Opening up the Future(s) of Synthetic Biology

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Opening up the future(s) of synthetic biology

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Abstract

Much of the discussion surrounding synthetic biology involves some degree of speculation about the future. This paper reports on two workshops we held with the aim of 'opening up' and exploring possible futures for synthetic biology, one at the Synthetic Biology 4.0 conference (Hong Kong, October 2008) and the other at the BioSysBio meeting (Cambridge, UK, March 2009). We developed an interactive 'causes and consequences' exercise for these workshops, with the aim of creating a space for members of the synthetic biology community to discuss issues about the future of the field that they might not regularly explore in their daily work. We analyse the outputs and discussions from these workshops in the light of three key themes: the connections between social and technical issues in synthetic biology, the roles and responsibilities of synthetic biologists in shaping possible futures for the field, and the suitability of this method for opening up discussions about the future.

Keywords: synthetic biology; expectations; futures; science & technology studies; reflexivity

Introduction

Synthetic biology is a field of research concerned with using engineering principles to design biological systems. The origins of this approach can arguably be traced as far back as the early twentieth century (Pauly 1987; Campos 2009), but over the past 10-15 years a school of synthetic biology concerned particularly with 'parts-based' genetic engineering has been growing rapidly (e.g. Endy 2005; Andrianantoandro et al. 2006). New teaching and research initiatives, communal repositories of biological parts and tools, and dedicated conferences and journal publications, are all being developed to advance this field. But securing support and resources for any new discipline is no trivial endeavour. Convincing others that they should invest their time and/or money often relies on making predictions about the potential payoff of such investments. Expectations about the possible future of a technology are also strategically important for generating enthusiasm and momentum within a research community. Indeed, much of the current discussion and interest in synthetic biology revolves around its *potential* — the potential of this technology for innovation, profit, misuse, and so on. The number of new and imaginative initiatives being developed by the synthetic biology community[3]

[1] ESRC Genomics Policy & Research Forum, University of Edinburgh, St John's Land, Edinburgh EH8 8AQ
[2] ESRC Innogen Centre, University of Edinburgh, High School Yards, Edinburgh EH1 1LZ
[3] Such initiatives include the development of a Registry of Standard Biological Parts (http://www.partsregistry.org/), an undergraduate competition designed to help populate the Registry with biological parts (the International Genetically Engineered Machine or iGEM competition,

suggests that its members are guided by a strong vision of the potential and the future of this field, one that differs somewhat from traditional life science disciplines.

Expectations about the future are not just important for generating support and momentum within a scientific research community, they can also be highly influential when it comes to decisions about the funding and regulation of particular technologies. Forecasting and analysing the future is an increasingly important part of science policy, and a number of approaches are routinely used to map, guide and intervene in possible futures (see below). As well as policymakers, sociologists of science are also interested in futures, expectations and technological potential, trying to understand how visions of the future might influence scientific cultures, practices and knowledge production in the present. The 'sociology of expectations' in particular is concerned with how technologies, industries, and ethical, legal and social issues are related to visions of the future (Borup et al. 2003). The aim of such research is "to engage with the future as an analytical object, and not simply a neutral temporal space into which objective expectations can be projected" (Brown and Michael 2003: 4). Indeed, research in the sociology of expectations suggests that discussion of the future is not idle speculation, but instead has real effects. Actions in the present are made legitimate by promises about the future (Brown and Michael 2003). Statements about expectations can mobilize funds and attention, and reduce uncertainty (Hedgecoe and Martin 2003). This makes promises (and the act of promising) essential characteristics of all new scientific and technological fields (Fortun 2005; Nowotny et al. 2001). Furthermore, research shows that the most radical claims about the future are likely to be found where there are *new* networks and activities (Brown and Michael 2003). This is because new fields "often require an incredibly visionary momentum in order to command investment and collaboration" (Brown 2003: 11).

The work we present here is an exercise designed to open up discussion about possible futures for synthetic biology. We are science & technology studies (STS) researchers who have been engaging with the synthetic biology research and policy communities since 2007.[4] We believe that one of the core contributions that a social science discipline like STS might make to emerging technologies such as synthetic biology is to 'open up' and draw attention to alternative possibilities for the future of the field (Stirling 2008). This is because STS studies the plural and socially situated nature of knowledge claims, and in doing so reveals "inherent indeterminacies, contingencies, or capacities for agency" (Stirling 2008, p.279) in technological development. 'Opening up' from this perspective involves drawing attention to the often implicit framing conditions and assumptions that underlie discussions of the future, and to the interconnections between social and technical choices. This can enable new questions to be asked, neglected issues to be addressed, and alternative technological pathways to be explored (Stirling 2008).

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http://2011.igem.org/), and an intellectual property framework for sharing biological parts (the BioBrick Public Agreement, available at http://hdl.handle.net/1721.1/50999).

[4] Over this period our engagement with synthetic biology and synthetic biologists has taken many forms: we have attended synthetic biology conferences and meetings (as observers and speakers), we are co-investigators on synthetic biology grants with scientists and engineers, we are advisors and teachers on undergraduate and graduate synthetic biology pedagogical initiatives, we participate in public engagement exercises on synthetic biology, we sit on policy advisory bodies relating to synthetic biology, and so on. We are in part ethnographers but clearly also participants in the making of this field.

Our aims in relation to this paper have been three-fold, two largely process-oriented and one more concerned with content. First, we wanted to draw the synthetic biology research community (including natural scientists, engineers, and social scientists) into thinking about and discussing different possible futures for their field. Second, we wanted to develop a flexible and lightweight methodology for beginning such conversations, in a style and format suited to the community we work with. And third, we wanted to explore how synthetic biologists imagine and understand different possible futures for their field, and the ways in which they connect the technical and social dimensions of the discipline they are creating.

Studying the future: Foresight, scenarios and other methods

At a policy level, one of the better-known approaches to engaging with the future is through the use of foresight exercises. These often use methods such as roadmapping, forecasting, and modelling. Foresight exercises are typically designed to develop recommendations that feed into policy discussions and decision-making,[5] and they remain a popular tool for European science policymakers.[6] However, there is an underlying tendency in many foresight exercises to presume that "development trajectories are stable and that the social implications of a technology are patterned into a technology at the outset" (Williams 2006: 336). Regardless of exactly which methods are used, Selin suggests that foresight exercises inevitably involve "a movement from open-ended complexity to simplicity" and "a radical constriction of variables" (Selin 2008: 1888). This sort of linear, 'essentialist' view of technological innovation that may be built into foresight exercises can project the future as largely determinate and imminent. This stands in contrast to a large body of empirical social science research that points to "the unpredictability, and indeed serendipity of social and technical outcomes" (Williams 2006: 329).[7]

Initiatives that are more interested in uncertainties and contingencies in different technological futures often rely on methods such as scenario-building and horizon-scanning. At least one detailed scenario-building exercise has already been undertaken for synthetic biology (Aldrich et al. 2008). The Woodrow Wilson Center's Foresight and Governance Project has conducted an exercise to study the policy implications of synthetic biology as well as its potential benefits and possible harmful effects.[8] The EU TESSY initiative (Towards a European Strategy for Synthetic Biology, 2007–2008) had a roadmapping component.[9] A Synthetic Biology Roadmap for the UK was also published in 2012.[10] This document outlines the conditions required for the development of synthetic biology in the UK, and addresses issues of responsible research and innovation.

[5] UK Government Chief Scientific Adviser John Beddington describes the aim of the UK Foresight programme as "to bridge the gap in policy making between the short and the long term" (http://www.foresight.gov.uk/index.asp).
[6] See for example the 2011-2012 European Commission foresight project on 'innovation futures' (http://www.innovation-futures.org/)
[7] To cite a frequently quoted example, who would have predicted that lasers would find uses in medical applications and DVD technology?
[8] http://www.synbioproject.org/
[9] http://www.tessy-europe.eu/index.html
[10] http://www.rcuk.ac.uk/documents/publications/SyntheticBiologyRoadmap.pdf

The interactive 'futures' exercise we have developed and tested does not fall neatly into either traditional foresight or scenario-based initiatives. Rather, it has different founding assumptions that are more closely aligned with social science methodologies such as Constructive Technology Assessment and Real-Time Technology Assessment (Rip et al. 1995; Guston and Sarewitz 2002). These explicitly experimental approaches attempt to integrate social science and policy research alongside natural science and engineering research from the earliest stages of R&D, often with the underlying normative commitment that such integration can help shape the future in more desirable ways. In practical terms, they aim to build a reflexive capacity into the R&D enterprise that encourages communication among potential stakeholders and "allows modulation of innovation paths and outcomes in response to ongoing analysis and discourse" (Guston and Sarewitz 2002: 100). Such reflexivity is not oriented towards predicting the future, and certainly cannot eliminate uncertainty about the future, but it can assist with identifying areas of uncertainty and maintaining a degree of flexibility in response to unanticipated developments.

Our target group for this work has been the synthetic biology research community. We wanted to create a space for synthetic biology researchers to identify and explore contingencies and uncertainties underlying some commonly articulated expectations about synthetic biology. Acknowledging that shared expectations can "become depersonalized and, as they travel more widely, take on a more mythic quality that is less tethered to technical practices or identifiable actors" (Selin 2008: 1887), our workshops aimed to explore and perhaps begin to 're-tether' some commonly articulated expectations in the synthetic biology community by means of group discussions relating to possible future developments in the field.

Methods

The results presented here are based on two synthetic biology 'futures' workshops: one held at the SB4.0 conference (Hong Kong, October 2008) and the second at the March 2009 BioSysBio meeting (Cambridge, UK). These are two major international scientific conferences in synthetic biology, notable in that they allow social science contributions to their programmes. Our motivation to hold these workshops at recognized synthetic biology conferences was to attract informed participants with an interest in the future of the field. We were not attempting to elicit views about synthetic biology from a diversity of stakeholders, but rather wanted to make use of our official place in the conference programmes to learn more about how synthetic biologists imagine the future of their field.

The workshops were open to all conference participants, but took place in parallel with (and thus competed for participants with) other talks and sessions. At SB4.0, the workshop had ten participants, five of whom were practicing scientists, with the other five being social scientists and policy/NGO representatives. The BioSysBio workshop involved approximately 30 participants, about half of whom were early-career researchers in systems or synthetic biology (PhD students and postdoctoral researchers), with the other half comprising more senior researchers in synthetic biology, and a small number of investors and social science participants. These sample sizes are not intended to be seen as representative of the field of synthetic biology, but they nonetheless provide insights into informed participants' thinking about their field.

Provocative statements

The workshops were based around 'causes and consequences' discussion of nine single-sentence, provocative statements (see Table 1). These are statements we devised on the basis of our observations of the synthetic biology community, and are also informed by our disciplinary approach and normative concerns (see Discussion for elaboration). Each of the statements referred to a concrete possible development in synthetic biology, and was anchored to claims or ideas we have heard during synthetic biology meetings and conferences, or to points made in the science and policy literature on synthetic biology. The statements were designed be readily understandable to the participants, and to have some relevance to the field as a whole. We intended the statements to open up possibilities for discussing a variety of issues in synthetic biology, relating to scientific and technological developments, economics, regulation, participation, privatization, ethics, and so on.

The idea behind presenting such statements is adapted from previous work by Oreszczyn and Carr (2008), who developed short, single-sentence scenario statements to explore the precautionary principle in relation to genetically modified crops in the UK.[11] They suggest that presenting a number of diverse scenarios "is particularly appropriate for situations involving controversy and scientific uncertainty" (p.478), both of which are characteristics of synthetic biology. We hoped to allow participants to explore different futures for synthetic biology in an "open, imaginative and non-confrontational way" (Oreszczyn and Carr 2008: 482). Several of the statements were purposely left somewhat ambiguous, to trigger discussion and allow scope for interpretation and creativity. Furthermore, the statements were not linked to specified points in the future, allowing participants to discuss how plausible, and how near or far away each scenario might be.

Workshop format

Each workshop lasted for 1.5 hours, and was facilitated by the authors of this paper and a third colleague (P. Robbins). The first 10 minutes were devoted to introducing the workshop. This introduction focused solely on explaining the exercise (not on providing background information or our conceptual and methodological rationale for the workshop).[12] Participants were then presented with the nine statements. They were asked to choose one statement in particular that appealed to them, and to stand by a poster on the wall displaying that statement. Either alone or in groups (depending on the number of people clustered beside each poster), participants had to think of possible causes and consequences for the statement. 'Causes' related to how or why the situation

[11] For an overview of methods for scenario building see Bradfield et al. (2005). We realise that our methods are less rigorous than longstanding, systemic, futures methods such as the Delphi technique (Strauss and Zeigler 1975), but the provocative statements we developed provided us with a simple and flexible way of quickly focusing discussion on possible future scenarios for synthetic biology.
[12] This was partially owing to time constraints, and also because we were interested to see what kind of conversations would be stimulated by this exercise without guiding participants as to the broader questions we were interested in as social scientists.

described by the statement might arise, and 'consequences' referred to what might happen if this situation did arise. Participants were asked to write their ideas on Post-It notes, and to stick them to the poster (with causes placed above the statement, and consequences below). They were also asked to cluster or link the Post-It notes if they thought this was appropriate. A slide of prompts was put up for participants to refer to if necessary (Fig. 1). This stage of the workshop lasted about 45 min, and participants were given the opportunity to move around and work on more than one statement if they wished. The interactive and experimental nature of the exercise was made clear; we encouraged participants to be open-minded, and to discuss the statements among themselves. We emphasized that there were no right or wrong answers, and that the aim of the exercise was not to produce consensus but to raise and explore a range of causes and consequences.

At the end of this stage, participants were given an opportunity to walk around and read each of the posters (and to add any further Post-It notes if they wished). We then held a plenary discussion for the final 30 min, to discuss the statements, the causes and consequences identified, and some of the issues they raised.

Digital photographs were taken of the posters; the causes and consequences posted are collated and represented in Figs 2–4 and Supplementary Figs 1–6. The content of these posters forms the basis of our findings and analysis. The plenary discussions as well as the 'causes and consequences' sessions also were voice-recorded and transcribed; this data source is used to supplement the analysis, as it allows us to hear how participants discussed the points that they wrote on Post-It notes, and to identify general levels of agreement or contention about the issues.

Results

Participants identified possible causes and consequences for each of the nine statements (see Figs 2–4, Supplementary Figs 1–6). These touched on a broad spectrum of issues, including technological factors, environmental considerations, economic, commercial and geopolitical concerns, regulatory developments, and public perceptions of synthetic biology. Notably, some statements were the focus of livelier discussion and generated more comments than others. Here we summarize the responses to the three statements that received the most comments, giving examples of some of the specific causes and the consequences that were identified in each case. Our first two statements – "A synthetic pet organism (like a Tamagotchi) becomes popular with teenagers" and "Synthetic biology delivers biofuel for under $10 a barrel" – are self-explanatory, if rather speculative. The third – "The iGEM competition is closed down" – needs some further explanation. iGEM stands for the International Genetically Engineered Machine competition. This is an annual event where interdisciplinary undergraduate teams work together over the summer break to design a genetic circuit to perform a function of their choosing. The competition has been very effective in bootstrapping the field of synthetic biology and enthusing students to pursue further research (see Frow and Calvert, forthcoming). As part of the competition the teams have to deposit standardized biological parts, or 'BioBricks', into an open-access Registry of Standard Biological Parts. The BioSysBio workshop group had several participants who had previously taken part in the iGEM competition.

A synthetic pet organism (like a Tamagotchi) becomes popular with teenagers

Causes

This statement triggered some of the more imaginative discussions in the workshops (Fig 2). The SB4.0 group identified some scientific developments that might be necessary for the production of a synthetic pet organism (including simple feeding requirements and disease resistance), but most of the discussion extended beyond scientific and technical concerns.

Both groups raised the issue of regulation early in the discussion, pointing out that appropriate regulation would have to be in place before a synthetic pet could be developed. They felt that there needed to be general societal acceptance of the safety of synthetic biology before synthetic pets could be developed. The SB4.0 group suggested that "much time" would have to elapse before such acceptance would be widespread, and the BioSysBio group suggested that "better education of kids" would be needed. One point raised by the BioSysBio group was that a synthetic pet could be produced by an iGEM team, raising questions about the responsibilities of synthetic biologists.

Both groups discussed the important role of economic factors in bringing about this future. SB4.0 participants mentioned corporate power, suggesting that Sony would have to have a monopoly in order for a synthetic pet to be developed. In the BioSysBio group, discussion of economic issues was more pragmatic, with talk of how the price of the pet would have to fall within a particular disposable income range in order to be affordable by teenagers. A question raised in this discussion was "What would sell?" (One answer given was "something furry.").

Consequences

Turning to the possible consequences of synthetic pet organisms, both groups suggested potential negative implications for the field of synthetic biology. Escape came up in both discussions. For example, a BioSysBio participant said "invariably one of them will escape and you'll have some glowing creature running round the countryside." The SB4.0 group talked about how synthetic biology pets might outcompete native ecosystems, whereas in the BioSysBio group the conversation went the opposite way, speculating about how synthetic organisms might "regress back" to their wild-type form. One possible consequence identified by the BioSysBio group was a call for a ban on the technology. Dystopian visions were prevalent in the SB4.0 group, with projections that new synthetic mutants might take over the world and enslave humans ("I for one welcome our new Tamagotchi overlords," one participant interjected). Both groups discussed the possibility of pet fights — "You'd have a Tamagotchi fight club. Who could breed the biggest baddest pet?" (BioSysBio) — and raised the issue of animal rights. The BioSysBio group talked about how synthetic pets might be maltreated, and suggested the formation of the "Royal Society for the Prevention of Cruelty to Synthetic Pets," adding "they're not just for Christmas you know!"

Both groups also suggested possible positive consequences for synthetic biology, such as increased interest in and acceptance of the technology. Other positive consequences noted by the SB4.0 group included more general development of synthetic biology and applications for many areas of the economy (e.g. biofuels, treatments for diseases, and new materials). They went on to talk about whether synthetic biology might become more normalized and domesticated, as we have seen with computers. This was linked to a broader discussion about whether synthetic biology might ultimately become a ubiquitous but somewhat mundane technology — merely a fun way to make new games, rather than developing 'major' applications.

BioSysBio participants were excited by the technological potential and applications of a synthetic pet, and engaged in wide-ranging and imaginative discussions around these issues. They discussed whether it was possible to put legs on a Venus fly-trap, or to make lava lamps using colour-changing mice, tortoises that are also TV screens, and mini fighting dinosaurs. There was also talk of pets being used as surveillance organisms by parents, pets as alarm clocks, and pets that smell of bananas or mint (drawing on past projects developed by iGEM teams). This led to discussion of pre-flavoured chickens (with chilli and cumin), which would then cook themselves when they died.

The possibility of biohacking was noted in both workshops. An SB4.0 participant pointed out that "something like this could become an accessible hacker platform that could start to be used for other things. It starts off as a pet and ends up as a sensor" (SB4.0). Participants moved on to talk about 'pets' that monitor biological states such as insulin levels, or detect sexually transmitted diseases, or pets that filter water.

Finally, this statement provoked references to science fiction throughout the discussions. *Jurassic Park* came up more than once, there was reference to *Red Dwarf*, and to the book *Do Androids Dream of Electric Sheep? Harry Potter* was mentioned in the context of a pet dragon. In a reflexive manner, one of the BioSysBio participants noted "This is science fiction, but it becomes science fact if we don't pay attention."

Synthetic biology delivers biofuel for under $10 a barrel

Causes

This statement generated lively discussion at both SB4.0 (where the workshop followed a number of biofuel-related talks earlier in the conference) and BioSysBio (Fig 3). By and large, this statement was discussed as being a realistic possibility; one Post-It note described it as "inevitable." The causes discussed in relation to this statement fall under three main headings: scientific and technological developments, economic factors, and geopolitical considerations.

Possible technological developments identified as leading to viable biofuel production included a breakthrough in cellulosic degradation, the generation of hydrogen-producing bacteria, and the development of mutation-free organisms. The BioSysBio group talked at some length about how the choice of feedstock would be crucial to the development of any biofuel scenario, and interestingly suggested that there would be quite different chains of causes and consequences depending on the feedstock.

Both groups highlighted the price of oil as a key economic factor in the development of cheap biofuels. They linked high oil prices to greater investment in alternative sources of energy (including biofuels), but one participant in the BioSysBio group noted that there have been previous spikes in the price of oil, and that "people have very short memories."

A number of geopolitical factors were also identified by both groups as influencing the price of biofuels. The United States, Brazil, China, India, and the OPEC nations were referred to explicitly. The growing demand for fuel from countries like China and India was identified by the BioSysBio group as a factor likely to keep oil prices high. Brazil was mentioned both in terms of its pioneering role in biofuel production, and as a source of biofuels from feedstocks such as sugar cane. The geographical origin of feedstock crops was identified as important by the BioSysBio group, and they distinguished between local production and the import of biofuels from other countries (particularly developing countries). Another geopolitical factor identified by the SB4.0 group was whether multinational oil companies would somehow intervene to stifle biofuel production, as they did with electric cars.

Consequences

In terms of consequences, this statement stands out among those presented here in that there was a noticeable difference between the two workshops. The discussion of consequences within the BioSysBio group was somewhat more speculative and exploratory than in the SB4.0 group, in which biofuel development at $10 per barrel was identified as largely negative.

For both groups, several of the consequences of producing biofuels at $10 per barrel were associated with environmental and agricultural changes. The SB4.0 group articulated a dystopic set of consequences for this scenario, including deforestation and landlessness due to increases in sugar and cellulose production; the development of an algal farming industry with negative impacts on marine ecosystems; and growing demand for feedstock and (nitrogen) fertilizers, resulting in increased greenhouse gas emissions. When we mentioned the largely negative tone of the consequences listed in the SB4.0 workshop during the plenary discussion, one participant maintained that "the positive [consequences] are pretty much taken for granted." The BioSysBio group discussed competition with land for food (crops and livestock) as part of scaling-up biofuel production, and identified competition for water as an additional consideration.

Both groups also discussed a number of consequences relating to industrial infrastructure, asking whether the business model of oil companies would have to change in light of increased biofuel production. One consequence identified by the SB4.0 group was that oil, energy, grain and forest companies might come to dominate synthetic biology. Both groups also discussed the implications of biofuel development for the automotive industry, one SB4.0 participant suggesting that the need for new cars that run on biofuel would result in a lot of scrap metal. The BioSysBio group questioned the assumption that the main use for biofuels would be as transport fuel for the automotive industry, asking what effect cheap biofuel production would have if battery-operated cars became the norm. They went on to discuss what one participant called more "banal" or domestic uses for biofuel, such as using biofuels to supply electricity, or to power water desalination efforts in drought-challenged areas.

The BioSysBio group treated biofuel production at $10 per barrel as a success and identified possible consequences for other areas of technology. For example, they asked whether growing demand for both food and fuel feedstocks might result in increased use of GM technology to deliver crops with higher yields. They also linked biofuel production at $10 per barrel to a decrease in the price of oil, predicting a possible shift in economic and geopolitical power away from OPEC countries toward biofuel-producing countries.

The iGEM competition is closed down

Causes

Both groups immediately identified biosafety and biosecurity concerns as possible reasons for the closure of iGEM (Fig 4). A cause noted by the SB4.0 group reads "One iGEM team creates something [that] if deliberately released is a threat to the world". The BioSysBio group noted that a superbug could be released by an iGEM team. The SB4.0 group discussed how the production of something merely 'provocative' might be enough to close down the competition. One participant elaborated: "It needn't be harmful or more damaging or needn't even work; it just needs to provoke people in a certain way – the Frankenfood way." The BioSysBio group also identified biosecurity issues as possible causes for iGEM closure: "The DoD [Department of Defense] just gets very paranoid about the whole thing and closes it down."

As well as biosafety and biosecurity concerns, both groups identified economic issues that could lead to the closure of iGEM. The BioSysBio group listed as their one of their causes "financial trouble for iGEM HQ," which they said could lead to "prohibitive costs for team entry". At SB4.0 there was discussion of how iGEM could become a more commercial, "corporate" and "serious" event. The SB4.0 group talked about how privatization of the Registry of Standard Biological Parts could result in iGEM closing down, as no open source parts would be available for competitors. (Interestingly, the BioSysBio group also explicitly linked the fates of iGEM and the Registry, but suggested that closure of the Registry would be a *consequence* of shutting down iGEM.) Key individuals were also linked to the future of iGEM: one cause noted by the BioSysBio group reads"2050: Randy [Rettberg] retires." This is interesting as it highlights the importance of a specific individual in ensuring the persistence of the competition (Randy Rettberg is the President of the iGEM Foundation, and is likely to retire long before 2050). An alternative cause noted by the SB4.0 group was that iGEM might close for non-controversial reasons, once the field of synthetic biology had been successfully established. This idea also came up in BioSysBio, with one participant saying that "maybe the role of iGEM is just to make the field self-sufficient, and build up a critical mass."

Finally, a scientific reason put forward by the BioSysBio group for the closure of iGEM was the suggestion that biology is just too complex. If this was the case it would undermine the premise on which iGEM is based — that biological systems can be built out of standardized biological parts — and make the competition unviable.

Consequences

In terms of consequences, both groups talked about how closing the iGEM competition could be devastating for synthetic biology as a whole. We see consequences such as "Game over for SB ☹" (SB4.0), and "synthetic biology field dies" (BioSysBio). Such consequences show that both groups identify iGEM as central to synthetic biology. The BioSysBio group mentioned in discussion that although the Synthetic Biology #.0 conferences are important for consolidation of the field, iGEM is perhaps more so. Another possible consequence of closing iGEM identified in both workshops was the dearth of young people entering the field. At SB4.0, one participant suggested that if iGEM were closed then new ideas for synthetic biology would become rarer, and that the field would become "business as usual." A BioSysBio participant explained that "one of the focal factors of the field is the influx of people – enthusiastic, creative people – and not existing established researchers", and that this influx would be jeopardised if the competition was stopped. Several of the postgraduate students taking part in this session said they would not be doing synthetic biology had it not been for the competition.

The BioSysBio group suggested that one consequence of closing iGEM could be that "industrial research takes off as a prime leader and academic research shrinks in comparison." Pursuing a slightly different line, they also suggested that shutting down iGEM could benefit the academic community and result in publication of more synthetic biology papers, because there would be less "babysitting" of students for academics to do over the summer. One of the participants added that a benefit would be that "undergraduates get their summer back."

Finally, a radically different future for iGEM was raised by both groups, suggesting that it might go underground if the official competition was closed (only the SB4.0 group put this in writing, however). At BioSysBio there was discussion of how the field might move into the garage or into the hands of DIY biologists.

Discussion

Here we analyse the data generated through the workshops with respect to themes outlined in the introduction. First, we consider the nature of the conversations about the future(s) of synthetic biology stimulated through these workshops. Next, we look at the connections that participants made between technical and social dimensions of synthetic biology during the workshop sessions, and the degree to which they implicated themselves as active agents in shaping the future of the field. In the conclusion, we evaluate the potential and limitations of this method for engaging with the future in both research and policy contexts.

Exploring diverse futures for synthetic biology

The dominant rhetoric of synthetic biology advances a powerful narrative of technological and social change through the engineering of life. One goal of these workshops was to open up discussion around different possible avenues for realizing the future of this technology, going beyond some of the familiar narratives we regularly hear associated with synthetic biology. To do this, we developed a series of statements drawing on our previous ethnographic fieldwork. These were designed to offer entry points for conversation across technical, political and social domains, and to touch on both nearer and longer term possibilities for the field. Some of the provocative statements we designed encapsulate key goals or ambitions that we have heard articulated repeatedly at synthetic biology conferences and meetings — for example, that the cost of DNA synthesis will continue to fall, that synthetic biology will deliver cheap biofuels, or that assembly and characterization standards for biological parts will be agreed upon. Some of the statements we devised were more speculative, for example proposing the domestication of synthetic biology through synthetic pets. This type of speculation certainly arises in synthetic biology meetings and papers, but is not as commonplace or as much a part of the 'assumed' future of synthetic biology as the first set of statements outlined above. And some of our statements drew on fears or concerns we have heard from the synthetic biology community, relating for example to the fates of community projects like the iGEM competition and the Registry of Standard Biological Parts. It is easy to assume that members of the still relatively small synthetic biology community would share the same goals, ambitions and understandings of the field. By crafting statements to encourage individuals to begin articulating their views, we were curious to see whether the causes and consequences identified by the workshop participants would be as straightforward as one might assume on the basis of how the field represents itself.

The discussions were rich, lively (sometimes hilarious), and wide-ranging. Furthermore, in a short period of time, the participants identified a variety of quite different causes and consequences around each of the statements provided, suggesting a number of possible futures for the field (including the possibility that synthetic biology as currently conceived might prove to be impossible). Interestingly, for a given statement participants often identified the possibility of contradictory futures. For example, the closing down of iGEM was linked to the possibility that synthetic biology would slow down ("SynBio field dies" / "field expansion slows") but also the increased productivity of research labs ("more SynBio papers" / "less babysitting of undergraduates"). We suggest that the diversity in possible narratives identified around many of the statements provides a potentially productive starting point for considering the plausibility and desirability of different synthetic biology futures.

Participants engaged seriously with each of the statements, while also injecting humour into the discussion. Many of the statements seemed to be treated as quite plausible in the short- to medium-term — for example, the SB4.0 group described the production of biofuels through synthetic biology as "inevitable," and to the statement "The BioBricks Registry becomes privatized" was added the pithy question "is it not already?" (Supplementary Fig 4). Other statements, such as the one about synthetic biology Tamagotchi pets, were projected further into the future ("much time elapses; no one worries about biosecurity any more"), and some of the statements were discussed without being anchored to any particular time point.

The data generated during these workshops reaffirm what Oreszczyn and Carr found in their research, that "the nature of the exercise allowed many voices to be heard rather than assuming that scientists speak with one voice" (Oreszczyn and Carr 2008: 492). Synthetic biology is an interdisciplinary field, and the workshops allowed expression of the diversity within this community. Furthermore, participants seemed to enjoy the freedom of the exercise — for example, in the BioSysBio workshop, one participant exclaimed "we're being creative!" while drawing connections between different comments on the group's poster. This demonstrates the flexibility of this method as a means of opening up conversation.

Connecting the social and the technical

In practice, many of the challenges facing synthetic biologists in developing this new field are social as much as technical, and this is something many of them are very much aware of.[13] In the data collected from these two workshops, we see clear interweaving of technical and social issues throughout the discussions, and in the written causes and consequences identified for each of the statements. This is consistent with findings from the sociology of expectations that suggest that creating visions for the future requires attending to the interconnections among technological, industrial, ethical, legal and social issues (Borup et al. 2003). The narratives that participants built around the workshop statements extended beyond the technical dimensions of synthetic biology; indeed, for several statements the number of sociopolitical considerations identified clearly outweigh the technical factors proposed (see for example the statements concerning iGEM, the Registry, BioBrick standards, synthetic pets, and the moratorium on synthetic biological products). Across the statements, participants raised a number of issues relating to economics, trade and geopolitics, biosafety, ownership, justice, education, and public engagement. In particular, economic issues came up in discussion of each statement, and ownership issues also feature prominently.

There was a tendency across the data collected to present quite broad and idealised representations of both the technical and social dimensions of synthetic biology. For example, discussion around the statement on synthetic pets suggested that basic technical breakthroughs would have to occur (such as the development of an organism with simple feeding requirements), that "acceptance of GMOs" would be necessary, and that "regulation" would have to be in place. By and large, the statements did not spark detailed discussions or problematization of what such regulation might look like, of what social acceptance might mean in practice, or of how the challenge of developing such an organism might be tackled. Thus, while the discussions clearly show that the workshop participants identify the interconnectedness of the technical and social dimensions of synthetic biology, there is a recurring tendency to assume straightforward or unproblematic developments in both respects. This is not intended as a criticism of the participants, but rather points to a limitation of the method used — with limited time for discussion, and an initial focus on opening up possible trajectories, it can be difficult to go beyond such broad or general statements. However, the comments and ideas generated by the workshop participants serve as useful starting points for more substantial discussions to explore possible futures in more detail.

Community and responsibility

One question we were interested in asking of the data collected is the extent to which synthetic biologists included or involved themselves in the narratives and trajectories they identified for the field, either as individuals or as a research community. A causal

[13] For example, see Endy in Lentzos et al. 2008 (pp.321-2).

and systematic analysis is not possible here; rather, our interest is simply to note how and when ideas relating to the roles and responsibilities of synthetic biologists came up during the workshop discussions. One superficial measure of this might be the mention of individuals or organizations associated with synthetic biology. Across the written causes and consequences, some names were specifically mentioned (including Drew Endy, Randy Rettberg and Craig Venter, who are all prominent actors in synthetic biology), the iGEM competition was discussed in conjunction with three of the statements, the BioBricks Foundation was identified twice, and synthetic biology companies including Amyris, Gingko Bioworks and LS9 were also mentioned.

iGEM teams were given an active role in some of the workshop discussions. In discussing the statement about synthetic pets, the BioSysBio workshop group came up with a number of ingenious ideas for possible characteristics of such pets. They also suggested that this hypothetical pet organism might be produced by an iGEM team, showing an awareness of the possible agency of young scientists engaged in synthetic biology. Interestingly, one participant noted than science fiction might become science fact "if we don't pay attention," suggesting he felt it was important that the synthetic biology community does pay attention. Similarly, several of the causes proposed for why the iGEM competition might close down related to the student teams doing something "provocative" or unsafe.

Explicit mention of the responsibilities of synthetic biologists at the community level were listed for some of the statements. For example, with regards to standard-setting, written causes included "BBF centralised decision making" [14] and "Government and scientists are responsible for biosafety and biosecurity" (Supplementary Fig 3). The future of standards for synthetic biology is clearly viewed as something that the research community sees itself involved in and having some responsibility for. With the statement regarding an EU moratorium on synthetic biological products, one of the causes listed is "Syn Bio scientists would be responsible as we bear the onus for public engagement" (Supplementary Fig 6). Here synthetic biologists are implicating themselves directly in this potential narrative, although exactly what they mean by 'being responsible' is unclear.

In contrast, in the biofuels discussion, the roles of individuals or the synthetic biology research community more generally did not emerge strongly in either of the workshops. Rather, nation-states and large-scale industries were the main actors implicated in this future. For example, Amyris Biotechnologies was mentioned only once in the conversations, and not at all in the written causes and consequences. This is despite the fact that biofuel production is presented as one of the nearest-to-market applications of synthetic biology (being pursued by high-profile researchers including Jay Keasling and Craig Venter), and may thus be a means through which the general public is first exposed to this technology. Given that a number of negative consequences were associated with this statement (particularly in the SB4.0 discussion), it would be interesting to probe further whether and how synthetic biologists see themselves involved in shaping this future.

[14] BBF stands for 'BioBricks Foundation'.

Conclusions

A key aim of the workshops reported here was to stimulate conversation among synthetic biologists regarding the possible future(s) of this field. Our ambition was not to generate formal predictions of the future, to develop fully articulated scenarios for synthetic biology, or to propose a series of concrete policy options; more systematic and rigorous studies are necessary for this (see Bradfield et al. 2005). Rather, we see this paper as a proof-of-principle that the type of workshop exercise we describe — short, informal, and fairly flexible in format (for example, with respect to time available, number of participants and their disciplinary backgrounds) — can foster open, creative and exploratory discussion within a community of research practitioners.

A question underpinning this paper is why we might want to stimulate discussion about the future of synthetic biology in the first place. As mentioned in the introduction, this motivation is tied to what we see one of the core contributions that the discipline of STS might make to engaging with the future as an analytical object — that of 'opening up' and drawing attention to alternative possibilities for technological development. In practical terms, this can involve interventions that challenge implicit assumptions, and create spaces and capacity for ongoing reflection among practicing researchers in the field. These workshops were partly designed as an exercise to promote reflexivity in the research community we study and engage with. Reflexivity not only involves 'opening up' and allowing a plurality of options to be considered, it also entails reconsidering or questioning one's own point of view. Wynne (1993) defines reflexivity as "the process of identifying, and critically examining (and thus rendering open to change), the basic, pre-analytic assumptions that frame knowledge-commitments" (p.324).[15] Although our exercise was not explicitly normative, we hoped that it would expose underlying assumptions and in this way 'render them open to change'.

We see these workshops as a potentially useful first step in an iterative series of discussions, and the data they have generated gives us several research threads to pursue. Not least, the causes and consequences identified in the discussions can be reflected back to the synthetic biology community, and can be used to stimulate further discussion regarding the plausibility and desirability of particular futures. For example, thinking around the possibility that the iGEM competition might close down might help participants to more clearly articulate what they see as the role of this competition within the community. Based on this, more practical questions might be asked, such as: if you would like to see this particular future realized (or conversely, if you would like to avoid it), what actions might be taken by you as an individual, by the synthetic biology research community, or by other players? Given the range of possible consequences identified, and the uncertainty of any particular outcome, what might be the result of prioritizing one course of action over another? Such questions arise naturally from the methodological approach we used, offering starting points for discussion that do not rely on a risk/benefit or opportunity/threat framing, but instead draw attention to the temporal dimensions of technology development. In asking participants to think about 'causes' that might bring about a particular future, they are encouraged to situate discussions of the future with respect to the current state of play in the field. We are interested in exploring whether this might encourage a different appreciation of

[15] Many forms of reflexivity have been identified, see Lynch (2000) for further discussion.

uncertainty, agency, and social choice within the research community that we work with.

In conclusion, we suggest that the short and interactive exercise we developed allowed participants to imagine the future of synthetic biology differently, not simply along the lines that are routinely set out in conference talks and policy documents. Policymakers and synthetic biologists could benefit from looking at the range of both positive and negative outcomes presented here, as well as the ambiguities and uncertainties that arose about how different trajectories might develop. As the field evolves, this type of broad-level mapping could assist us in identifying which futures are being foregrounded at the expense of others, and what possibilities remain unexplored.

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