding science more than ever before, with ‘the power of industry to make claims on what counts as science’ (Bennett in Lentzos, et al., 2008:

320). This is the basis of the ETC group's critique of synthetic biology; British Petroleum for example recently invested \$500 million in synthetic biology research at UC Berkeley. There are many joint ventures between energy companies, agribusiness, chemical, pharmaceutical, automobile and synthetic biology companies and involves major companies such as DuPont (chemicals), Tate & Lyle (sugar), ConocoPhillips (energy), Shell (energy), General Motors (automotive), Syngenta (biotechnology), Monsanto (biotechnology), Bristol-Meyers Squibb (pharmaceuticals), Chevron (energy) as well as the US Department of Energy (ETC, 2008). The critique is based on the capitalist appropriation of biomass to develop the post petroleum economy that synthetic biology is said to deliver, and the effects this will have on land degradation and appropriation in the South as well as on climate change.

PLAYING GOD?

In an earlier introduction to synthetic biology ETC (2007) also criticised suggested that synthetic biologists were playing God without accountability. 'Today scientists aren't just mapping genomes and manipulating genes, they're building life from scratch – and they're doing it in the absence of societal debate and regulatory oversight. Dubbed "genetic engineering on steroids", the social, environmental and bio-weapons threats of synthetic biology surpass the possible dangers and abuses of biotech' (Thomas, 2007: 1). When Keasling is asked whether he's playing God by creating new life forms he responds 'it's easy to say those kinds of things when you don't have malaria. It's quite another thing when you're ill and don't have the means to come by effective, safe drugs' (Keasling cited in Zimmer, 2007). The ETC response is 'Advocates insist that synthetic biology is the key to cheap biofuels, a cure

for malaria and climate change remediation – media friendly goals that aim to mollify public concerns about a dangerous and controversial technology. Ultimately, synthetic biology means cheaper and widely accessible tools to build bioweapons, virulent pathogens and artificial organisms that could pose grave threats to people and the planet. The danger is not just bio-terror but “bio-error”. (ETC, 2007: 1)

CONCLUSION

This paper has illustrated how the BioBricks approach to synthetic biology was conceived and developed, focusing on its boundary-crossing nature, and the way it destabilises notions of discipline, access, and pedagogy, focusing on the unique method by which its founders developed a new scientific field. It also outlined many of the challenges faced the synthetic biology as it grows. As biological products get closer to market, synthetic biologists and publics will have to engage with the private versus public aspects of intellectual property, regulatory and ethical questions attendant with the technology. Synthetic biologists have built in public engagement with the development of the field, and continued commitment to legitimacy, through governance structures, will be crucial if the field is to enjoy public support, particularly around issues related to safety, bioterrorism, and corporate control.

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