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Running title: Using synthetic biology to assist microbiology education

Promoting Microbiology Education Through the iGEM Synthetic Biology Competition

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One-sentence Summary

The iGEM competition involves research in synthetic biology, a rapidly developing area of science that combines principles from engineering and biology; iGEM projects frequently tackle biotechnology-associated problems and their broad reach offers excellent educational opportunities for microbiology-based students and researchers.

Keywords

Bioethics; biotechnology; iGEM; microbiology education; synthetic biology; transferable skills.

Running title

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Abstract

Synthetic biology has developed rapidly in the 21st century. It covers a range of scientific disciplines that incorporate principles from engineering to take advantage of and improve biological systems, often applied to specific problems. Methods important in this subject area include the systematic design and testing of biological systems and, here, we describe how synthetic biology projects frequently develop microbiology skills and education. Synthetic biology research has huge potential in biotechnology and medicine, which brings important ethical and moral issues to address, offering learning opportunities about the wider impact of microbiological research. Synthetic biology projects have developed into wide-ranging training and educational experiences through iGEM, the International Genetically Engineered Machines competition. Elements of the competition are judged against specific criteria and teams can win medals and prizes across several categories. Collaboration is an important element of iGEM and all DNA constructs synthesised by iGEM teams are made available to all researchers through the Registry for Standard Biological Parts. An overview of microbiological developments in the iGEM competition is provided. This review is targeted at educators that focus on microbiology and synthetic biology, but will also be of value to undergraduate and postgraduate students with an interest in this exciting subject area.

Background

Synthetic Biology (SynBio) is an interdisciplinary field that integrates expertise across the arts, humanities and, importantly, a range of scientific disciplines. Therefore, this subject area represents a challenging environment in which to prepare and train microbiologists. As we describe below, the International Genetically Engineered Machine (iGEM) competition provides an excellent platform to develop this training. We will provide an introduction to SynBio and to iGEM. We will also explore how the iGEM competition, along with the tools and the approaches and methodologies of SynBio, prepares early career microbiologists for this exciting area of science.

Synthetic Biology

SynBio has developed rapidly in the 21st century. It incorporates principles from engineering to take advantage of and improve biological systems, usually with applications to tackle specific problems (Kelwick, MacDonald, Webb *et al.* 2014). Thus, SynBio research often follows closely to the model favoured by engineers to "design, build and test" (McDaniel and Weiss 2005; Khalil and Collins 2010; Kitney and Freemont 2012; Agapakis 2014; Beal 2014). A number of definitions of SynBio are used. For clarity, this article uses the definition described by ERASynBio (Minssen, Rutz and van Zimmeren 2015): "the deliberate (re)design and construction of novel biological and biologically based parts, devices and systems to perform new functions for useful purposes, that draws on principles elucidated from biology and engineering". The "biology" in SynBio adds a number of significant challenges to problems usually tackled by engineering (Kwok 2010), but solutions to many of the challenges are gradually being identified (Kitney and Freemont 2012; Kelwick, MacDonald, Webb *et al.* 2014). Thus, SynBio has been proposed as one of the scientific technologies that can help address the challenges in health and energy and food security that societies across the globe will face in the 21st Century (Alberts 2011; Editorial-NatB 2011). Notably, one such challenge is the crisis in resistance of bacteria to antibiotics, which has been described as an impending catastrophic global threat (Bowater 2015; Roca, Akova, Baquero *et al.* 2015). Several recent reviews and monographs have highlighted the potential for SynBio to be applied to address such problems (Khalil and Collins 2010; Baldwin, Bayer, Dickinson *et al.* 2012; Chen, Galloway and Smolke 2012; Muller and Arndt 2012; Kelwick, MacDonald, Webb *et al.* 2014; Liljeruhm, Gullberg and Forster 2014; Breitling and Takano 2015). Here we focus on the usefulness of this topic to assist the education of the microbiologists of the future.

An important issue in developing SynBio solutions to the challenges of the 21st century relates to their potential to apply genetic engineering methods outside of laboratory situations. Such suggestions bring with them significant ethical, legal and regulatory dilemmas, especially if they require development of genetically modified organisms (GMOs). Progress with developing real-world applications of GMOs has been slow, which is partly due to distrust that has developed between some protagonists for genetic engineering and the wider population of society (Rowland 2002; Marris 2014). Importantly, a significant driving force during the development of SynBio research has been to ensure good engagement between the scientists, funders of the research and the wider general public. This has led to increased visibility for ethical considerations of SynBio research, particularly in relation to its potential impact on society and the environment (Agapakis 2014; Church, Elowitz, Smolke *et al.* 2014; Minssen, Rutz and van Zimmeren 2015).

Developments in SynBio mesh well with the consensus among the scientific community that the demonstration of the impact of research projects are a necessary component of their evaluation, whether that be by the direct funders or wider society. This requirement has led to improved dialogue between scientists and wider communities, allowing good scientists to demonstrate the responsible nature of their research. In the UK, the major funders of SynBio research have developed a roadmap for future developments in this subject area (see: http://www.rcuk.ac.uk/RCUK-prod/assets/documents/publications/SyntheticBiologyRoadmap.pdf). This increased awareness of the opportunities and limitations of scientific developments is influencing scientific policy, as can be seen with research involving GMOs. Within European Union (EU) countries, concerns about biotechnological applications of GMOs have produced tight regulatory regimes that have limited the potential for research to be translated to wider impact. Changes to governance in early 2015 mean that each country within the EU will be able to apply its own regulations for use of GMOs, which could lead to wider opportunities for responsible scientists to develop applied uses of them (Editorial-NatB 2015). These changes to regulations are timely to allow scientists to apply SynBio methods to such future development of GMOs.

iGEM - an international competition for synthetic biology research projects

The International Genetically Engineered Machine competition (iGEM) is a series of competitions involving university or high school teams that develop and undertake synthetic biology research projects. Here we focus on the iGEM competition for university students, which began in 2003 at MIT, Massachusetts, USA, and grew into a summer competition with five teams in 2004. The Collegiate competition became international with 13 teams in 2005 and increased each year to 245 teams by 2014 (Figure 1). As described below, microbiological methodologies are important for the overwhelming majority of iGEM projects.

The iGEM competition continues to be run and overseen by the iGEM Foundation, a not-for-profit organisation that is dedicated to education and advancement of synthetic biology, particularly through the development of open communities and collaborations. Importantly, teams require a significant amount of funding to participate in the iGEM competition. Some funds are required to cover the costs that are intrinsic to the competition (registration fee to cover iGEM administration costs, fees and travel to attend required events), and some are associated with the project (research consumables and equipment). Some teams provide stipends to students to cover their own costs for being part of the team, although this is not used by all teams. There may also be "hidden" or unclaimed costs, such as those associated with the time of staff who act as advisors or mentors. A summary of the likely costs for running an iGEM team is available at: http://2015.igem.org/Funding. Since there is significant variability in the plans and remit of iGEM projects, their costs also vary significantly. It is likely that a minimum of €30,000 (£20,000) will be required for a small team to complete the iGEM competition, in line with a previous estimate from 2014 that the average cost per team was $20,000–50,000 per year (Vilanova and Porcar 2014). Thus, covering the costs associated with participating in iGEM is a significant challenge and the requirement to secure and manage funding is an important learning process for many team members. Some teams have been able to access funding from national or international organisations, including charities, but the majority of costs are recovered through the team's home institutions and with sponsorship agreements (with relevant industry or other appropriate partners). Many iGEM teams have adopted innovative approaches to raise funds, including through their development of crowdfunding opportunities.

Through participation in iGEM, teams develop SynBio-based projects and compete for medals and prizes. An important component of the iGEM competition is that researchers should collaborate, and it is seen to be good practice to assist in the development and testing of systems developed by other teams. Nevertheless, the competitive aspect of iGEM helps motivate teams to push harder on their projects, often helping teams to develop innovative approaches that may otherwise be considered too challenging for student-based research. Some of the competition elements are judged against specific criteria, which lead to the award of Gold, Silver or Bronze medals; importantly, since the medals are awarded based on the quality of the project, all teams can achieve any one of these medals. To obtain the higher levels of medals teams must collaborate with other iGEM teams and/or improve DNA constructs prepared by other teams. This collaborative aspect of iGEM means that team members become genuinely interested in the projects from other teams, helping to foster understanding and enjoyment of different aspects of SynBio research.

There are also prizes for the best team or project across a significant number of categories within the competition, which are judged by a group of experts who are selected because of their detailed knowledge about iGEM, SynBio and developments in science policy (Marris 2014; Vilanova and Porcar 2014). The prizes and medals are awarded at the final "Jamboree" that takes place at the end of the competition. Each year the competition has culminated in a "World Championship" Jamboree in Boston, and in some years (2011-2013) there were also preliminary "Regional Jamborees" that took place in several different regional locations around the world. One prize, termed the "iGEMmers Prize", is awarded for the favourite team, as voted by all who attend the final Jamboree. Microbiology-based projects have performed well in many of the prize categories, including the iGEMmers Prize, which was won by the Dundee iGEM teams of 2013 (Earl 2014) and 2014, focusing on cyanobacteria in the environment in 2013 and bacterial infections in cystic fibrosis in 2014.

Throughout the iGEM projects, a vast range of topics have been addressed. In accordance with the aims of many SynBio studies, iGEM projects often focus on applied areas of science, and many are commensurate with plans to tackle the challenges of the 21st century. Since the iGEM projects typically last only a few months, their specific advances are often limited to demonstrating "proof-of-principle" in model systems. Nevertheless, many teams have developed projects that use complex experimental systems (Vilanova and Porcar 2014; Editorial-NatP 2015).

An important aspect of the iGEM projects is that they must aim to generate and characterise new standardised DNA constructs, which are termed "BioBricks". Previous analysis of iGEM projects have characterised the number and quality of parts submitted as part of the competition (Shetty, Endy and Knight 2008; Smolke 2009; Cai, Wilson and Peccoud 2010; Vilanova and Porcar 2014). At the end of each competition each new BioBrick must be submitted to the iGEM Registry of Standard Biological Parts, from which it is made freely available to all other iGEM teams (Muller and Arndt 2012). SynBio research has helped develop a plethora of DNA assembly methods that aid the creation of modular, reusable DNA parts (Ellis, Adie and Baldwin 2011; Patron 2014; Casini, Storch, Baldwin *et* *al.* 2015). To assist exchange of BioBricks between teams and ensure there is transparency within the competition rules, each team must follow specific regulations that require cloning into specific backbones (Shetty, Endy and Knight 2008; Muller and Arndt 2012). However, even in iGEM projects complex gene assembly and editing approaches have been introduced, for example using Golden Gate cloning (Patron, Orzaez, Marillonnet *et al.* 2015) and the CRISPR-Cas system (Wu, Wang, Cao *et al.* 2014). There is a close relationship between iGEM and SynBio research, but the two are not synonymous. This is particularly the case in terms of DNA constructs as SynBio research in general is not constrained by the same limited, specific range of backbones that assist the competition and team element of iGEM. For example, although the iGEM approach to ensure that all researchers can share DNA constructs is widely accepted among the SynBio community, most SynBio researchers do not use the Biobricks that have been popularised by iGEM.

Alongside the preparation and submission of the BioBricks, teams must prepare information that is submitted to the iGEM Registry that describes the gene sequence contained in each BioBrick and describes how it has been characterised. (Details of all BioBricks available in the iGEM Registry is given at: http://parts.igem.org/Main_Page.) The gene sequences included in the BioBricks take a variety of forms, including promoters, protein coding sequences, terminators and other regulatory sequences. Each of these specific sequences is referred to as a “part”, but importantly the BioBricks must be prepared in such a way that the different parts can be moved easily between them. As would be expected, as the number of teams participating in iGEM has grown then the number of parts submitted to the iGEM Registry has increased (Figure 1). Over recent years the competition has placed a greater emphasis on the ensuring that the parts submitted to the iGEM Registry are of good quality and that they are well characterised. Thus, the number of parts submitted to iGEM has reached a plateau since 2010 at approximately 1600 parts (Smolke 2009; Vilanova and Porcar 2014).

Importantly, many of the underlying principles for iGEM projects build on the standard methods of molecular biology that are fundamental to much microbiological research, such as promoter sequences and vector backbones. Furthermore, since the vast majority of iGEM projects will require use of bacteria (usually *Escherichia coli*) at some stage, virtually every participant in iGEM develops a good grounding in basic microbiological principles, including a knowledge of how to handle microorganisms, practice of aseptic technique etc.

Responsible Research and Innovation in Synthetic Biology

The iGEM competition is structured so that each team's project relates to the broader engineering framework that uniquely defines SynBio as a new scientific discipline. Significantly, part of the educational value of iGEM BioBricks is that they represent several of the core engineering principles adopted in SynBio, including the agreed dogma to "design, build and test".

Since BioBricks are discrete biological parts that must adhere to specific assembly requirements, the characterised BioBricks that iGEM teams submit are intrinsically engineered for reuse (modularisation) by other iGEM teams, engineers and scientists. Thus, students learn and gain first-hand experience of several of the core engineering principles of SynBio. Special prizes within the iGEM competition for BioBricks or engineered biological systems that are well characterised and provide a solution within an application area provide additional incentives for teams to robustly apply these engineering principles throughout their project. As of 2014, application areas include Art & design, Energy, Entrepreneurship, Environment, Food & nutrition, Foundational advances, Health and medicine, Information processing, Manufacturing, Measurement, Microfluidics, New applications, Policy & practice and Software. The submission of BioBricks to the iGEM Registry also introduces iGEM teams to ongoing questions concerning open innovation (Calvert 2012). A strong proponent for open innovation within the field is the BioBricks Foundation, a not-for-profit organization that seeks to accelerate the pace of responsible innovation by ensuring that the BioBricks within the iGEM Registry and other professional registries are publically available for both research and commercial applications (Shetty, Endy and Knight 2008; Smolke 2009; Muller and Arndt 2012). Interestingly, commercial utilization of publically accessible BioBricks may come from iGEM teams themselves. Through the inclusion of prizes for entrepreneurship, iGEM teams are encouraged to build business models around their technologies. A list of successful startups that have been founded by former iGEM team members is available on the iGEM website (http://igem.org/IGEM_Startups).

Due to the intense time and resources required to successfully lead a team through the iGEM competition, many academic advisors encourage their teams to consider publishing their results. Whilst few teams from early competitions published papers (Vilanova and Porcar 2014), recently several peer reviewed journals have featured iGEM-inspired research (Cai, Wilson and Peccoud 2010; Boyle, Burrill, Inniss *et al.* 2012; Hesselman, Koehorst, Slijkhuis *et al.* 2012; Radeck, Kraft, Bartels *et al.* 2013; Zhang, Lin, Shi *et al.* 2014; Azizi, Lam, Phenix *et al.* 2015). The peer review journal American Chemical Society (ACS)

Synthetic Biology has direct relevance to this field and it has published several papers from iGEM-inspired research (Chen, Zhang, Shi *et al.* 2012; Harger, Zheng, Moon *et al.* 2013; Chen, Rishi, Potapov *et al.* 2015; Jack, Leonard, Mishler *et al.* 2015; Storch, Casini, Mackrow *et al.* 2015; Wright, Delmans, Stan *et al.* 2015). Indeed, there was a noticeable boost in iGEM team publications in 2014 when the journal published several papers as part of an iGEM special issue (http://pubs.acs.org/toc/asbcd6/3/12). Several of these publications were particularly relevant to research involving bacteria (Atanaskovic, Bencherif, Deyell *et al.* 2014; Buren, Karrenbelt, Lingemann *et al.* 2014; Daszczuk, Dessalegne, Drenth *et al.* 2014; Hendrix, Read, Lalonde *et al.* 2014; Libis, Bernheim, Basier *et al.* 2014; Nielsen, Madsen, Seppala *et al.* 2014; Wang, Ding, Chen *et al.* 2014; Wu, Wang, Cao *et al.* 2014). Significantly, the development of innovative pathways to publish research data has opened up new opportunities for iGEM projects. For example, microbiology research that originated as part of the Imperial College London iGEM 2013 project was published in the open access journal, PLoS One (Kelwick, Kopniczky, Bower *et al.* 2015), whilst the NRP-UEA_Norwich 2012 iGEM team published data on figshare, an open repository of citable, shareable and discoverable research (Dobson, Edwards-Hicks, Gritton *et al.* 2014). Furthermore, some iGEM teams have highlighted their progress and successes in magazines associated with learned societies of microbiology, such as the Society of General Microbiology (Earl 2014).

Whether iGEM teams ultimately result in academic (e.g. papers) and/or commercial outputs (e.g. patents and products) the overall success of a project is largely judged in terms of the social, ethical and legal context in which it exists. Responsible Research and Innovation is instilled at every level and teams must consider good laboratory practice, biosafety, biosecurity, bioethics and the potential wider societal impact of their project. Teams must engage with stakeholders, whether that be the potential users of their technologies, governments, Non-Governmental Organisations or the broader general public to ensure that their projects are designed to maximize the public good. Thus, students gain a direct appreciation for the importance of professionalism within microbiology and SynBio that equips them for a lifelong career in academia or industry. Importantly, the overall amount of time that the team members spend on the various activities highlighted here is much greater than they would experience within the majority of undergraduate teaching sessions, such as in regular laboratory practicals. A similar point can also be made in relation to public engagement activities, as we go on to discuss in the next section. Thus, it is clear that iGEM team members gain excellent skills and graduates from iGEM teams have excellent records for gaining employment, particularly as PhD students. Similarly, the advisors and mentors to many iGEM teams often include early career researchers who are also able to boosting their

CVs with project and people management skills that they would not normally be able to demonstrate at such stages of their careers.

Public Engagement and Responsible Research

As already outlined, iGEM projects are about more than simply conducting SynBio experiments and teams are expected to engage in a wide spectrum of activities that are important components of scientific research. For example, teams have to undertake Human Practices, which requires them to engage with stakeholders of their project, which can include potential users of their technologies, funding bodies or the broader general public. Other important examples are that teams have to consider the ethics and safety issues associated with their project. Several iGEM projects have also reflected on what it is that generates a good iGEM team, including in terms of important issues such as gender balance within teams. The Paris-Bettencourt 2013 team undertook detailed analyses on the subject of women in synthetic biology and iGEM and a summary of their results is available at: http://2014.igem.org/Gender. Some important findings from this study were: gender balance correlated with successful iGEM projects; as of 2013 women were underrepresented in iGEM, particularly in mentor and advisory roles (37% of students and 22% of advisors participating in iGEM were women. The study concluded that approaches to improve team gender balance for students and advisors would improve the overall quality and experience of iGEM science, and the iGEM Foundation encourages teams to actively consider this.

It is also a requirement that all iGEM teams record information about their project on publicly-accessible web pages – their "wiki" – and links to the full details of all iGEM projects is available to anyone at: http://igem.org/Main_Page. The wiki pages provide evidence that the training and expertise developed within the iGEM teams extends beyond simply laboratory experimentation. The iGEM teams must consider different routes to communicate details about their project to diverse audiences, and the wiki pages provide excellent examples of the high standards of design and information technology skills that are developed by the teams.

In developing their public engagement activities, iGEM teams have used a wide range of skills and expertise. Many of the teams have chosen to work with people who have creative skills, such as artists and designers. A good example of this relates to the NRP-UEA 2012 iGEM team, which developed bacterial biosensors of nitrogen-based compounds. In imagining how this project could develop in the future, the team prepared a short video, which is freely available to view at: https://www.youtube.com/watch?v=StNFePmymbc.

Several iGEM teams have also developed animations or comic strips to take their science to wider audience, including the "ToxiMop" project from the Dundee 2013 iGEM, which focused on tackling the microbiological problem of toxic blue-green algae (Earl 2014).

Several iGEM teams have developed multi-step approaches to public engagement that aim to ensure opinions are conveyed accurately and without bias. Generally, iGEM public engagement activities are developed in accordance with the ethics regulations of the local institution; this can be a lengthy process to reach agreements, but it highlights many useful issues to team members, including how to remove bias from studies and to not ask leading questions. Of importance to these aspect of iGEM projects are that many of them involve genetic modification of organisms. As already discussed, in general terms much of the media and general public has not been supportive of GMOs that will be released in the environment. Therefore, teams have often queried whether the wider public think scientists have an ethical obligation in their experiments and if they think that biotechnology and SynBio should be used to tackle the challenges in health and energy and food security. To address these issues, teams often hold public engagement events and speak to students at high schools that are local to them. Some teams have developed Human Practices events for different audiences, with some leading to events that continue beyond the particular iGEM project. For example, Science Cafés (or Café Scientifiques) have established themselves as useful tools for scientists to engage with non-scientists (Clery 2003; Dallas 2006). In collaboration with a local arts centre, the NRP-UEA 2014 team established a Science Café, which has now become a regular, monthly event.

Generally, these varied activities have highlighted that the general public is quite open minded to this type of research, though there are still significant concerns about the bio-safety of any applied work in the future. Importantly, these activities help iGEM team members to learn skills in science communication and highlight the requirement for public consultation in developing research projects.

Research-led Teaching

Research intensive universities pride themselves on the links that are made between teaching and research, and significant scholarship in this area has examined where teaching and research meet in the curriculum (the teaching research symbiosis/nexus) (Barnett 2005). The iGEM competition provides an excellent example of research-led teaching, but it is usually done on an extra-curricular basis. As outlined here, such extra-curricular projects provide excellent opportunities for students to obtain additional training, but it is important to recognise the challenges associated with running such projects, particularly the costs associated with student/staff time and the costs of research reagents. Despite such challenges, iGEM team members have clearly identified that taking part in the competition provided a range of experiences and skills that will benefit their undergraduate studies and their future career choices. These experiences and skills were wide ranging and included those that are directly associated with life as a bench scientist/laboratory researcher, but also included skills that will add value to alternative employment opportunities/career paths (Figure 2). Notably, graduates from iGEM teams have excellent records for gaining employment across a wide variety of careers.

The skills and experience developed through iGEM projects are attractive to all microbiology and biotechnology undergraduates, and several universities have developed teaching activities that build on the good practices gained from iGEM teams. These include Uppsala University from Sweden, which has prepared detailed material for a 5-week laboratory based course, including associated assessments (Liljeruhm, Gullberg and Forster 2014). Linking of iGEM-inspired activities to undergraduate teaching leads to opportunities for a wider range and larger number of students to gain from them. The enthusiasm by which students greet such courses and the benefits they obtain suggest that possibilities are ripe for further exploitation within curricula developed by universities (and other teaching institutions).

The experience gained through the iGEM programme offers an intellectual freedom and an investment in "student-led" research that undergraduate students do not often experience. Projects within iGEM offer opportunities for students to put into practice and recognise the value of the laboratory techniques they usually experience within practical sessions organised as part of their undergraduate degree. Importantly, though, iGEM projects provide team members with an authentic research experience that involves participation in all stages of the research project, from asking a research question, designing and planning the experiments, raising research funds, undertaking the research process, analysing results and finally presenting and disseminating data to different audiences (Figure 2). An overwhelming majority of iGEM projects use microbiology-based techniques, with many projects focused on applications of specific microorganisms, though often the bacteria are used only as tools during genetic engineering processes. Significantly, and somewhat unusually for bioscience-based degree programmes and projects, the iGEM competition also offers opportunities for students to be creative and to express themselves.

Conclusions

SynBio projects are applied to tackle specific problems, and these approaches have the potential to impact upon the upcoming challenges in health and energy and food security that will be faced by populations from across the globe. In doing so, SynBio research has to address important ethical and regulatory issues, especially in research involved in biotechnology and medicine where there is huge potential to make an impact. These issues are relevant to the iGEM competition, which provides wide-ranging training and educational experiences in SynBio for students, particularly those that focus on microbiology. Although there is a close relationship between iGEM and SynBio research, the two are not synonymous and SynBio research in general is not constrained by all of the principles that are important to bring the competition and team element to iGEM. Extra-curricular projects (usually in the summer) such as iGEM provide excellent opportunities for students to obtain microbiology-specific skills, including in-depth exposure to research-led teaching. More significantly, they link closely to transferable skills that are important in “real-life” employment, requiring students to have good planning and time-management. Importantly, the overall amount of time that the team members spend on the various activities associated with iGEM projects is much higher than they would experience within the majority of undergraduate teaching sessions. It is, therefore, unsurprising that graduates from iGEM teams have excellent records for gaining employment, particularly as PhD students. Projects designed for iGEM also allow academic staff to develop (new) projects and obtain preliminary data, but it is important to remember the challenges associated with them, particularly the costs associated with student/staff time and the costs of research reagents and participating in the competition. In the future it would be worthwhile to try and rein in (or reduce) costs of iGEM teams, which could widen participation to groups of students with lower financial means. Additional future developments that emanate from iGEM will be the potential to develop its good practices within curricula developed by universities (and other teaching institutions), particularly for microbiology. Despite the challenges associated with iGEM projects, the excellent research developed over its 10-year history suggest that the outlook is bright for SynBio and its microbiological researchers of the future.

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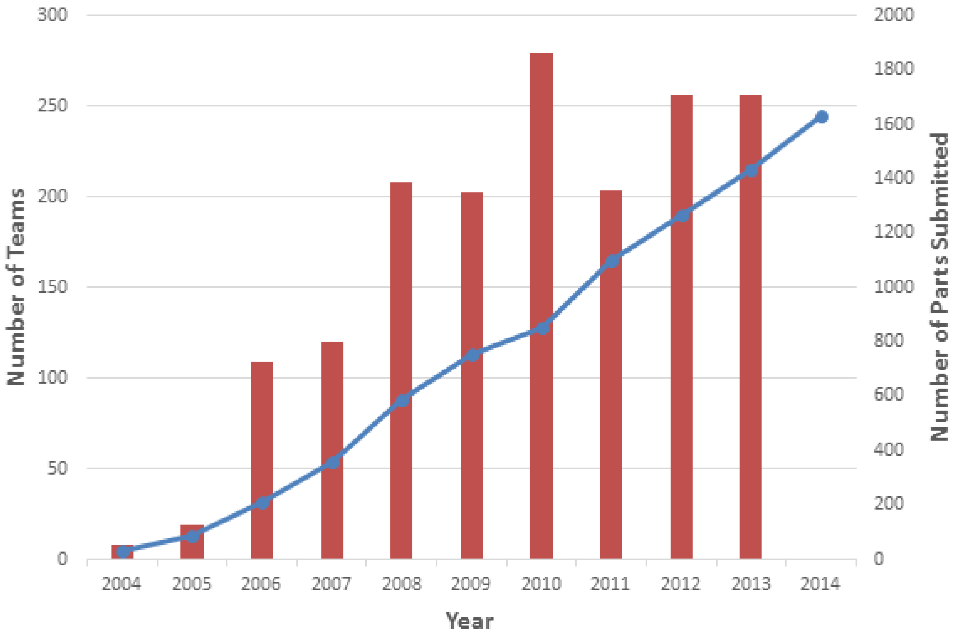
Figure Legends

Figure 1. Participation in iGEM competitions from 2004-2014. For each year the data represents the number of teams entered in the competition (line, left-hand axis) and the number of parts submitted by the teams (bars, right-hand axis). Data is taken from: http://igem.org/Previous_iGEM_Competitions. Note that the final number of parts submitted in 2014 is not yet available.

Figure 2. Team members find iGEM to be an enriching and enjoyable experience. Comments from students from NRP-UEA and Imperial iGEM teams identified that the competition had helped develop and improve research-focused skills, as well as transferable skills including communication and project management skills.



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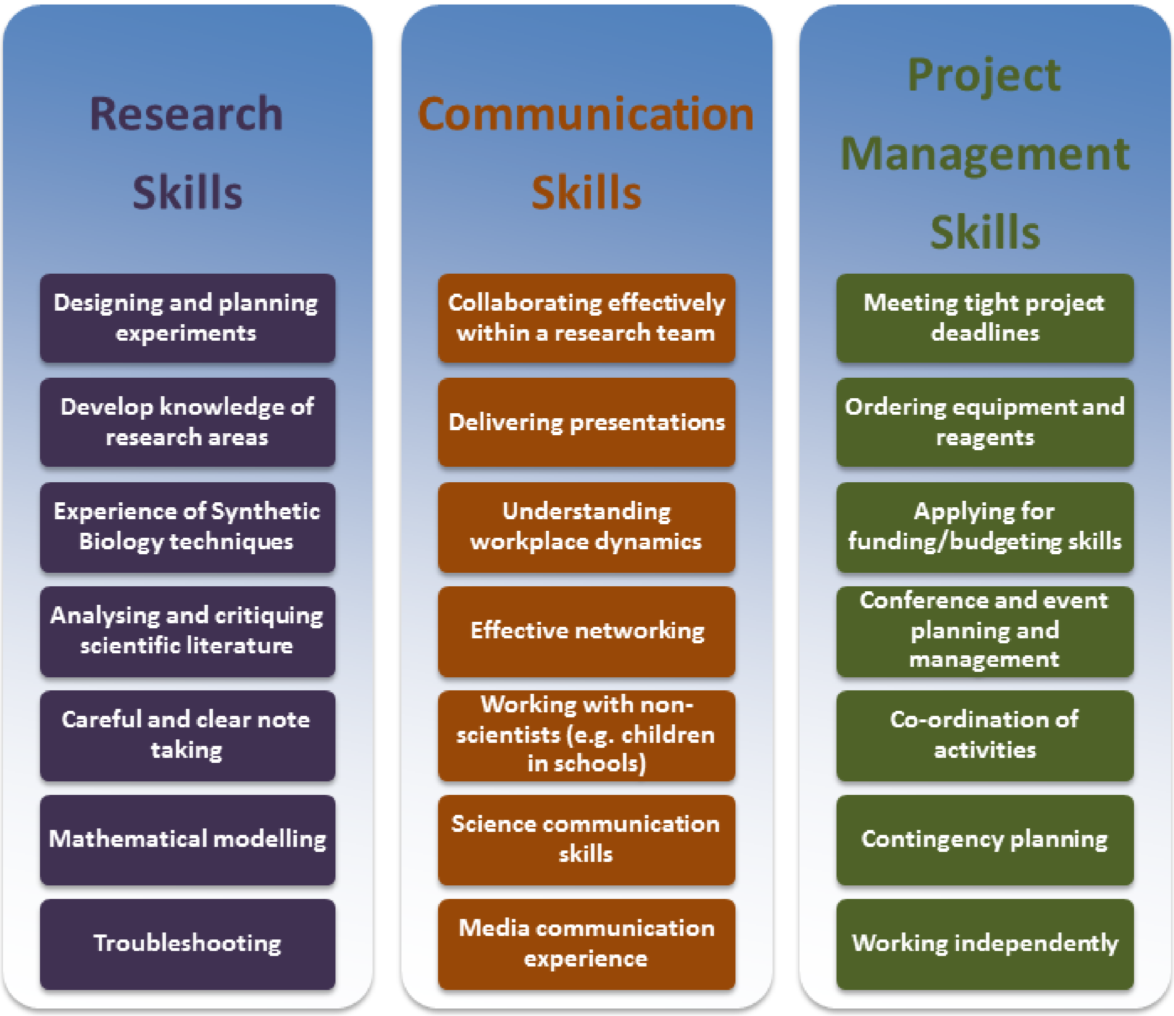
FEMS review Figure 1



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FEMS review Figure 2

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