The Social Benefits of iGEM

By Benjamin Couillard

With assistance from Abraham Ogbaslase, Steffi Tran, Jacob Rumsey, and Pavel Shmatnik

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The objective of this paper is to demonstrate that the International Genetically Engineered Machine (iGEM) competition in synthetic biology has a large social benefit, in terms of education and tangible impacts, and accordingly that barriers to participation should be lowered in the interest of expanding this social benefit. There is a substantial literature on how various aspects of iGEM- problem-based learning, engineering competitions, and undergraduate research- provide academic benefits and/or signal the acquisition of skills to potential employers. There is also some literature on how participation in iGEM specifically teaches important scientific skills and higher-order thinking, generates a passion for science, and occasionally results in scientific publications. Besides reviewing this literature, this paper will demonstrate that the act of publishing scientific research based on an iGEM project indicates a larger educational benefit than participation alone, since publication is often done by finalist and gold medal-winning teams (issues of causality will also be addressed). It will also demonstrate that the number of scientific publications and businesses resulting from an iGEM project is non-trivial, and will demonstrate how businesses resulting from iGEM teams connect to the greater economy.

The paper is organized thusly: Section One is an introduction to iGEM and synthetic biology. Section Two is a review of the literature on the pedagogical benefits of different aspects of iGEM and some literature on iGEM itself. Section Three is an analysis of patterns in the publication of 82 papers based on iGEM projects. Section Four is an analysis of 20 startups affiliated with iGEM teams, either because a former iGEM participant is a co-founder or because the startup is directly based on an iGEM project. Section Five concludes.

Section One

While no universally-accepted definition of synthetic biology exists, it can be pithily summarized as the application of engineering principles to biology, primarily through the creation and alteration of DNA sequences in bacteria, in order to achieve some human-chosen objective. It offers many applications that would benefit humanity, such as synthetic organisms that can fight disease or create compounds that are costly or environmentally harmful to produce currently (König et al., 2013). One particular technology enabled by synthetic biology, the gene drive, is being considered as a tool to stop Zika and other diseases (Min and Church, 2015). However, in order to realize these benefits, society needs skilled synthetic biologists.

Born as an internal competition at MIT in 2003 and growing rapidly since then, iGEM is a mainly undergraduate synthetic biology competition. Teams receive sequences of DNA from the Registry of Standard Biological Parts to help with their project, and submit the parts they have created or modified at the end. Submissions must follow the ‘BioBrick’ standard for ease of modularization, which was invented in 2003 by a professor at MIT affiliated with iGEM and has grown in popularity in tandem with iGEM since then. Each competition culminates in a Jamboree, where teams are judged on a variety of factors and assigned a gold, silver, bronze, or no medal. There is also an overall winner, several finalists, and numerous special awards.

Section Two

iGEM has a strong impact on the education and career preparation of its participants. This is the result of the nature of iGEM itself- a problem-based, socially aware undergraduate research project competition. It is also a result of growing awareness of employers of the skills that iGEM imparts to its participants. In the paragraphs below, we will review evidence from academic literature, media, and interviews that there are significant personal benefits to participation flowing from exposure to undergraduate research, competition, problem-based learning (PBL), and project-based service learning (PBSL). This is borne out by the results of a survey of 2007 and 2008 iGEM participants. We will also expound on the role of participation in iGEM in signalling skills to employers. Thus, iGEM promotes the acquisition of skills, as well as providing a means to capitalize on these gains.

As an engineering competition, iGEM poses iterative problems that are open-ended and poorly-defined; evidence from experiments in public schools shows that problem-based learning (PBL) provides problem-solving skills that are more applicable to the professional world than traditional pedagogy *and* that it instills superior knowledge of subject matter. Boaler (1997) observed two UK high schools' math classes, one which emphasized structure and rote learning and one that emphasized self-directed problem-solving. The school that emphasized problem-solving performed better on the applied math test that Boaler administered. It also boasted a higher pass rate and smaller gender gap. Stepien, Gallagher, and Workman (1993) compared several problem-based high school courses with conventional courses and found that the students who were exposed to complex and ill-defined problems not only gained better problem-solving skills but also a better understanding of the subject material. Mehalik, Doppelt, and Schunn (2008) observed 46 grade 8 science classes in one urban public school district and found that an engineering, systems-based approach to teaching electricity was superior to the standard pedagogy, particularly with regard to poorly-achieving blacks. Thus, based on the repeated complex problems that an iGEM project poses, we would expect iGEM participants to see gains to problem-solving abilities and knowledge of synthetic biology vis-à-vis those who only learn through traditional methods.

Competition also provides benefits to engineers. Shehata and Schwartz (2015) wrote that

> the benefits of engineering competitions for students, as supported by recent engineering education research, can be summarized in the following ten points: increase student motivation, encourage deeper learning, improve student research methods, give students control over their learning, engage students with academic writing, provide opportunities for interdisciplinary or multidisciplinary work, encourage student innovation, increase student-to-student and student-to-faculty interaction, provide students with professional engineering skills including project management and professional communications skills, and provide students with real-world engineering design experience.

Their study of the Concrete Canoe Competition, Concrete Toboggan Competition, and American Concrete Institute Construction Competition subsequently confirmed all of these points. Recall that iGEM stands for international Genetically *Engineered* Machine; we would expect all of these benefits to accrue to participants of this particular engineering competition as well.

iGEM teams who wish to win a silver or gold medal at the Jamboree are now required consider the human practice implications of their project. This is similar to Project-Based Service Learning (PBSL), which focuses the standard engineering PBL around a problem facing a local or international community. While an iGEM team faces a choice of which problem to pursue and may never actually implement their solution, both involve deviating from a purely technical solution based on consultation with the afflicted stakeholders. Bielefield, Paterson, and Swan (2009) provide a litany of benefits to young engineers from participating in a PBSL course. First, interpersonal skills like teamwork, communication, leadership, and project management are improved from working with non-technical partners. PBSL students exhibit greater sensitivity to the social, cultural, environmental, and ethical considerations when they can easily see the consequences of their decisions, and the constraints on decision-making that these considerations impose foster creativity in their circumvention. Additionally, young engineers report better self-confidence, self-esteem, interest in volunteering, and civic engagement, suggesting that the benefits pass through to their personal lives and role as a citizen. Lastly, the participation rate of under-represented groups is greater than their representation in the population of engineers, suggesting that the inclusion of social considerations can draw in minority engineers that might otherwise be pushed away. This then suggests that iGEM's professed commitment to the consideration of issues "beyond the [lab] bench" confers those same benefits on its participants.

Empirical evidence also demonstrates that participation in undergraduate research improves cognitive abilities and increases the likelihood that a student goes on to become a researcher. Fechheimer, Webber, and Kleiber (2011) demonstrated a correlation between participation in undergraduate research and a student's cumulative GPA, while controlling for innate ability with SAT scores. Of course, this is not a strong claim in favour of causality. Kuh (2007), writing in the annual report for the National Survey for Student Engagement, reported that undergraduate researchers performing various research activities (designing the study, reviewing literature, collecting data, analyzing data, interpreting findings, writing up findings, presenting findings, and submitting a paper) saw statistically significant increases in various measures of deep learning (in higher order thinking, integrative learning, reflective learning, and overall deep learning). Lopatto and Tobias (2010) surveyed undergraduate researchers and found that they "were better able to think independently and formulate their own ideas, had become more intrinsically motivated to learn, and had become more active learners," (2009). He also ran focus groups with undergraduate researchers and a control group; he observed that undergraduate researchers exhibited cognitive development and argued that there was a concomitant strengthening in the desire for knowledge that would lead undergraduates to stay in academia. Lastly, Bauer and Bennett's (2003) survey of university alumni revealed that undergraduate researchers were 10% more likely to pursue graduate school, lending credence to the claim that undergraduate researchers were more likely to pursue research as a profession. It would be difficult to argue that these cognitive benefits and increased propensity to pursue research do not apply to iGEM, which offers applied research, access to faculty advisors, and sometimes even wages to undergraduates.

The academic literature predicts that there are myriad personal benefits to be gained from participating in iGEM. By learning from problem-solving, rather than lessons, one gains superior problem-solving skills *and* a superior command of the material. By participating in an engineering competition, one receives all ten benefits that Shehata and Schwartz enumerate. The incorporation of social considerations improves one's interpersonal skills, makes one more sensitive to the concerns of others, and improves mental well-being. Participation in research as an undergraduate facilitates cognitive development and an innate thirst for knowledge that manifests as being 10% more likely to pursue a graduate degree.

Mitchell, Dori, and Kuldell (2010) performed a survey on iGEM participants that provides solid evidence of some of these effects. At least 60% of participants in 2007 and 2008 reported moderate to great increases in their ability to identify relevant questions, plan experiments, interpret results, connect old and new data, organize information, integrate published information, and communicate ideas. This is in addition to those students who reported learning techniques like PCR, cloning, and culturing prokaryotic cells at rates of 34%, 47%, and 44% respectively in 2007. Despite one in three participants having never worked in a lab before iGEM, another one in three worked more than 40 hours a week on their project. Two in three participants reported becoming more interested in lab research and four in five reported becoming more interested in biological engineering. This is clear evidence that iGEM instills basic lab skills, higher order cognitive and scientific skills, and a passion for science in participants. This increases their future earnings potential, and while the focus of this section is on personal benefits accruing to participants, it also speaks to the greater societal benefit resulting from an increase in the stock of skilled and passionate young scientists.

iGEM also facilitates the conversion of these skills, higher cognitive function, and passion for science into careers and further education. Knowing that iGEM attracts the brightest and most enthusiastic young synthetic biologists, firms and graduate universities pay up to $5000 for a booth at the Jamboree's career fair (2015.iGEM.org, 2015). iGEM alum and co-founder and CEO of Caribou Biosciences Rachel Haurwitz told synthetic biology media company Synbiobeta that Caribou had success recruiting interns at the 2014 Jamboree and planned to do so again in 2015. This is because Haurwitz, who was named to Forbes' Top 30 Under 30 (Herper, 2014), knows what an effect iGEM has on those who participate: "I was an iGEMer in 2005, and it definitely helped shape and fuel my own personal scientific curiousity," (Chatsko, 2014). This sentiment is echoed by Steven ten Holder, former iGEM participant and co-founder and CEO of Acorn Cryotech, who described iGEM as "a place [he] knows [he] can recruit great talent," (ten Holder, 2016) and noted that his co-founders are also iGEM alumni. Kevin Chen told us that his experience with iGEM helped him land a job at Synbiota immediately after graduating, a step on his path to co-founding Bricobio and Hyasynth Bio (Chen, 2016b).

Even if one does not get recruited at the Jamboree, engineering competitions like iGEM can still help turn skills into jobs. Shehata and Schwartz (2015) point out that that engineering competitions provide useful fodder for open-ended job interview questions and résumé enhancement, as well as industry contacts among sponsors and judges. Cheung et al. (2015) note that competitions provide a basis for external assessment of one's abilities, particularly relative to one's peers; it follows that if that external assessment is favourable, it will make a job applicant more attractive.

According to academic literature, iGEM confers myriad benefits on those who participate, including specific lab skills, transferable problem-solving skills, higher cognitive functioning and a better understanding of the social aspects of synthetic biology. These effects have been proven to exist when tested empirically, albeit according to self-reporting in surveys. One self-reported benefit that we can take at face value is a passion for science and research, which will increase the supply of professional synthetic biologists, benefiting greater society. Participation in iGEM also connects one to employers and boosts résumés. While tangible impacts of iGEM form the basis for the rest of this paper, iGEM is at its heart an educational venture and its educational benefits should not be underestimated.

Section Three

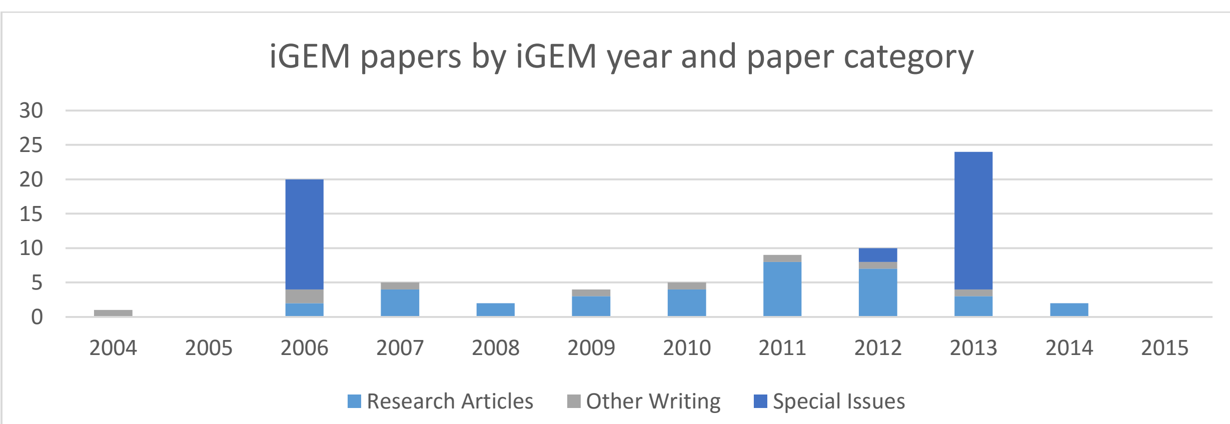
This section lays out our analysis and interpretation of 82 publications by iGEM teams. In total, we expect a given iGEM team to publish 0.025 papers. This buttresses the point that the purpose of iGEM is primarily educational. However, iGEM teams do contribute to the synthetic biology literature to some degree, particularly those that fare better at the Jamboree by winning gold medals or being named finalist teams. When a team does publish, it is evidence of educational success far beyond what one would expect of a team of undergraduates. According to Ontario's Degree Level Expectations, this is an educational outcome that one would expect at the doctoral level. We cannot say for certain what causes success at the Jamboree or publication- it could be that high-performing teams do well because their undergraduates are more meritorious, or have access to better resources, like lab materials, graduate-level advisors, or Primary Investigators. However, we do know that this is evidence that participation and success at iGEM provides large educational benefits, and that any barrier to participation and success- lack of interest among students, lack of access to lab space and materials, lack of funds for registration, lack of access to qualified supervisors, advisors, or PIs- should be lowered in the interest of creating a labour force with the skills to succeed in the rapidly-growing field of synthetic biology.

Methodology

We define an iGEM publication as any paper published in an academic journal that is coauthored by at least two undergraduate team members and on a subject discussed on the official team webpage or wiki. We found these papers by using the 'onesearch' function available to students at the University of Toronto, which searches all journals and databases accessible to University of Toronto students at once. These papers can be separated into three categories: 35 full research articles, 9 other pieces of writing (technical notes, reports, etc.), and 38 articles published in two special journal issues specifically featuring the work of iGEM teams. We define an iGEM team as any team that applied, was accepted by iGEM, and registered.

Year, Category, and Region

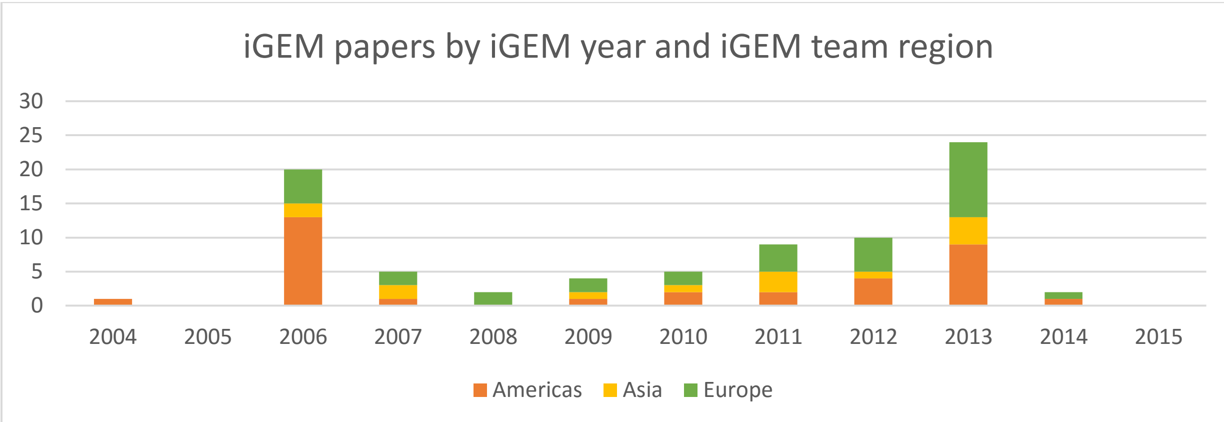
A graphic depicting the category and year the publishing team competed is below.



We can see that the spikes in 2006 and 2013 are completely due to the two special issues, including the sole issue of *The Institute of Engineering and Technology Synthetic Biology* and an issue of

The American Chemical Society Synthetic Biology. Aside from the special issue articles, iGEM papers reached a high in the early 2010s.

A graphic depicting the publishing team's region and year of competition is below.



Here we can see with the exception of North American dominance of the special issue of 2006 the regions have been generally balanced.

Publication Rates

In 2007, iGEM began awarding teams gold, silver, bronze, or no medal based on the quality of their project. Starting in 2006, several finalist teams and one grand prize winner were selected. A chart depicting publication rates for the different medal statuses and finalists is below.

	TOTAL	NA	NONE	BRONZE	SILVER	GOLD	FINALIST
RESEARCH ARTICLES	0.025	0.028	0.000	0.003	0.004	0.050	0.244
OTHER WRITING	0.007	0.042	0.006	0.000	0.000	0.008	0.073
SPECIAL ISSUES	0.028	0.222	0.000	0.000	0.000	0.036	0.122
ALL PUBLICATIONS	0.060	0.292	0.006	0.003	0.004	0.094	0.439

The publication rates for teams that do not fall into any medal status is higher than we would expect because many 2006 teams were published in the special issue, before the medal system began. Aside from that, we can see that gold medal winning teams and especially finalist teams are more likely to have their work published, to the point where nearly half of finalist teams have their work published in some form. Out of 62 papers published by teams who competed after the medal regime began, 58 were published by teams that won gold.

While Björk and Solomon (2013) note that delays between article submission and acceptance in the biomedical sciences are about 6 months, iGEM papers were published an average of 1.66 years after the Jamboree. Removing papers published in the two special issues, which featured articles on projects done in the previous year, raises this figure to 2.18 years. This implies that removing teams and papers from the last two years provides a better picture of iGEM team publication rates, with the caveat that the Jamboree occurs very late in the calendar year and any paper published more than two months later is coded as being published one year later. Nonetheless, 72.73% of research articles and other writings were published two or more years after the Jamboree.

There are two other reasons why we believe it is appropriate to remove the most recent two years from the analysis. First, the graphics above show that research articles and other writing fell to two from the 2014 Jamboree and zero from the 2015 Jamboree so far. The second is how the results from a similar exercise performed by Porcar and Vilanova (2013) holds up after two years.

Porcar and Vilanova's set of recommendations for iGEM included an observation that relatively few academic papers result from iGEM projects which was intended to emphasize the primarily pedagogical purpose of the competition. We agree with this interpretation of iGEM's purpose and our own evidence shows that only .06 papers result from each project. However, their assertion that "to the best of [their] knowledge, fewer than half of the finalist projects have been published so far," (Porcar and Vilanova, 2014) supported by their own review of finalist projects 2006-13 is false. Since 2014, seven articles by Groningen 2012, Paris Bettencourt 2013 (twice), Slovenia 2012, Heidelberg 2013, Munich 2013, and Imperial 2013 (Daszczuk et al., 2014, Atanaskovic et al., 2014, Libis et al., 2014, Lebar et al., 2014, Beer et al., 2014, Morath et al., 2014, Kelwick et al., 2015) have been published. All seven papers were published by teams in the two years before Porcar and Vilanova published their article. This is in addition to two articles by Slovenia 2006 and Peking 2010 (Ciglič et al., 2007, Zhang et al., 2013) that were published before 2014 but were missed by their review. The seven articles later published that were based on work from the two previous Jamborees show that one must account for the time it takes to publish an article. However, their missing two articles outright demonstrates the pitfalls of their and our approach of simply trying to find as many articles as possible; the figures we supply should be taken as a lower bound. Our own figures on publications rates excluding 2014 and 2015 are below.

	TOTAL	NA	NONE	BRONZE	SILVER	GOLD	FINALIST
RESEARCH ARTICLES	0.034	0.029	0.000	0.005	0.007	0.071	0.300
OTHER WRITING	0.010	0.043	0.010	0.000	0.000	0.012	0.100
SPECIAL ISSUES	0.041	0.232	0.000	0.000	0.000	0.053	0.167
ALL PUBLICATIONS	0.087	0.304	0.010	0.005	0.007	0.137	0.567

Our own figure for the total publication rate of finalists 2006-13 is 0.567, notably more than Porcar and Vilanova's figure of 0.3. This is exclusive of a patent application based on the work of Heidelberg 2009, a paper written by the supervisors of Imperial 2006, and a paper written by the supervisors of Slovenia 2007 included in Porcar and Vilanova's analysis, but inclusive of a transcript of an oral presentation by Imperial 2006 that was published as a supplement by *BMC Systems Biology* as well as the 9 articles mentioned above.

Citations and Impact Factor

A table depicting average citations and journal impact factor with and without outliers for the different paper categories is below. Journals with no impact factor were treated as having an impact factor of zero.

	CITATIONS	IMPACT FACTOR	CITATIONS, NO OUTLIERS	IMPACT FACTORS, NO OUTLIERS
RESEARCH ARTICLES	27.74	5.13	19.94	4.34
OTHER WRITING	58.67	8.52	15.38	4.40
SPECIAL ISSUES	3.87	3.52	3.87	3.52
ALL PUBLICATIONS	20.07	4.76	11.85	3.95

The two outliers are papers based on the work of University of Texas' Austin team in 2004 (Levskaya et al., 2005) and 2006 (Tabor et al., 2009). The first was a "Brief Communication" published in *Nature* (impact factor of 41.456) in 2005, garnering 405 citations. The second was a research article published in *Cell* (impact factor of 32.242) in 2009, cited 293 times. Their removal nearly halves the average number of citations for all publications and reduces slightly the average journal impact factor. After removing these outliers, the next highest number of citations is 91 and the next highest journal impact factor is 12.996. It is important to note that on the other end of the distribution are 12 articles that have been cited zero times and 17 articles that were published in journals with no impact factor and that we treat as having an impact factor of zero. There is a wide variance in the quality of these contributions to the literature, and the optimistic figure for average citations is influence heavily by two outliers.

Discussion

The basis for our claim that publication of a paper indicates a superior educational outcome is Ontario's Degree Level Expectations. Amid the propagation of new degree-granting institution, the Council of Ontario Universities sought to develop benchmarks for Bachelor's, Master's, and Doctoral degrees. While many of these 7 metrics are somewhat subjective- for example, in our opinion an argument can be made that iGEM participants exhibit "a critical awareness of current problems and/or new insights, much of which is at, or informed by, the forefront of their academic discipline, field of study, or area of professional practice," (Council of Ontario University, 2011) which would demonstrate attainment of a Master's Degree Level Expectation in Depth and Breadth of Knowledge- we will focus on one metric that is much less subjective. This is attainment of a Doctoral Degree Level Expectation in Research and Scholarship:

> The ability to conceptualize, design, and implement research for the generation of new knowledge, applications, or understanding at the forefront of the discipline, and to adjust the research design or methodology in the light of unforeseen problems; the ability to make informed judgments on complex issues in specialist fields, sometimes requiring new methods; and the ability to produce original research, or other advanced scholarship, of a quality to satisfy peer review, *and to merit publication*.

Emphasis ours; this is a precise description of what the publication of an iGEM project entails.

There are caveats to this analysis. iGEM teams that publish often achieve this expectation collectively, although many papers did not list all undergraduate members as authors, and some were screened out for having one or zero undergraduate members as authors. iGEM teams are supported by multiple advisors who are in pursuit or possession of a doctoral degree already; we suspect that having advisors who already have been published and who are often listed as last authors on iGEM publications helps greatly with getting these papers published. On the other hand, doctoral students themselves often have advisors who provide similar assistance.

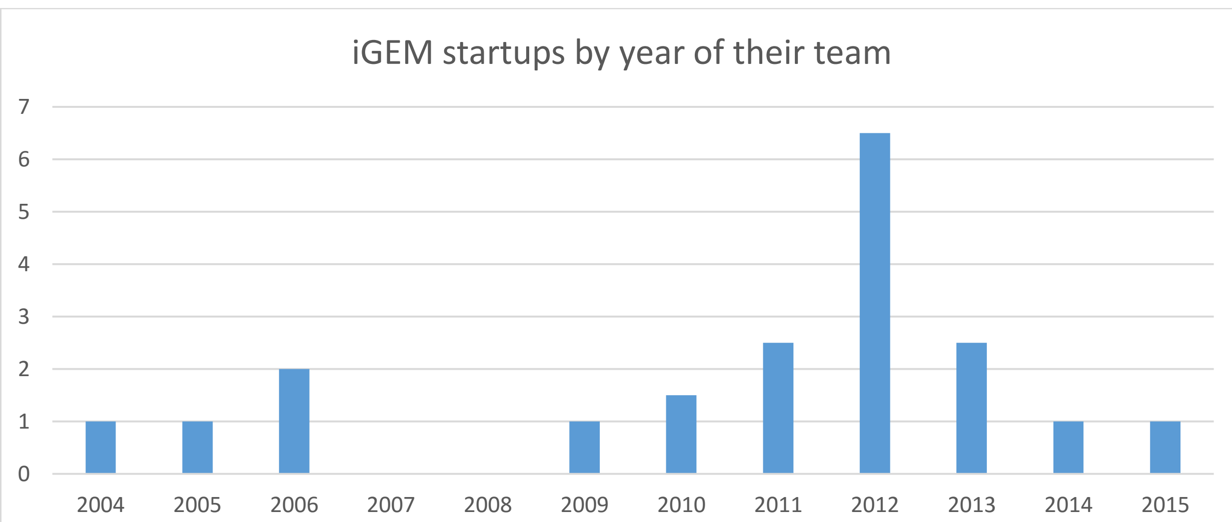
Beyond the educational benefit of simply participating, members of teams who publish gain skills that will prove incredibly useful should they pursue graduate studies. While our literature review shows how participating helps to give skills to a workforce, our study of iGEM publication shows how iGEM prepares members of the most successful teams for joining academia. This is aside from the fact that iGEM teams have produced 82 additions to scientific literature, have supported the research of professors in work published only on their team wikis, and worked on projects that are eventually published but without authorship for two or more undergraduates.

There are many determinants to whether an iGEM team is successful and thus more likely to publish. However, there are many barriers to participation that would prevent success and publication. Lowering these barriers, through assistance in paying registration fees, assistance in acquiring materials and lab space, or generating greater enthusiasm among potential advisors, would increase the likelihood that a given team goes on to participate, win a gold medal or be named a finalist, and publish- with a concomitant greater likelihood for large educational benefits.

Section Four

Synthetic Biology has tremendous potential to improve how goods and services are provided and generate new goods and services, making iGEM-affiliated startups an obvious example of the social benefit of participation in iGEM. iGEM incentivizes teams to consider implications outside of the lab through Human Practices Projects, demonstrate feasibility through proof-of-concept and prototypes (Judging/Medals, 2016.igem.org, 2016), and plan for implementation through the short-lived entrepreneurship track (2012e.igem.org, no title, 2012). When the entrepreneurship track ended after the 2014 Jamboree, it was not because iGEM did not value entrepreneurship but because there was a growing realization that “entrepreneurship is something all teams can aspire to do with their project,” (Entrepreneurship, 2015.igem.org, 2015). As a result, there is now a Best Supporting Entrepreneurship Award that is open to all teams. In this section, we will describe trends in where and when they were formed and provide two taxonomies of iGEM startups. Information on each startup including the iGEM team they came from, the team’s university, the company’s native country, and a brief description of what the company offers is in the appendix.

We found a list of 18 iGEM startups from the iGEM website (iGEM Startups, 2016), one more through internet research (Chatsko, 2015), and one more from a member of an iGEM team that generated that startup (Balbon, 2016). Our list includes companies that were founded by iGEM members and thus not every company we study is based on an iGEM project; this decision was made because the list on iGEM’s website includes teams like Hyasynth that are not based on an iGEM project and the information needed to determine whether this is the case for a given business is not always available. Seven company-founding teams were in the entrepreneurship track, while three competed in years where the entrepreneurship track was available but did not participate in the entrepreneurship track. Below is a visualization of when the teams that generated the startups competed at the Jamboree (half teams indicate when two consecutive years were credited by iGEM.org with forming a startup).



The early 2010s were a very fruitful period for iGEM entrepreneurship. 2012 was the first year of the entrepreneurship track, and this might have something to do with the large number of startups formed from teams in that year. We believe the drop-off after 2012 is similar to the drop-off in publications after 2013: it takes time to start a business. Any businesses from 2013-15 that were not uncovered by our research are likely either still in the very early stages and have not reported the startup to iGEM or do not have a sufficient online presence to be found by our research.

Our list of twenty includes businesses that were formed from teams exclusively from North America and Europe. They also show a remarkable degree of clustering on a sub-national level. London has produced four- two from Imperial College of London (CustoMem, LabGenius) and University College London (Bento Lab, Morph Bioinformatics) each. MIT (Benchling, Ginkgo Bioworks) and the University of Washington (Experiment.com, PVP Biologics) have also produced two each. The University of Alberta (Upcycled Aromatics and Genomikon, which merged with Synbiota) has two as well and the University of Calgary's (FREDSense) one brings Alberta's total to three. Lastly, Ontario is home to two startups from Queen's (Hyasynth Bio) and Waterloo (Acorn Cryotech). This leaves seven startups that are not part of a cluster; their American universities are the University of California Davis (Ambercycle), the University of Pennsylvania, (BioBots) Brown University (SynBioBeta), and the University of Texas Austin (Caribou Biosciences), and their European universities are Erasmus University/the Delft University of Technology/Leiden University/the Royal Tropical Institute (Amplino), the University of Edinburgh (Gene Advisor), and the Technical University of Denmark (Labster).

To understand the qualitative impact of these companies, we undertook two taxonomy methodologies. The first was to sort companies based on whether their product was a good, a service, or a platform, and then based on whether their good was a final good or an input to further production, a service aimed at consumers or industrial partners, and a platform for intended for a general audience or for technical work. Final goods, consumer services, and general platforms are roughly analogous to each other since they are an end product intended for mass consumption, while input goods, industrial services, and input goods, industrial services, and technical platforms are also analogous in that they contribute to further production. The table below was created with these classifications in mind. Some companies provide secondary products that are in a different category from their primary product; these were put in the appropriate box with their name in italics and added to the sum of each row/column in italics. Companies with teams in the entrepreneurship track have asterisks.

	Input/Industrial/Technical	Final/Consumer/General	sum
Good	CustoMem, FREDSense*, Ginkgo Bioworks, Hyasynth Bio, PVP Biologics	Amplino*, BioBots, Bento Lab*, *Synbiota*	8+*1,*3E
Service	Ambercycle*, LabGenius, Morph Bioinformatics*, Upcycled Aromatics*, Caribou Biosciences, *CustoMem*	Acorn Cryotech, *Amplino**	6+*2*, 3E+*1E*
Platform	Benchling*, Experiment.com, Gene Advisor, Synbiota, *BioBots*	Labster, SynBioBeta	6+*1*, 1E
sum	14+*2*, 5E	6+*2*, 2E+*1E*	

Product Taxonomy

Four things stand out from this table. First, the industrial services cell has the most businesses. Second, the number of companies that produce goods, services, and platforms are roughly equal. Third, the number of companies that make products that feed back into further production is roughly twice those who market their product to the general public. And fourth, teams in the entrepreneurship track tended to create businesses that feed input markets rather than final markets and provide services rather than goods or platforms. Below is the same table as above, but with team names instead of business names and geographical clusters colour-coded.

Product Taxonomy with Team Names, Geographical Cluster Colours

	input/industrial/technical	final/consumer/general	
Good	ICL 2014, Calgary 2012/Calgary E 2013, MIT 2004, Queens 2012, Washington 2011	Amplino E 2012, Penn 2013, UCL E 2013, *Alberta 2010*	8+*1*, 3E
Service	UC Davis E 2012, ICL 2011, UCL E 2012, Alberta E 2012, Austin 2005, *ICL 2014*	Waterloo 2015, *Amplino E 2012*	6+*2*, 3E+*1E*
Platform	MIT E 2012, Washington 2010/2011, Edinburgh 2006, Alberta 2010, *Pennsylvania 2013*	DTU Denmark 2009, Brown 2006	6+*1*, 1E
	14+*2*, 5E	6+*2*, 2E+*1E*	

Clustered teams tend to feed input markets, and their share of input market businesses (.79) is much higher than their share of final market businesses (.33). When including secondary products, these figures are .75 and .375, slightly closer. Clustered teams also comprise higher shares of businesses that produce goods (.75) than services (.67) and platforms (.5). When including secondary products, these figures are .78, .625, and .43, a more pronounced difference. One possible explanation for these differences would be if clustered teams had access to networks of contacts in industry (from being physically proximate to iGEM startups) that prompt them to take approaches that lead to founding businesses that create tangible goods and feed other industries.

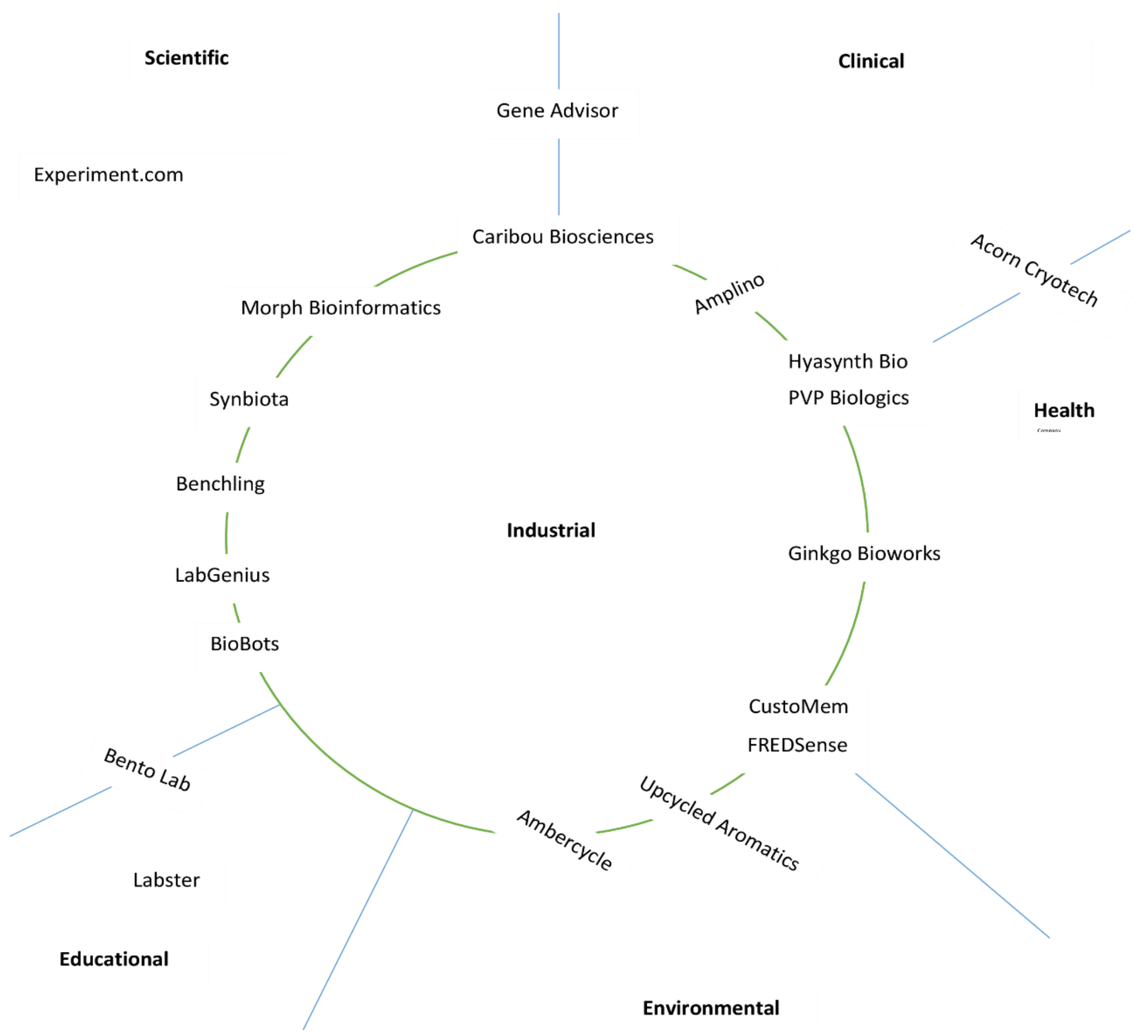
Product Taxonomy with Country, Continent

	input/industrial/technical	final/consumer/general	
Good	UK:1, Canada:2, US:2	Holland:1, UK:1, US:1, *Canada:1*	Holland:1, UK:2, US:3, Canada:2, *Canada:1*
Service	UK:2, US:2, Canada:1, *UK:1*	Canada:1, *Holland:1*	UK:2, US:2, Canada:2, *Holland:1*, *UK:1*
Platform	UK:1, US:2, Canada:1, *US:1*	Denmark:1 US:1	Denmark:1, UK:1, US:3, Canada:1, *US:1*
	UK:4, US:6, Canada:4, *UK:1*, *US:1*	Denamrk:1 Holland:1, UK:1, US:2, Canada:1, *Holland:1*, *Canada:1*	

Here we can see that while there is not much a discrepancy between the continents, the US, UK, and Canada tend to generate iGEM startups that sell to input markets, whereas Denmark and Holland generate iGEM startups that sell to final markets.

Our other taxonomy was based on how and where the company's product is used. We chose six categories: industrial, clinical, scientific, environmental, educational, and health. Industrial means the firm has a place in the value chain of other goods and basically means the same as selling to input markets. Clinical means the product has medical applications. Scientific means the firm supports laboratory efforts or does research of its own. Environmental means it benefits the environment somehow. Educational means it can be used to educate. And health means it promotes well-being outside of conventional medicine. Three firms (Experiment.com, Benchling, Labster) are only in one category while four firms (Hyasynth Bio, Ginkgo Bioworks, CustoMem, and FREDSense) are in three; the rest are in two. The graphic below shows which categories the companies fall into.

iGEM Startup Application Areas

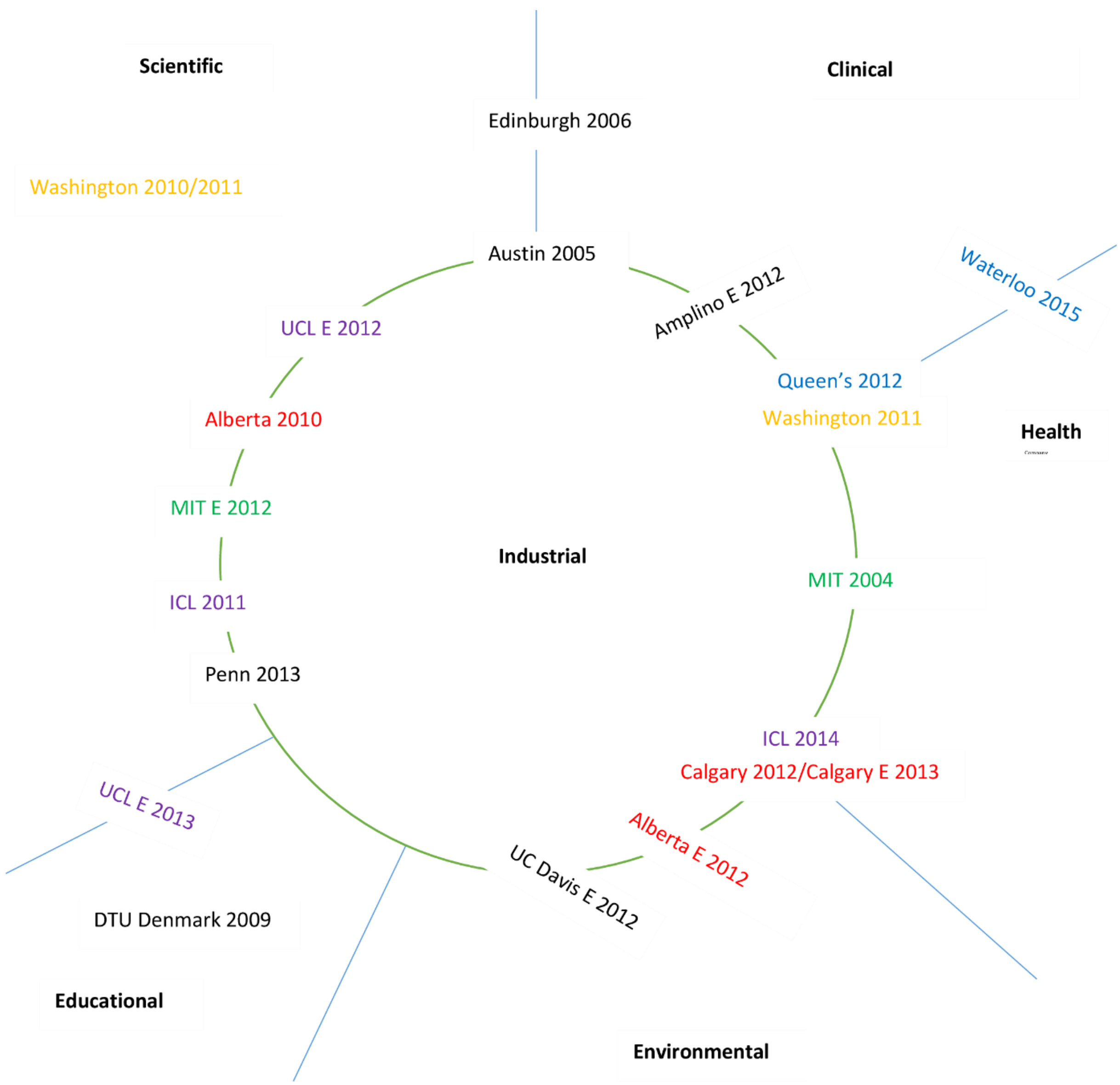


Firms that fall into one category are located squarely within that section. Firms that fall into two categories are located on the boundary of that section. And firms that fall into three categories are located on the corners of all three. SynBioBeta, as a synthetic biology-centric media platform, does not fall into any category here and is excluded from the graphic. The frequency of each category is given in the table below.

category	industrial	scientific	clinical	health	environmental	educational	other
frequency	14	7	6	6	4	2	1

After industry, firms in the scientific, clinical, and health categories are most prevalent. Meanwhile, some firms have environmental and educational applications. Five firms are industrial and scientific, because their products can be used in academic or industrial labs. Five firms are industrial and health-promoting, by virtue of all four firms that fall into three categories including those two. This makes sense- three of those firms focus on synthesizing new compounds that can be used in medication, while two have applications in water safety. Four firms are industrial and clinical (two of which are also industrial and health-promoting), and another four are industrial and environmental. One of the many beautiful things about synthetic biology is that industrial applications are often more environmentally friendly than current methods. Only six firms are *not* industrial. Below is the same figure, but with team name instead of firm name.

iGEM Startup Application Areas by Team



Four of seven European firms have scientific applications, driven by three of four London firms, while the same is true for only four of thirteen North American firms. Both Ontarian firms have health and clinical applications. Two of three Albertan firms have environmental applications. So geographical location does seem to have an effect on the kind of products firms provide.

Some firms offer very similar products and might find themselves competing in the future. When Ambercycle and Upcycled Aromatics start operating, they will recycle textiles and plastics into higher value chemicals and wastepaper into aromatics and platform chemicals. Both offer ‘upcycling’ services – turning waste into valuable products – and it is easy to imagine Ambercycle scaling into paper or Upcycled Aromatics scaling into textiles. Similarly, Hyasynth Bio will produce natural molecules that can be used in medicine, whereas PVP Biologics will produce therapeutics for food allergies. It is possible that some potential allergy therapeutics are natural molecules, especially given that “natural molecules or derivatives make up more than half of the current drugs on the market with applications to nearly every disease known to humans,” (Hyasynth Bio, 2015). Synbiota and Benchling are both currently operating and are likely already competitors given that they both offer software to support synthetic biology lab work.

However, cooperation is a far more prominent theme in all of these businesses. Every industrial firm depends on building partnerships with firms in the industry that they offer their services to, and supposed competitors could find that overlap in customers is minimal compared to overlap in areas where information sharing is beneficial. It could be that there is no overlap between the compounds that Ambercycle and Upcycled Aromatics will upcycle and that they can discover natural compounds and allergy therapeutics better by cooperating. The same is true for Hyasynth Bio and PVP Biologics. FREDSense and CustoMem could offer a combo deal- A water filter form CustoMem and a sensor from FREDSense to ensure it is working properly. It’s possible that the next generation of synthetic biologists will start their training with Labster’s lab simulator before moving on to Bento Lab’s beginner synthetic biology lab. That young synthetic biologist could work in a lab that is supplied DNA libraries by Lab Genius, is connected to customers who desire DNA tests through Gene Advisor, 3D prints with a BioBot 1, receives bioinformatics support form Morph Bioinformatics, and is funded by Experiment.com. Ambercycle and Upcycled Aromatics could partner with the same municipal government to upcycle that lab’s waste. In the emerging synthetic biology economy, the potential gains from trade and cooperation are enormous.

Section Five

In this paper, we have sought to collect and centralize information on three main benefits of to society of iGEM. First, there is the educational benefit to the emerging synthetic biology workforce as shown by our literature review. Then there is the related benefit to synthetic biology academia from giving team members an opportunity to produce work worthy of publication, preparing them for academic careers and strengthening knowledge-generation capacity. Third, there is the direct economic benefit of assisting in the creation of dynamic, young firms that will put the synthetic biology workforce and knowledge generated by academic to use. However, there are other benefits that we have not discussed at length heretofore.

Many iGEM teams engage in outreach activities towards the youth and general public in order to generate interest in genetics and synthetic biology. It's not really possible to study this quantitatively, but we will provide some examples to illustrate the creativity and enthusiasm of iGEMers.

University College London's 2013 team (University College London Wiki, 2013) instigated a TED Debate on neuroethics. This formed the basis for their later speed debate on ethics in synthetic biology, which featured speakers from academia and industry before splitting into moderated debates in small groups that were periodically shuffled and posed new questions. Participants' animated discussion inspired a creative writing competition on the human practices of their project to fight Alzheimer's Disease.

MacQuarie Australia's 2015 team (MacQuarie Wiki, 2015) continued with their web-based reality video series "So You Think You Can Synthesise". The team was able to integrate laboratory practices and their project into the show while allowing viewers to influence the outcome through online voting.

Purdue iGEM's 2013 team (Peking wiki, 2013) worked with high school biology teachers to incorporate mathematical modeling into their classrooms to ease the transition into synthetic biology. The team also collaborated with Biomaker Bench to help organize outreach efforts to K-12 students in Indiana. Lastly, they organized and implemented a workshop for Girl Scouts to learn about biotechnology.

Washington's 2011 team (Washington, 2011) introduced their project to university students and students at the K-12 level. They created an interactive cloning project, where students use ribbons and balloons to visualize the processes of digestion, ligation, and cloning of vectors into cells. Their program then introduced students to the functions of proteins and let them use 'Foldit', an interactive protein folding and design computer game. The team presented their interactive activity at the Bellevue School District Bennett Elementary School Young Scientist Week to K-5 students, parents, and teachers.

At a time when scientific progress provides great opportunities and poses great risks, good scientific governance is essential. However, trust in public institutions is declining (Gallup Inc., 2016) and attitudes towards settled scientific concepts like climate change are deeply polarized (Funk and Kennedy, 2016). Groups like iGEM that generate interest in and comfort with science, especially increasingly politicized areas of science such as genetically modified organisms, will be necessary to shape public opinion such that society can navigate challenges and capitalize on opportunities.

From a policy perspective, the implications are clear. iGEM provides a multifaceted benefit to society. Governments that want their countries to succeed in the coming decades would do well to boost participation in iGEM. As we wrote in Section Three, this should be down through lowering barriers to participation: providing assistance in paying registration fees, assistance in acquiring materials and lab space, or generating greater enthusiasm among potential advisors. Don’t delay- the synthetic biology economy is coming.

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