Future-proofing synthetic biology: educating the next generation

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Abstract: Synthetic biology is a relatively young field, although it builds upon disciplines whose roots go back centuries. Recently, its practitioners have tended to move into the field out of interest or by chance, and come from a wide variety of backgrounds. It is also a very fast-moving field; new protocols, laboratory equipment, computational facilities and algorithms are being developed at a rapid pace. Students who start studying synthetic biology at an undergraduate or postgraduate level will, in the course of their careers, work with technologies as yet undreamt of, and will do so mostly in the context of highly interdisciplinary teams. In this study, the authors identify some of the key areas required for the education of new synthetic biologists to equip them with both adequate background and sufficient flexibility to tackle these challenges and therefore to future-proof synthetic biology.

1 Introduction

Synthetic biology [1–4] is a challenging field in which to carry out research, and perhaps even more so to learn. Its component fields – molecular biology, biochemistry, computer science, statistics, engineering, design, and many more – have traditionally been geared towards providing students with knowledge and skills within a single discipline, but synthetic biology is inherently interdisciplinary. In molecular biology, the quip by Andrew Murray of Harvard University ‘one gene, one PhD’ was, until quite recently, not so much a joke as a statement of reality. The advent of computational and systems biology ushered in an era of large-scale genomics. For example, in molecular biology, the cost of nucleotide sequencing has dropped from nearly $USD10,000 per megabase in 2001 to $USD0.012 in July 2017 [https://www.genome.gov/sequencingcostsdata/], while concurrently the advent of technologies such as Cloud computing and eScience approaches [5] has led to dramatic decreases in the cost of computing facilities. The development of the field of synthetic biology necessitates the training of practitioners with a broad range of knowledge and technical approaches, plus the ability to acquire new expertise as needed [6] (Fig. 1).

Students entering the world of synthetic biology must acquire a diverse set of skills, and universities are well equipped to teach the individual fields which comprise synthetic biology. However, providing an individual student with all of the necessary skills to flourish as a synthetic biologist is a daunting task. As well as mastering existing knowledge and technology, we need to give students the skills to identify relevant new developments as they come along, and recognise their potential benefits and challenges.

The key to future-proofing synthetic biology lies in equipping students with a fundamental understanding of several different disciplines, and to provide them with the tools required to work with others; i.e. to be multidisciplinary, and to integrate approaches from these disciplines into their own field of expertise [7]. Most importantly, students must be supported to develop the flexibility to learn, appreciate, and apply new concepts: either existing knowledge from unfamiliar fields, or completely new technologies, algorithms, and understandings, developed throughout their working lives. Much has been written about the gulf between different fields; in modern science, the publication of C. P. Snow’s ‘The Two Cultures and the Scientific Revolution’ in 1959 [8] sparked intense debate, which has continued and been built upon, ever since. It is imperative that educators of synthetic biology students move beyond their scientific and cultural comfort zones, and enable their students to follow this lead.

Synthetic biology training can be divided into two major areas: undergraduate [9] and postgraduate [10]. At present, most synthetic biology training is conducted at the postgraduate level. Students enter the system from a specialised undergraduate degree; usually molecular biology, biochemistry, computing or engineering, although this list is not exhaustive. Students also learn from academics and postdoctoral researchers in a laboratory setting, while possibly also undertaking a formal lecture component.

At the undergraduate level, lectures and hands-on practicals are the main modes of teaching, and a wide range of topics can be covered. The advent of online learning systems which allow access to teaching material in a variety of formats (lecture slides, online videos, code examples etc.) and the development of easy-to-use...
experimental kits, such as BioBits™ [11] which enable the demonstration of cutting-edge science without the need for a professional laboratory, help in communicating synthetic biology at the undergraduate level.

Practical experience in identifying valid research questions, researching background information, designing, modelling and implementing solutions, and managing a project is, however, equally important. Many universities are currently offering undergraduate courses incorporating these important research skills, and postgraduate students usually build upon this knowledge on the job.

There is no currently agreed curriculum for the training of potential synthetic biologists, even as the community is developing standards for designing synthetic genetic circuits [12–15], data acquisition [16], incorporating metadata into designs [17, 18], communicating designs between laboratories [19, 20], and implementing the final designs in vivo [18, 21, 22].

Probably the most well-known teaching effort in synthetic biology is iGEM: the international Genetically Engineered Machines competition [https://igem.org/Main_Page]. iGEM started in 2003, as an Independent Activities Period of the synthetic biology group at MIT [23], and expanded into an international competition. In 2018, there were 371 teams competing. Perhaps the most appealing aspect of iGEM is the opportunity for students to observe and participate in the entire synthetic biology process, including presenting the results of their work to an audience of their peers [9]. A similar approach to undergraduate teaching is the Build-a-Genome project [24], developed at Johns Hopkins University within the context of the Synthetic Yeast Genome Project [http://www.syntheticyeast.org]. As part of Build-a-Genome, students attend lectures, undertake practical classes, and then work in the lab to assemble Saccharomyces cerevisiae chromosomes using the Yeast2.0 protocol.

Exercises such as iGEM and Build-A-Genome are valuable both for the students involved, who tend to find them extremely motivating, and for the field itself, which benefits from observing novel and exciting ideas, some of which may be developed beyond the life of the competition. However, these projects are generally conducted as additions to an established curriculum, rather than being an integral part of the teaching process. It is important to take some of the lessons that we, as educators, have learned from the competition experience and incorporate them into the core teaching curriculum for synthetic biology students. We need to provide a learning environment which focuses upon interesting tasks, productive teamwork, innovative technology, and the flexibility to develop these skills as needed. Importantly, students must be equipped to produce and adapt to new approaches and technologies as they arise.

The rest of this paper is organised as follows: In Section 2, we describe the need to overcome intra-, inter- and multi-disciplinary challenges in education. In Section 3, we introduce several fundamental in silico and in vivo tools for such training. In Section 4, we briefly review some of the principal ethical, social and legal implications of synthetic biology. We then conclude with a description of the MSc in Synthetic Biology at Newcastle University (UK), developed and run by the authors, which is presented here as a use case in which we attempt to implement the considerations mentioned above, and which is, obviously, a work in progress.

2 Interdisciplinary groups: overcoming potential communication barriers

One major challenge of teaching synthetic biology to graduate students is the dissimilar backgrounds from which these students are drawn. Typically, students have good intradisciplinary training, with in-depth knowledge within a single discipline. While a synthetic biology group is typically multidisciplinary, including researchers from several disciplines working together, but with the little intersection between them, the ultimate goal is to develop interdisciplinary teams, in which individuals borrow tools and methods from others with differing expertise. Due to the inherent interdisciplinarity of the field, students from very different areas of knowledge study synthetic biology. Engineers, architects, biologists, mathematicians and social scientists must share lectures, syllabi and teachers. It can be a significant challenge to find the language and teaching styles that can be equally understood by all students. Winowiecki et al. [25] identify a set of six tools for facilitating interdisciplinary communication:

i. The use of structured dialogue to talk about research assumptions.
ii. The development of an integrated timeline by brainstorming with all participants and disciplines about historical events that led to a current scenario.
iii. Mind mapping as a visual aid for brainstorming factors and drivers that influence the problem at hand.
iv. Cross-impact analysis to explore the relationships between each major theme identified in the mind-mapping exercises.
v. Imagining the ideal outcome or solution to the research problem.
vi. Backcasting by undertaking a scenario-building exercise that works backward from imagining the problem is solved and explores the paths to get there.

Structured approaches such as this emphasise the importance of communication, and are aimed at ensuring that all members of an interdisciplinary team participate in discussion and decision making, and understand the importance of collaboration for the solution of complex problems.

This approach may not be feasible for all students of synthetic biology. Most students, both at the undergraduate and the postgraduate level, undertake some form of Research Methods training. While such units currently tend to focus upon the skills important for a specific field, such as the use of statistical software or the structuring of academic papers, adding a component focused upon interdisciplinary team participate in discussion and decision making, and understand the importance of collaboration for the solution of complex problems.

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Another approach, widely used in engineering and software development, is the team project. Teamwork, although a valuable training tool, is frequently unpopular amongst those students required to participate in it. One way of overcoming student concerns about possibly unequal participation, and hence workloads, within teams is to have a small proportion of the final marks for each team member depending upon their peers’ assessment of their contribution.

From the teachers’ point of view, a potentially valuable approach to unifying the students’ understanding is the use of metaphors and abstractions, relating novel concepts to those already familiar to individual students. Metaphors can provide real insights into new fields; Feynman and Leighton [26] detail how an understanding of the functioning of interlocking gears led to his comprehension of other aspects of the physical world. However, metaphors should be used with caution.

The use of metaphors in synthetic biology is a double-edged sword. Metaphors can help to convey a message to an audience. Metaphors can be used to elide very specific details or to efficiently explain complex concepts. For instance, referring to bacteria as computers or to genetic networks as circuits [27] (concepts from computer science and electrical engineering) are easily comprehensible metaphors that can quickly communicate one of the principal goals of synthetic biology. However, metaphors must be carefully chosen, since they do not only explain a thing but also determine how others think about that thing [28]. This duality can be the source of many misinterpretations. For instance, metaphors like ‘chassis’ and ‘orthogonality’ may be understood differently in different fields [29].

Abstractions can help to provide a framework for interdisciplinary communication. To share ideas across disciplines before their implementation, messages need to be clear and often non-technical. In many cases, a message can be abstracted to the extent that all field-specific details are removed. An example of abstraction is the use of Boolean logic functions [30] such as the NOT logic function: the so-called inverter (Fig. 2).

Boolean logic abstracts the flow of information into relationships between two values: high (1) or low (0). Although
this description does not represent the physical flow of electrons through electronic devices, or the expression of proteins from a gene, it provides a useful framework that is easy to interpret by students from different disciplines. Therefore, it has been extensively used in synthetic biology. The NOT function converts an input to an output that is not the same as the input: it inverts the signal. Such abstract functions can have different technological implementations [31]. In electronic engineering, CMOS components can be arranged to build a NOT function; computer scientists can write a piece of code to perform such behaviour; and molecular biologists would build a NOT device with DNA components. The functionality of each gate is the same, in terms of input-output relationships, but the physical implementation is different. In synthetic biology, the physical tools are provided by molecular biology, although the discussion about what would be the equivalent of computer hardware and software in biological systems is still open [32]. Fundamental concepts such as modularity can help in bridging the gaps between disciplines and can shape synthetic biology as an interdisciplinary engineering field [33].

In fact, the concept of a logic gate is straightforward in the context of synthetic biology. An AND gate is simply the need for two or more transcription factors to be present to trigger the expression of a gene; an OR gate is a situation in which any one of several transcription factors may initiate transcription and so on. However, to make this equivalence clear to both computer scientists and molecular biologists, these relationships should be spelled out explicitly.

A major challenge in education is to find an optimal balance between field-specific specialisation and interdisciplinary expertise [34]. Specialisation in a field such as a computer science or molecular biology usually requires several years of training in that field. However, specialists are not really ready to join a synthetic biology team without additional interdisciplinary training. It would therefore appear logical that students should be prepared for a synthetic biology specialisation, at an undergraduate level, by undertaking in-depth units in areas such as molecular biology, biochemistry and computer science in the first one-to-two years of their degree, before being exposed to courses which synthesise material from a range of backgrounds in the last years of their degree.

A not insignificant drawback of this approach is that students who are motivated to study synthetic biology may be de-motivated by the necessity to study foundation courses exclusively at first; a phenomenon which most experienced course directors have observed. The inclusion of such students in exercises such as iGEM teams, workshop series and social events can help to overcome this issue.

One of the fundamental characteristics of synthetic biology, from the iGEM competition to the most successful laboratories, is that students and professionals participate as members of teams, rather than as individuals. Building and successfully managing a team of synthetic biologists involves a balance between discipline specialisation and interdisciplinarity in team members. In the case of iGEM, organisational strategies vary amongst teams, mostly based on the expertise and backgrounds available. Some teams identify students’ strengths at the beginning of the process, and make maximum use of those already-established skills, while others make a point of exposing students to as many new skills as possible.

3 Tools and resources

Technologies, computational tools and algorithms for synthetic biology are under constant development. The OpenWetWare site, for example maintains a fairly comprehensive list of resources for all molecular biologists, including some specifically for synthetic biology [https://openwetware.org/wiki/Synthetic_Biology]. The sheer magnitude of the work being done, and the resources provided can be overwhelming. However, several basic principles must play an important role in the education of future researchers. Here we do not discuss all of the many tools available, but we identify four important categories.

3.1 Organisms

Until recently, most synthetic biology projects, particularly those aimed at education, have used as model organisms the bacterium E. coli or the yeast Saccharomyces cerevisiae. These organisms are particularly useful for teaching because they are quick-growing, easy to manipulate, have numerous well-characterised parts and devices available, and are generally regarded as safe. However, as the field grows, different organisms have been identified as potentially suitable for specific synthetic biology purposes, including, for instance, the bacteria Pseudomonas putida [35] and Bacillus subtilis [36]. It is inevitable that the range of organisms to which students are exposed will increase, particularly with the advent of technologies such as CRISPR-Cas9 [37], which facilitate precise engineering of the genomes of organisms which are otherwise challenging to manipulate. Considerable progress has been made in mammalian cell [38] and plant [39] synthetic biology, and there is a significant amount of research in the area of cell-free synthetic biology [40], an approach which has the advantages of being highly controllable, and of avoiding some of the legal and social issues raised by the use of genetically modified organisms.

3.2 Computational tools

Engineers have been using Computer-Aided Design (CAD) and Computer-Aided Modelling (CAM) since the first practical deployment of computers in the 1950s [41]. Most engineering problems involve the construction of systems, physical or computational, where the functioning of the basic components is well understood, but the properties of the final system may be hard to predict, due to emergent features arising from interactions between components. CAD is important for the design of such systems, making the design process faster, cheaper, and more reproducible than design by an individual, or team of individuals. CAM is equally important, since it allows exploration of the range of behaviours which may be expected of the final construct, although classic engineering failures have provided evidence that this system is not foolproof [42, 43]. The use of CAD/CAM does not guarantee success, but it facilitates the development and analysis of large-scale projects, and its use must be an important part of the education of all synthetic biology students [44].

Computational design and analysis is important in synthetic biology, as the problems tackled become larger; it is impossible for the human brain to comprehend all of the genes, gene products, and interactions inherent in a single cell, let alone in a population of interacting cells. Synthetic biology, as a field which emerged well into the computational era of molecular biology, has inspired the development of numerous computational tools for the design, simulation, automation and analysis of synthetic genetic circuits.
There are many tools available [46–49], and it is important for educators to carefully select those ones with on-going support for student use. A recent survey [50] found that, of software referred to in the biological literature, only 29% of packages were available in any form, whilst only around 40% of those provide source code. It is therefore important for academics to choose carefully the computational tools that are to be used within a given course.

It is easy to download software, run it, and examine the results. However, any researcher routinely using software must fully understand the algorithms involved, and be able to interpret the output of the programs. In a dynamic software environment, students must acquire the skills necessary to investigate, assess, and use new software as it is developed, and hopefully, to develop new tools and algorithms themselves. Skills in programming, while not essential, may help in shaping the modes of thought of students approaching a complex problem. Even if students never write code themselves, they can learn to look at the overall vision of a problem, break that problem down into solvable parts, and think about how those parts fit together. By the same token, students educated in mathematical modelling can bring to CAD/CAM development the expertise needed to facilitate software usage by non-experts.

3.3 Workflows and databases

Synthetic biology owes its rapid development to, among other factors, the availability of a wide range of online resources. As of 2018, the Database Issue of Nucleic Acids Research lists 181 highly-regarded databases of molecular biology [51], and there are many hundreds more which are valuable to researchers, freely available online, and which deal with the specifics of tiny, but crucially important, aspects of molecular biology [52, 53]. This embarrassment of riches can be overwhelming for students new to the field, so it is important to focus their attention, initially, on the most reputable sites, with the greatest consistency of interface. Consistent interface design for distinct databases makes it much easier for students to transfer skills from one task to another. Chief amongst such sites are the US National Centre for Biotechnology Information (NCBI) [https://www.ncbi.nlm.nih.gov/] and the European Bioinformatics Institute (EBI) [https://www.ebi.ac.uk/services]. Once students are familiar with these resources, their interfaces and the interpretation of their results, this knowledge can be expanded. One of the advantages of an individual or small group projects is that additional data sources can be explored in the context of a specific problem, and away from the pressures of the laboratory.

Another benefit of this abundance of resources is that students can be encouraged to integrate different types of data to gain deeper insight into issues. Data integration is an exciting field of research in its own right, and a plethora of algorithms have been developed for data integration to inform areas such as network analysis [54] and genomics [55].

A natural extension of the use of individual computational tools is the development of workflows: sets of connected applications that cover an analytical process from the design of a genetic device to its implementation and testing [56–58]. Workflows bring together different resources to build a comprehensive resource for a specific synthetic biology problem.

Workflows can be developed on an ad-hoc basis, but there are many benefits to using existing workflows. Firstly, the tools used in these workflows are usually developed to be compatible. Tools should communicate using specific data formats, so that the output of one tool can be directly fed into the next. Results achieved through established workflows can be reproduced more easily than by using an in-house modification of specific tools. Workflows facilitate the automated combining of design and analysis tools, drawing upon computationally-accessible databases and repositories, for the development of automated computational support for large-scale synthetic biology. Workflow tools are currently highly variable concerning implementation, support, and ease of use; this situation will inevitably change, and current standards in synthetic biology should be factored in with the principles of workflows, and the direction in which the software is likely to evolve [53].

3.4 Standards

As an engineering field, synthetic biology draws upon standardisation for the design and implementation of complex systems. Information, tools and processes must be standardised to allow the rigorous definition of models, parts and systems. Therefore, synthetic biology students must be made aware of, and encouraged to adhere to, community-accepted standards wherever possible. Synthetic biology builds to some extent upon systems biology, which has its own set of computational standards, including the Systems Biology Markup Language (SBML) [59] and associated technologies; while standards such as the Synthetic Biology Open Language (SBOL) [60] are being developed by the research community specifically for the communication of synthetic biology designs.

Standardisation efforts are not restricted to in silico resources. For instance, the Standard European Vector Architecture (SEVA) [61] defines a standard structure for plasmid vectors that facilitates the characterisation and predictability of these vectors by establishing basic compositional rules. The iGEM competition defines an assembly standard to ensure the compatibility of constructs designed by teams of researchers in laboratories all over the world. Recent standards for assembly methods such as Golden gate [62], Mo-Clo [22] and Gibson assembly [63], enable the fast implementation of designs. Biomedical research has a community-based set of standards, the Open Biological and Biomedical Ontology (OBO) Foundry [http://www.obofoundry.org/], which can serve as a valuable resource for students who either want to use existing standards or who are keen to be involved in the development of new synthetic biology standards. Moreover, standards in metrology allow us to measure systems’ output consistently [64], enabling the direct comparison of performance under different conditions.

4 Responsible research and innovation

From the inception of synthetic biology, social scientists have taken different, and fundamental, roles within the field [65]. It is widely acknowledged that, because of the breadth of the potential applications of synthetic biology, how research is carried out, and the context in which it is performed, must be considered as closely as its biological and technological aspects [66]. Synthetic biology education should place ethical concerns, as well as responsible research, at its core. An important take-home message is that such issues are not to be considered after the research, but should be incorporated into it from the beginning.

The original paradigm for social responsibility in genetic engineering, espoused by the biotechnology community nearly two decades ago, and subsequently by the synthetic biology community was dubbed ELSI: consideration of the ethical, legal and social implications of the technologies and their applications. However, criticism of the ELSI paradigm [67] has led to the exploration of a more nuanced approach to these issues, known as responsible research and innovation [RRI]. RRI can be understood as a way of framing the relationship between science and society, and provides a framework to enable a scientist or researcher to reflect upon the care they should have when fulfilling their roles as scientists, researchers and innovators. While ELSI programmes were generally conducted by bioethicists or other specialists, the RRI approach requires scientists and researchers themselves to consider the impact of their work on the society of which they are part. Early training in RRI is therefore highly desirable.

The RRI approach emphasises active and forward-looking aspects of innovation in which researchers exercise their capacity by showing care about responsibility, sometimes described as a virtue of responsibility. This active form of responsibility is not about compliance with rules and regulations, but is rather an active engagement with the challenge of developing societally acceptable forms of science and innovation.

The model for RRI, developed by Stiglec et al. [68], identifies key features that should guide any researcher throughout their
career. We believe these can be incorporated into educational systems

i. **Anticipate:** describing the impacts (economic, social, environmental etc.), that might arise. This aspect does not seek to predict, but rather to support an exploration of possible implications that may otherwise remain uncovered and little discussed.

ii. **Reflect:** reflecting on the purposes of, motivations for, and potential implications of the research.

iii. **Engage:** opening up research to broader deliberation, dialogue, engagement and debate in an inclusive way.

iv. **Act:** using these processes to influence the direction and trajectory of the research and innovation process itself.

Incorporating RRI into the teaching of synthetic biology usually involves the involvement of domain experts in the appropriate social sciences in the core synthetic biology curriculum. Teaching exercises such as iGEM and individual institution-based projects should incorporate RRI issues – in iGEM such work is compulsory – and feedback from social scientists with interest in this area, ethicists, legal faculty and philosophers can be invaluable if such can be obtained. Very often, specialists with this sort of expertise with interest in synthetic biology and its implications are simply not available, and acquiring such experts is an on-going challenge for those running synthetic biology courses.

5 Use case: MSc in synthetic biology at Newcastle University

Newcastle University has become an active hub of synthetic biology research [69]. A significant part of this program is a one-year Masters in Synthetic Biology, to which all of the authors have contributed, and which is currently run by AG-M and AW. This course attracts students from a range of different backgrounds. We have hosted students from architecture, engineering, biology, medical sciences, computing and philosophy backgrounds. When developing the syllabus and structure of the course, we tried to address the practical and pedagogical issues discussed in this paper (Fig. 3).

5.1 Lectures

The goal of the lecture schedule is to familiarise students with the main procedures and methods of the field. The course covers basic concepts of molecular biology, advanced methods in genetic engineering, the use of databases, the application of standards, and responsible research and innovation. The lecture program emphasises using the different stages of the synthetic biology life cycle (design, build, test, learn) to complete projects that integrate both in silico and in vivo developments [56, 70].

5.2 Multidisciplinary teaching

A valuable feature of this course is our ability to cater to students from a wide range of backgrounds. Students from non-life science backgrounds are taught basic molecular biology, whilst life scientists receive training in the basic principles of computing science and data management. All students are taught the fundamentals of computer programming in Python, and receive training in mathematical modelling, discrete mathematics and statistics. By the end of the first semester, we aim to ensure that all students can program and build mathematical models.

5.3 Guest lectures

To complement the main body of lectures, experts in different aspects of synthetic biology are invited to give guest lectures. These lectures range from DNA assembly methods, to in vitro synthetic biology, to the simulation of complex systems.

5.4 Practicals

There are two practicals. Students are given the specification of a genetic device for a specific application. The description of this device is half complete, so the first task of the students is to fill in the gaps by finding appropriate parts, systems and circuits to meet the stated requirements of the device. The first practical is in silico, and the students must use appropriate software packages and databases to design, model and simulate their constructs (using tools from Section 3). The second practical takes place in the wet lab, where students must build their design in vivo and measure its properties.

5.5 Synthetic biology group projects

This exercise is team-based. The goal of the group project is to build a set of skills that will allow students to work as part of an interdisciplinary laboratory. Students are grouped to run a mini-iGEM project. The goal is, however, not to compete against each other but to develop teamwork skills.

5.6 Complementary skills and seminars

As part of the MSc, students take modules that complement their backgrounds and can improve their synthetic biology skills. These modules range from programming to evolutionary genomics. During the year, students are encouraged to attend the regular seminar series of the Interdisciplinary Computing and Complex Biosystems (ICOS) group, an active interdisciplinary research community.

5.7 iGEM competition

Several students from the MSc in Synthetic Biology have been involved in the local iGEM teams. This involvement varies from year to year and can range, on an individual basis, from full involvement in a post-graduate team to have a supervisory role over undergraduates. The point of the competition, of course, is not necessarily to produce world-changing breakthroughs, and the students are intellectually well aware of this fact. However, we have found that the very idea of international competition is very motivating; our students are prepared to put in considerable efforts to complete the projects and their associated tasks.

Newcastle has been involved in the iGEM competition since 2008 with the gold-winning BugBuster project [https://2008.igem.org/Team:Newcastle_University], which designed a biological implementation of an artificial neural network in bacteria to perform as a biosensor. Soon after, in 2010, the project BacillaFilta [https://2010.igem.org/Team:Newcastle] was key in strengthening interdisciplinary links at Newcastle University. In this project, *Bacillus subtilis* was used as the basis for a designed aimed filling in cracks in concrete. The genetic modules designed by the students included a tendency to swim away from oxygen, to encourage the bacteria to migrate to the depths of the crack and the inclusion of genes for the production of biologically-based glue. This project laid the basis for collaborations between biologists and...
architects within our university that are still active. The research environment, as well as student education, benefits from this program. For instance, a recent project Sensynova [http://2017.igem.org/Team:Newcastle] (2017, Gold medal and four nominations for Special Prizes), led to the opening of PhD studentships to continue research into this project.

Of particular interest in the current context is the need for considerations of RRI and Human Practices. For all of the projects, students are required to carefully consider the wider implications of the research, which involves talking to potential industrial partners, public engagement and potentially the establishment of links with Newcastle City Council to evaluate policy measures. Altogether, participation in an iGEM team is a valuable learning experience for the students involved.

5.8 Final project

The last part of the MSc is an individual project supervised by an academic member of the University. Synthetic biology students can opt to pursue a wet-lab project, an in silico based project, or a combination of both, regardless of their background. Some students may choose to reinforce a set of existing skills; others might opt to expand their knowledge by pursuing a project that is far from their previous background. A typical mixed wet-dry lab project can involve the application of several of the techniques described in Section 3: the use of different organisms, including Escherichia coli and Bacillus subtilis, modelling tools such as iBioSim and COPASI, and standards such as SBOL, SEVA, and MoClo. During this time, students are encouraged to join the daily activities of established teams and groups, including attending meetings and presentations, to gain an understanding of academic dynamics. The main goal of the final project is education and training in synthetic biology, rather than the production of research output.

5.9 Assessment objectives

In a highly interdisciplinary field such as synthetic biology, the assessment must be considered carefully. There is clearly a role for the assessment of rote learning via conventional examinations – synthetic biologists do need to have a certain body of knowledge, as do all scientists – but with the ubiquitous availability of information online, it becomes ever more important to train practitioners in how to find, assess and use data sources, whether online, in the library, or from commercial partners. Assessment should also focus on developing critical thinking and the integration of knowledge. The group projects are a good way to start this assessment. As part of the assessment process, students are required to evaluate the contributions of other team members. Students are not marked down because they come from a different background, but are evaluated in respect to their contribution to a common goal, whatever their initial field of study.

6 Conclusions

Much of the literature regarding teaching in synthetic biology emphasises a shift from the traditional expert-teacher versus bored-student model of pedagogy to a more informal, flexible, hands-on learning approach [6, 24]. The very fact that synthetic biology projects, even for undergraduates, tend to be genuinely novel experiments – even if the aim is as seemingly trivial as making E. coli smell like bananas [71] – means that students are likely to be more engaged with the synthetic biology learning process than with ‘experiments’ which have been carried out by thousands of previous students, and whose outcomes are predictable and explicable. To foster this experience of commitment and interest, educators have a fundamental role.

We have described here what we, as current synthetic biology educators, think are the key features of a comprehensive synthetic biology programme. One of the major defining characteristics of synthetic biology is its interdisciplinarity. Many students progressing through universities are encouraged to specialise; a student may graduate knowing a lot about cell biology, but next to nothing about software requirements engineering, and vice versa. It is clearly impossible for any one student to be knowledgeable in the entire range of subjects required for successful synthetic biology, but it is far from impossible to teach students how to identify problems which they are not equipped to solve and to locate domain experts with whom to collaborate.

There are four fundamental issues to the teaching of synthetic biology:

- Interdisciplinarity, and the teamwork necessitated thereby.
- The use of standards, wherever possible, to facilitate communication between members of interdisciplinary teams and the wider research effort.
- The use of computation in the design, simulation, and analysis of complex synthetic systems, to reduce, as far as possible, the time and expense of laboratory work, and to improve the design of predictable biological systems.
- The incorporation of social, ethical and legal considerations and notions of responsible innovation, at an early stage, into the practice of a field which has the potential to shape much of the future of biology.

The education of students in the fundamental skills required to advance the field of synthetic biology is already a core task of current educational institutions. However, future-proofing synthetic biology involves teaching our students not only to understand and work with existing technologies, but also to be intellectually and technologically flexible enough to work with, and develop, new technologies, algorithms, and understandings of concepts important to biology and synthetic biology, and to interact productively with other researchers with complementary skills. Synthetic biology is already making significant contributions to human wellbeing, and will only benefit from considered education of its future practitioners.

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8 References
