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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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1 **One-sentence Summary**

2 The iGEM competition involves research in synthetic biology, a rapidly developing area of
3 science that combines principles from engineering and biology; iGEM projects frequently
4 tackle biotechnology-associated problems and their broad reach offers excellent educational
5 opportunities for microbiology-based students and researchers.
6

7 **Keywords**

8 Bioethics; biotechnology; iGEM; microbiology education; synthetic biology; transferable
9 skills.
10

11 **Running title**

12 Using synthetic biology to assist microbiology education
13

14 **Abstract**

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

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35 **Background**

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

44

45 **Synthetic Biology**

46 SynBio has developed rapidly in the 21st century. It incorporates principles from
47 engineering to take advantage of and improve biological systems, usually with applications to
48 tackle specific problems (Kelwick, MacDonald, Webb *et al.* 2014). Thus, SynBio research
49 often follows closely to the model favoured by engineers to “design, build and test”
50 (McDaniel and Weiss 2005; Khalil and Collins 2010; Kitney and Freemont 2012; Agapakis
51 2014; Beal 2014). A number of definitions of SynBio are used. For clarity, this article uses
52 the definition described by ERASynBio (Minssen, Rutz and van Zimmeren 2015): “the
53 deliberate (re)design and construction of novel biological and biologically based parts,
54 devices and systems to perform new functions for useful purposes, that draws on principles
55 elucidated from biology and engineering”. The “biology” in SynBio adds a number of
56 significant challenges to problems usually tackled by engineering (Kwok 2010), but solutions
57 to many of the challenges are gradually being identified (Kitney and Freemont 2012;
58 Kelwick, MacDonald, Webb *et al.* 2014). Thus, SynBio has been proposed as one of the
59 scientific technologies that can help address the challenges in health and energy and food
60 security that societies across the globe will face in the 21st Century (Alberts 2011; Editorial-
61 NatB 2011). Notably, one such challenge is the crisis in resistance of bacteria to antibiotics,
62 which has been described as an impending catastrophic global threat (Bowater 2015; Roca,
63 Akova, Baquero *et al.* 2015). Several recent reviews and monographs have highlighted the
64 potential for SynBio to be applied to address such problems (Khalil and Collins 2010;
65 Baldwin, Bayer, Dickinson *et al.* 2012; Chen, Galloway and Smolke 2012; Muller and Arndt
66 2012; Kelwick, MacDonald, Webb *et al.* 2014; Liljeruhm, Gullberg and Forster 2014;
67 Breitling and Takano 2015). Here we focus on the usefulness of this topic to assist the
68 education of the microbiologists of the future.

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

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

98

99 **iGEM - an international competition for synthetic biology research projects**

100 The International Genetically Engineered Machine competition (iGEM) is a series of
101 competitions involving university or high school teams that develop and undertake synthetic
102 biology research projects. Here we focus on the iGEM competition for university students,

103 which began in 2003 at MIT, Massachusetts, USA, and grew into a summer competition with
104 five teams in 2004. The Collegiate competition became international with 13 teams in 2005
105 and increased each year to 245 teams by 2014 (Figure 1). As described below,
106 microbiological methodologies are important for the overwhelming majority of iGEM
107 projects.

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

130 Through participation in iGEM, teams develop SynBio-based projects and compete for
131 medals and prizes. An important component of the iGEM competition is that researchers
132 should collaborate, and it is seen to be good practice to assist in the development and testing
133 of systems developed by other teams. Nevertheless, the competitive aspect of iGEM helps
134 motivate teams to push harder on their projects, often helping teams to develop innovative
135 approaches that may otherwise be considered too challenging for student-based research.
136 Some of the competition elements are judged against specific criteria, which lead to the award

137 of Gold, Silver or Bronze medals; importantly, since the medals are awarded based on the
138 quality of the project, all teams can achieve any one of these medals. To obtain the higher
139 levels of medals teams must collaborate with other iGEM teams and/or improve DNA
140 constructs prepared by other teams. This collaborative aspect of iGEM means that team
141 members become genuinely interested in the projects from other teams, helping to foster
142 understanding and enjoyment of different aspects of SynBio research.

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

155 Throughout the iGEM projects, a vast range of topics have been addressed. In
156 accordance with the aims of many SynBio studies, iGEM projects often focus on applied
157 areas of science, and many are commensurate with plans to tackle the challenges of the 21st
158 century. Since the iGEM projects typically last only a few months, their specific advances are
159 often limited to demonstrating “proof-of-principle” in model systems. Nevertheless, many
160 teams have developed projects that use complex experimental systems (Vilanova and Porcar
161 2014; Editorial-NatP 2015).

162 An important aspect of the iGEM projects is that they must aim to generate and
163 characterise new standardised DNA constructs, which are termed “BioBricks”. Previous
164 analysis of iGEM projects have characterised the number and quality of parts submitted as
165 part of the competition (Shetty, Endy and Knight 2008; Smolke 2009; Cai, Wilson and
166 Peccoud 2010; Vilanova and Porcar 2014). At the end of each competition each new BioBrick
167 must be submitted to the iGEM Registry of Standard Biological Parts, from which it is made
168 freely available to all other iGEM teams (Muller and Arndt 2012). SynBio research has
169 helped develop a plethora of DNA assembly methods that aid the creation of modular,
170 reusable DNA parts (Ellis, Adie and Baldwin 2011; Patron 2014; Casini, Storch, Baldwin *et*

171 *al.* 2015). To assist exchange of BioBricks between teams and ensure there is transparency
172 within the competition rules, each team must follow specific regulations that require cloning
173 into specific backbones (Shetty, Endy and Knight 2008; Muller and Arndt 2012). However,
174 even in iGEM projects complex gene assembly and editing approaches have been introduced,
175 for example using Golden Gate cloning (Patron, Orzaez, Marillonnet *et al.* 2015) and the
176 CRISPR-Cas system (Wu, Wang, Cao *et al.* 2014). There is a close relationship between
177 iGEM and SynBio research, but the two are not synonymous. This is particularly the case in
178 terms of DNA constructs as SynBio research in general is not constrained by the same
179 limited, specific range of backbones that assist the competition and team element of iGEM.
180 For example, although the iGEM approach to ensure that all researchers can share DNA
181 constructs is widely accepted among the SynBio community, most SynBio researchers do not
182 use the Biobricks that have been popularised by iGEM.

183 Alongside the preparation and submission of the BioBricks, teams must prepare
184 information that is submitted to the iGEM Registry that describes the gene sequence
185 contained in each BioBrick and describes how it has been characterised. (Details of all
186 BioBricks available in the iGEM Registry is given at: http://parts.igem.org/Main_Page.) The
187 gene sequences included in the BioBricks take a variety of forms, including promoters,
188 protein coding sequences, terminators and other regulatory sequences. Each of these specific
189 sequences is referred to as a “part”, but importantly the BioBricks must be prepared in such a
190 way that the different parts can be moved easily between them. As would be expected, as the
191 number of teams participating in iGEM has grown then the number of parts submitted to the
192 iGEM Registry has increased (Figure 1). Over recent years the competition has placed a
193 greater emphasis on the ensuring that the parts submitted to the iGEM Registry are of good
194 quality and that they are well characterised. Thus, the number of parts submitted to iGEM has
195 reached a plateau since 2010 at approximately 1600 parts (Smolke 2009; Vilanova and Porcar
196 2014).

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

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204

205 **Responsible Research and Innovation in Synthetic Biology**

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

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

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

239 Synthetic Biology has direct relevance to this field and it has published several papers from
240 iGEM-inspired research (Chen, Zhang, Shi *et al.* 2012; Harger, Zheng, Moon *et al.* 2013;
241 Chen, Rishi, Potapov *et al.* 2015; Jack, Leonard, Mishler *et al.* 2015; Storch, Casini, Mackrow
242 *et al.* 2015; Wright, Delmans, Stan *et al.* 2015). Indeed, there was a noticeable boost in iGEM
243 team publications in 2014 when the journal published several papers as part of an iGEM
244 special issue (<http://pubs.acs.org/toc/asbcd6/3/12>). Several of these publications were
245 particularly relevant to research involving bacteria (Atanaskovic, Bencherif, Deyell *et al.*
246 2014; Buren, Karrenbelt, Lingemann *et al.* 2014; Daszczuk, Dessalegne, Drenth *et al.* 2014;
247 Hendrix, Read, Lalonde *et al.* 2014; Libis, Bernheim, Basier *et al.* 2014; Nielsen, Madsen,
248 Seppala *et al.* 2014; Wang, Ding, Chen *et al.* 2014; Wu, Wang, Cao *et al.* 2014).
249 Significantly, the development of innovative pathways to publish research data has opened up
250 new opportunities for iGEM projects. For example, microbiology research that originated as
251 part of the Imperial College London iGEM 2013 project was published in the open access
252 journal, PLoS One (Kelwick, Kopniczky, Bower *et al.* 2015), whilst the NRP-UEA_Norwich
253 2012 iGEM team published data on figshare, an open repository of citable, shareable and
254 discoverable research (Dobson, Edwards-Hicks, Gritton *et al.* 2014). Furthermore, some
255 iGEM teams have highlighted their progress and successes in magazines associated with
256 learned societies of microbiology, such as the Society of General Microbiology (Earl 2014).

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

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

276

277 **Public Engagement and Responsible Research**

278 As already outlined, iGEM projects are about more than simply conducting SynBio
279 experiments and teams are expected to engage in a wide spectrum of activities that are
280 important components of scientific research. For example, teams have to undertake Human
281 Practices, which requires them to engage with stakeholders of their project, which can include
282 potential users of their technologies, funding bodies or the broader general public. Other
283 important examples are that teams have to consider the ethics and safety issues associated
284 with their project. Several iGEM projects have also reflected on what it is that generates a
285 good iGEM team, including in terms of important issues such as gender balance within teams.
286 The Paris-Bettencourt 2013 team undertook detailed analyses on the subject of women in
287 synthetic biology and iGEM and a summary of their results is available at:

288 <http://2014.igem.org/Gender>. Some important findings from this study were: gender balance
289 correlated with successful iGEM projects; as of 2013 women were underrepresented in
290 iGEM, particularly in mentor and advisory roles (37% of students and 22% of advisors
291 participating in iGEM were women. The study concluded that approaches to improve team
292 gender balance for students and advisors would improve the overall quality and experience of
293 iGEM science, and the iGEM Foundation encourages teams to actively consider this.

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

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

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

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

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

334

335 **Research-led Teaching**

336 Research intensive universities pride themselves on the links that are made between
337 teaching and research, and significant scholarship in this area has examined where teaching
338 and research meet in the curriculum (the teaching research symbiosis/nexus) (Barnett 2005).
339 The iGEM competition provides an excellent example of research-led teaching, but it is
340 usually done on an extra-curricular basis. As outlined here, such extra-curricular projects
341 provide excellent opportunities for students to obtain additional training, but it is important to

342 recognise the challenges associated with running such projects, particularly the costs
343 associated with student/staff time and the costs of research reagents. Despite such challenges,
344 iGEM team members have clearly identified that taking part in the competition provided a
345 range of experiences and skills that will benefit their undergraduate studies and their future
346 career choices. These experiences and skills were wide ranging and included those that are
347 directly associated with life as a bench scientist/laboratory researcher, but also included skills
348 that will add value to alternative employment opportunities/career paths (Figure 2). Notably,
349 graduates from iGEM teams have excellent records for gaining employment across a wide
350 variety of careers.

351 The skills and experience developed through iGEM projects are attractive to all
352 microbiology and biotechnology undergraduates, and several universities have developed
353 teaching activities that build on the good practices gained from iGEM teams. These include
354 Uppsala University from Sweden, which has prepared detailed material for a 5-week
355 laboratory based course, including associated assessments (Liljeruhm, Gullberg and Forster
356 2014). Linking of iGEM-inspired activities to undergraduate teaching leads to opportunities
357 for a wider range and larger number of students to gain from them. The enthusiasm by which
358 students greet such courses and the benefits they obtain suggest that possibilities are ripe for
359 further exploitation within curricula developed by universities (and other teaching
360 institutions).

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

375 **Conclusions**

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

404 **Acknowledgements**

405 Our inspiration to write this review was the many excellent iGEM projects that we have
406 experienced through participation as Advisors to specific iGEM teams. The large number of
407 projects developed during the history of the iGEM competition made it practically impossible
408 to select a small number of examples of good practice that could be referred to directly within
409 the limitations of a Minireview. To gain a wider perspective of the vast range of good practice
410 produced by iGEM teams we encourage readers to review details via the team wiki pages,
411 which are all available to anyone via: http://igem.org/Main_Page.

412

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415 participation in the iGEM competitions from 2011-2015, with teams from the University of
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418 iGEM web pages.

419

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533 **Figure Legends**

534

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

540

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

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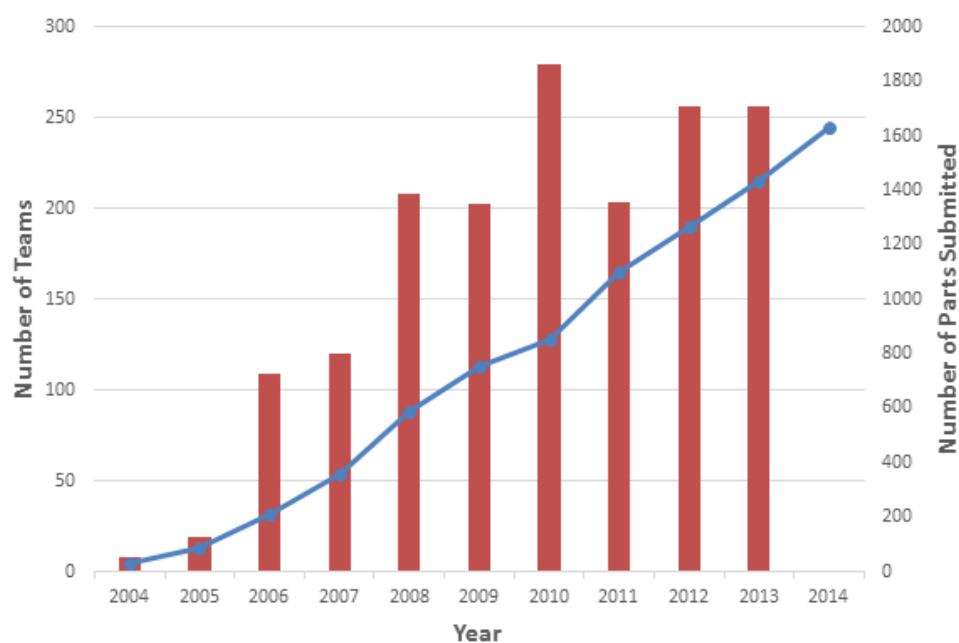


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FEMS review Figure 1

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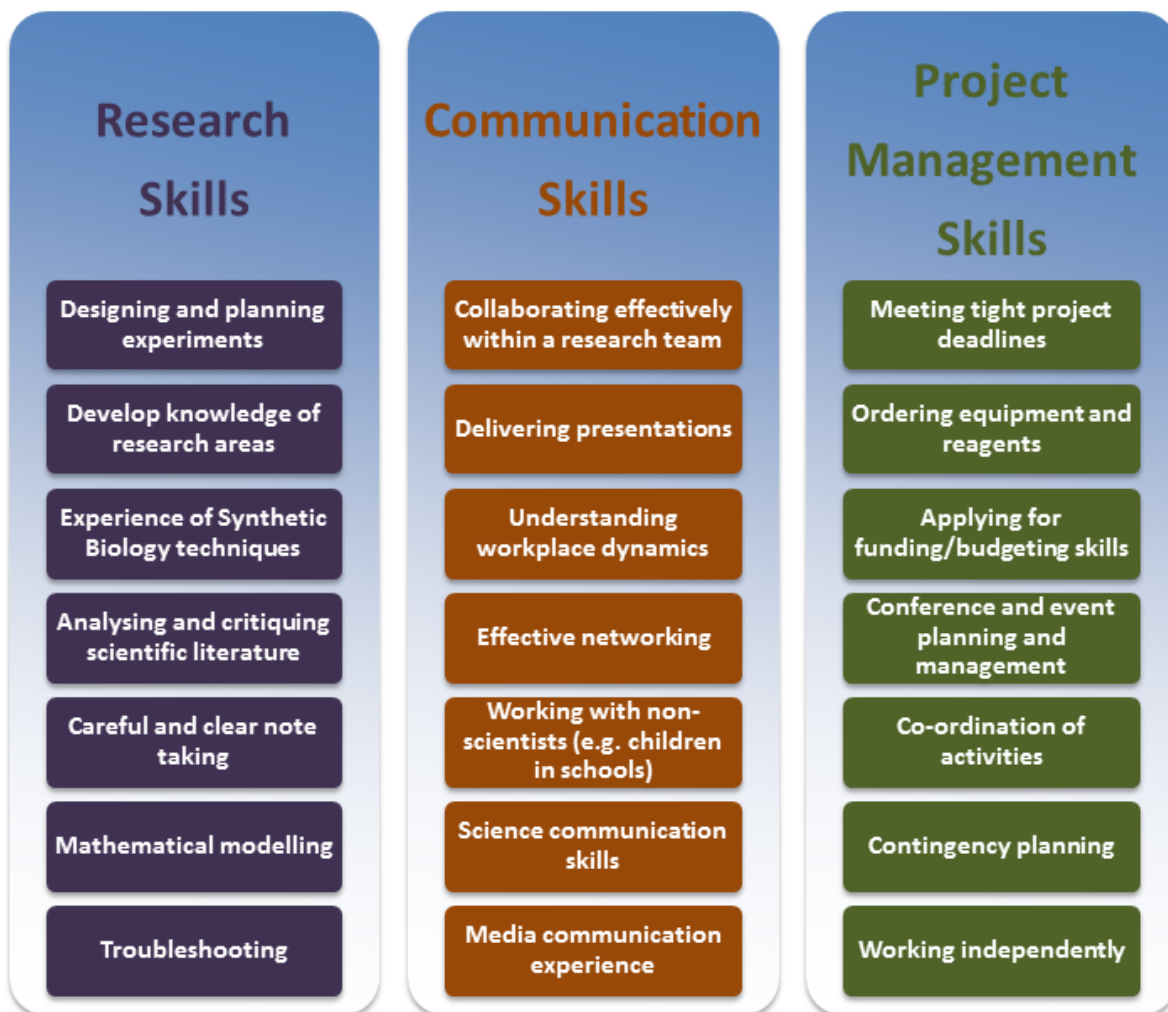


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