Chapter 1

Synthetic biology: A new and promising technology

Opinions on what synthetic biology actually is range from a natural extension of genetic modification and recombinant DNA technology to a new manufacturing paradigm. Synthetic biology attempts to bring engineering standardisation to biotechnology to enable many decades of biotechnology research to pay off in the form of mass-market applications. It has been championed and popularised through the international Genetically Engineered Machine (iGEM) competition, and now several governments are investing in developing national synthetic biology capabilities. However, it remains to some a controversial technology. Public policy issues range across R&D investment and commercialisation, education and training, biosafety and biosecurity, intellectual property issues, and public perception.

Introduction

Synthetic biology is at such an early stage of development that there is as yet no general agreement on what it is. To some, it is simply a natural extension of genetic engineering ("GM+"). To others, it is a route to mass manufacturing based on decades of biotechnology research and may lead to a new manufacturing paradigm. These views are apparent in the many proposed definitions of synthetic biology.

The critical technical differences between synthetic biology and genetic engineering and recombinant DNA technology are the much greater requirement for DNA synthesis and the concept of rational design, which brings the life sciences closer to engineering and thus the need for standardisation of procedures, parts and assembly (all essential to manufacturing). Concepts such as orthogonality, hierarchies of abstraction, separation of design from manufacture, standardisation and interoperability, all of which are central to engineering disciplines, have been largely absent from biotechnology. Instead, the research community has struggled to describe the overwhelming complexity of the life sciences and understanding it at the molecular level has been the work of many decades.

The broadest message regarding synthetic biology and associated policy needs is that, in many respects, there is no need for entirely new approaches. In its earliest applications, synthetic biology's basic tools and platforms are being created in industrial biotechnology, with the bio-based production of fuels, chemicals and materials. In many cases, this calls for the replacement of existing fossil-derived chemicals, usually with identical molecules, and the current regulatory systems appear adequate. New medicines are likely to require the extension of existing regulation, rather than a *de novo* approach. In specific instances synthetic biology appears to challenge details of the intellectual property (IP) system, but would not call for its overhaul. The most likely cause for concern is agricultural applications involving deliberate release to the environment and/or human consumption. However, experience with genetic modification (GM) regulation over several decades indicates modifications rather than massive changes that would hold up development.

Synthetic biology is still in its infancy, and policy issues that are just arising will have to be addressed. They include the need to ensure: a critical mass of trained researchers and other professionals; support for research and innovation through public funding and technology transfer; investment-related subsidies; clarity on intellectual property issues; and governance in terms of the regulation of synthetic biology. Moreover, it is essential that the

various publics and stakeholders play an essential role in its development. This report seeks to clarify some of the policy issues and their implications.

Perhaps the most significant policy signal is the emergence of national roadmaps. A roadmap conceptual design appeared in a European Union project in 2009 and in July 2012 the United Kingdom Technology Strategy Board published a roadmap for synthetic biology reaching out to 2030 (see Chapter 7). Technology roadmaps focus on the challenges and opportunities related to the development of a technology, consider possible future developments in the technology and its environment and create a framework to help to plan and co-ordinate actions (e.g. research, development, finance, legislation, stakeholder engagement and wider communication) to meet short-, medium- and long-term goals. Roadmaps can also lead to the identification of barriers (e.g. technical, social, ethical) to the development and/or use of a technology.

Given that public opinion will be an important factor in the development of synthetic biology, roadmaps can have an extremely important function. If the applications of the technology are widely discussed with the public, the roadmap could include the applications that are most acceptable to the public, and this transparency may help reduce negative perceptions, such as those that have arisen in the past for biotechnology. In a limited UK survey of opinion, "conditional" support was given to synthetic biology applications that were perceived as beneficial.

The international Genetically Engineered Machine (iGEM) competition is considered instrumental in the birth of the discipline of synthetic biology. It was initiated at the Massachusetts Institute of Technology (MIT) in 2003 for undergraduate students, and has rapidly grown in popularity. It has played an essential role in making synthetic biology an international discipline. Its appeal to young minds has captured the attention of industry, academia and governments. Since those early days, synthetic biology research has expanded very rapidly. By around 2010, synthetic biology-based companies were reaching the stage of initial public offering (IPO), with successes especially pronounced in the United States. For a discipline that lacks engineering standards and therefore a means of mass production, this is an astonishing rate of progress.

What is synthetic biology?

There are many definitions of synthetic biology, of varying degrees of complexity, and several organisations are working on a definition. A simple definition that seems to crystallise the issue without resorting to the jargon of the life sciences or engineering comes from the Royal Academy of Engineering (2009):

> "Synthetic biology aims to design and engineer biologically-based parts, novel devices and systems as well as redesigning existing, natural biological systems."

The use of the terms "design", "engineer" and "devices" sets synthetic biology apart from systems biology. A theme that is implicit in synthetic biology is that of rational design. Biology has always been a very descriptive science that does not lend itself to standardisation, a necessity in manufacturing (see Box 1.1).

Box 1.1. Synthetic biology for a better understanding of biology

In many academic courses on synthetic biology, the emphasis is on the application of engineering principles to deliver a new means of production. However, another definition of synthetic biology contains the idea of using synthetic biology to advance basic biological theory: "Synthetic biology is the design and construction of biological systems guided by engineering principles, with the aim of understanding biology or producing useful biological technologies." (Bayer, 2010) In other words, while biotechnology focuses on the use of controlled biological circuits in the design and manufacture of new products, synthetic biology offers new opportunities in the opposite direction – the use of artificial biological circuits to understand fundamental biological problems.

Biological systems are, in essence, extraordinarily complex genetic systems that maintain, repair and build themselves in highly integrated environments. One of the most fundamental biological problems is our limited understanding of how these genetic systems work. Expressed in another way, we do not know the basic design principles of gene regulatory systems (Elowitz and Leibler, 2000).

Using an analogy with electronics and electronic circuits, one way of increasing our understanding is to use synthetic biology to construct simple biological components that can be linked to form very simple, elementary biological systems or "circuits" whose functions can be studied, followed by the progressive construction and study of systems or circuits of increasing complexity that mimic the behaviour of real genetic systems:

"The possibility of a minimal core network driving robust cellular behaviour has inspired the development of an alternative approach to the study of gene-regulatory networks: create the network, beginning with a one or two-component system and then rebuild the network from the bottom up. In this way, we can gradually assemble increasingly complex systems that mimic the native network, while maintaining at each stage the ability to model and test the network in a tractable experimental system." (Cookson et al., 2009)

The major contribution of synthetic biology to basic science is likely to be an increased understanding of gene regulation and expression, which has long been hypothesised to be the basis of the evolution of phenotype rather than changes in encoded proteins (Dickinson, 1988), all of which makes the potential contribution of synthetic biology to biological theory enormous.

Panke (2008), summarising a number of influential papers, identified five points that are crucial in engineering but are by and large absent from biotechnology.

1. *Comprehensiveness of available relevant knowledge*. In mechanics, electrical and chemical engineering, the mathematical formalities are well known. In biology, this is far from the case.
2. *Orthogonality* i.e. independence. This is absolutely essential in engineering. For example, a car must be able to accelerate independently of its wing mirrors, electric windows, alternator, steering, etc. In biology, changes in one metabolic pathway effect changes in another as they are often interlinked. A change in one often causes interference in, or from, others. In a bacterial cell, the cytoplasm hosts hundreds of different simultaneous chemical reactions, and orthogonality is largely missing.
3. *Hierarchy of abstraction*. If the overall system can be divided into meaningful subsystems that can again be divided into meaningful subsystems, and so on, the design task can be distributed over several levels of detail at the same time. The advantages are two-fold: parallel advances reduce development time and specialists can address specific levels of detail in the system. The description of biological systems, by contrast, usually focuses on the molecular level, and formalised, abstract or functionalised descriptions in the above sense are rare.
4. *Standardisation*. The lack of standards in biotechnology has far-reaching consequences: different lengths of promoters used in different plasmids, with different copy numbers, used in different *E. coli* strains, grown on different media at different, and often variable, temperatures show why it is extremely difficult to standardise data output. Mining the literature to discover all the different variables involved is very time-consuming.
5. *Separation of design and manufacturing*. This is a mantra of engineering. Going back to the car analogy, the design of a car is separate from its assembly at the assembly line, which requires comparatively little effort. The different groups of employees have different specialist training; this makes it feasible to design and manufacture a car. In biotechnology, the manufacturing of the system is still a major part of the research project and in many cases a research project on its own.

Synthetic biology differs from genomics. Genomics, or gene sequencing, can be viewed as the ability to read the genetic code, and the relevant technology has made huge strides in recent years. Since 2003, the cost of sequencing has dropped by at least one million fold. The acceleration of sequencing speeds in successive generations of equipment has exceeded even computer processing's Moore's Law (Moore, 1965).

Synthetic biology relies on the ability to make gene sequences routinely. The fundamental difference with genomics is that gene synthesis is the ability to write the genetic code, not read it (Goldberg, 2013). This has proven altogether more difficult than sequencing. The problems include the accuracy, reliability, cost and turn-around time of DNA synthesis. These capabilities currently lag far behind the ability to sequence DNA. Given the importance of DNA, this is a very serious impediment.

Technology roadmaps for synthetic biology

In considering how to bring technologies from the laboratory to commercialisation, a roadmap can help to clarify the challenges and opportunities related to the development of a technology, to consider possible future developments, and to create a framework to help to plan and co-ordinate actions (e.g. research, development, finance, legislation, stakeholder engagement and wider communication) to meet short-, medium- and long-term goals. Roadmaps can also lead to the identification of barriers (e.g. technical, social, ethical) to the development and/or use of a technology.

Roadmaps addressing these issues exist or are being developed for synthetic biology in various countries (e.g. the United Kingdom) and are under consideration elsewhere (e.g. the United States, the European Union). Relevant policy issues include education, skills and training; infrastructure for research; technology transfer and commercialisation; and issues relating to companies and public-private co-operation (see Chapter 7).

A major function of roadmaps is to identify problems that could become major roadblocks (Galvin, 2004). Policy discussions in these early days of synthetic biology therefore cannot be restricted to the near term. It is clear that synthetic biology can make major contributions to a bioeconomy but will also create challenges, so that, from the start, policy must also look to the long term.

Workshops that include as wide a range of stakeholders and experts as is practicable are needed to achieve an effective roadmap. Public engagement will be needed from the start to try to avoid the situation that has arisen with recombinant DNA technology. A monitoring strategy will also be needed to follow developments in the area. A co-ordinated international effort has the

potential to increase the efficiency of the development of synthetic biology by minimising overlaps and duplication of effort and resolving issues arising in terms of governance and regulation.

The need for education, skills and training in synthetic biology

As a multidisciplinary field, synthetic biology incorporates elements of biology, engineering, chemistry and, when it leaves the laboratory, environmental science. Its multidisciplinary nature challenges traditional scientific education, which separates disciplines such as microbiology, chemistry and computing. In particular, there is a fundamental difference between the education of scientists and engineers. Scientists need to be able to question, and freedom is important. Engineers need rigour and standards. Systems modelling and design are well established in engineering disciplines but until recently have been rare in biology. Synthetic biology is clearly a hybrid field that will require a barrier-breaking approach to education.

The education system has been responding to the needs of the growing synthetic biology community. Educational programmes are already available in some countries from school to postgraduate and postdoctoral levels. However, the institutions offering these programmes are still pioneers. A web-based resource[1] quotes over 100 different institutions offering graduate-level education in synthetic biology.

As a mainly postgraduate subject in higher education, synthetic biology lends itself to a research Master's degree that emphasises practice-led research combined with relatively few taught modules compared with other Master's degrees. This type of Master's degree is generally designed to prepare students for doctoral research, but is also useful for those considering a career in the commercial world where research is a key focus but a PhD is not required. As synthetic biology leaves the laboratory and more applications are commercialised, a research Master's degree of this type may become a popular route to entering the field.

There are concerns that the lack of a skilled cadre of workers could be a roadblock to the development of synthetic biology. One option would be to develop truly interdisciplinary education, leading to graduates with science, engineering and computing skills along with the business skills found in a typical MBA programme (change and risk management, venture capital skills, intellectual property management, entrepreneurship skills).

Different countries and organisations are responding to these educational needs in different ways. For example, the Danish Council for Strategic Research has prioritised synthetic biology and is encouraging scientists to work in international networks in order to pool competences and resources.

In addition to performing world-class research in synthetic biology, it is developing an education programme at the undergraduate, postgraduate and doctoral levels. In the United States, many of the best-known universities offer education in synthetic biology. MIT, for example, has a course, intended for the 12th grade, to demonstrate the complete process for cloning a gene. It is also developing integrated interdisciplinary graduate courses that are accessible to students from different backgrounds. An undergraduate programme at Princeton covers the core material of introductory physics, chemistry, biology (genetics and biochemistry), and computer science in an integrated manner, in that they are taught together, with examples drawn from biology.[2] It is argued that the continuing relationship between technology and discovery means that in the next 50 years cell biologists will have to be conversant with fundamental concepts from physics, chemistry and genetics and especially with the mathematical and computational ideas and methods that dominate technology development (Botstein, 2010).

Practitioners of synthetic biology must manage complexity rather than describe it as traditional biologists have generally done, and engineers must build using material under evolutionary pressures in the absence of fixed standards. Students who enter synthetic biology perceive the promise and limitations of the emerging discipline, but they are still required to define themselves as engineers or as scientists. Although the quantitative theoretical and computational component represents a fundamental departure from the tradition of the life sciences, Tadmor and Tidor (2005) stressed that modelling should not be construed as a replacement for experimentation. The major departure experimentally for students is that this is the experience of working with DNA by "making it" instead of recovering it from biological samples (Czar et al., 2009). This exposes the classic conundrum of multidisciplinary education: laboratory skills require depth but also breadth, and achieving the optimum balance of depth and breadth is difficult.

Education in synthetic biology must go beyond science and engineering. Given the history of the GM debate, public perceptions will also play a role. There is already evidence that political and economic pressures, as well as technical achievements, will guide the development of synthetic biology (Rai and Boyle, 2007). Kuldell (2007) argues that education must equip students to deal with these aspects of the emerging discipline. A recent textbook (Schmidt et al., 2010) purports to be the first comprehensive overview of societal issues relevant to synthetic biology, setting the scene for important discussions within the scientific community and with civil society.

Any discussion of education and training must inevitably consider high-school students. Capturing the interest of students at an early age can be critical to the development of synthetic biology and may have a positive effect on public opinion. If parents see that their children are interested in synthetic

biology, that it offers career prospects, and that they are enthusiastic and develop related social networks, they may be less inclined to develop the negative perceptions associated with GM technology.

The role of competitions

National and international competitions can drive innovation and drive down costs, encourage school leavers to want to become students, provide opportunities to spot talent, and increase awareness of synthetic biology. They may also serve a role in changing the negative perceptions of biotechnology. The educational experience gives the participants hands-on laboratory experience and vital skills that other students would find it hard to acquire. Generally they are an excellent means of allowing various stakeholders to network, potentially improving the job prospects of students and exposing industry to the best young talent.

iGEM BioBricks competition

Arguably, synthetic biology has been best championed and publicised by the influential international Genetically Engineered Machine competition, created at MIT in 2003. This annual interdisciplinary competition was originally designed for undergraduates. It has grown rapidly, with 32 teams in 2006, 84 in 2008 and 165 in 2011. It has proven so popular that the 2011 competition was expanded to include a high-school division, and again in 2012 to include an entrepreneurship division. In January 2012 the iGEM Foundation was spun out of MIT as an independent non-profit organisation located in Cambridge, Massachusetts. The iGEM Foundation[3] supports scientific research and education through the iGEM competition.

The goal of the competition is to design and assemble creative genetic systems by combining existing BioBrick parts[4] and creating new ones. The climax of the competition is the convergence of all teams in Cambridge for the iGEM Jamboree. If iGEM is a summer project for most teams, some universities are taking advantage of this event to create innovative educational programmes (e.g. the Genome Consortium for Active Teaching, GCAT[5]).

The iGEM competition has generated so much information over the years that a company has built a map interface[6] using the Creative Commons data available from iGEM.org. This tool can be used to search, navigate and sort through hundreds of projects and get access to videos, posters and presentations directly from the interface.

BIOMOD

Launched for the first time in 2011, BIOMOD[7] is a bio-molecular design competition that provides undergraduates with an opportunity to engineer the self-assembly of biological macromolecules into complex nanoscale machines for scientific and technological purposes.

Students form teams in the early spring, and then spend the summer to design, build and analyse their systems. All teams converge at the Wyss Institute for Biologically Inspired Engineering at Harvard in the autumn to present their work.

CAGEN

The Critical Assessment for Genetically Engineered Networks (CAGEN)[8] is designed to improve the robustness and performance of human-designed biological circuits and devices operating in cells. The competition aims to bring together leading research groups in biological circuit design to demonstrate their ability to design circuits that perform in a prescribed manner in a variety of cellular contexts.

Each year, a steering committee proposes a challenge involving the design of an increasingly complex set of biological functions in a range of environments. Teams must submit their sequences, plasmid DNA implementing their circuit and data characterising the performance of their system against a specified test suite. The three to five best performing designs are selected as finalists and results are reviewed and verified by the CAGEN steering committee, which selects the overall winner based on a set of quantitative metrics. The CAGEN competition is sponsored by the Keck Foundation, as part of the National Academies Keck Futures Initiative.

Gen9 G-Prize

Gen9 has developed a unique technology to synthesise DNA constructs and has used it to build a novel fabrication capability for next-generation gene synthesis. The inaugural G-Prize contest, conceived and sponsored by Gen9, was launched to foster creative and innovative approaches to using synthetic DNA libraries to advance industries such as pharmaceuticals, chemicals, biofuels and agriculture. The competition is open to academic and non-profit scientists. In 2012, the G-Prize judges identified five separate winners, and Gen9 awarded them 1 million base pairs of dsDNA. In 2013, in order to further catalyse innovation, Gen9 awarded the entire 1 million base pairs to one research group,[9] a group from Yale University that will utilise these made-to-order DNA constructs to decipher cellular signalling networks and to create the largest-ever data set of *in vivo* protein-protein interactions.

Competitions for industry

On 18 November 2013, the UK Technology Strategy Board (TSB), the Biotechnology and Biological Sciences Research Council (BBSRC), the Engineering and Physical Sciences Research Council (EPSRC) and the Welsh government opened a competition for business-led projects. An investment of GBP 3.8 million aims to develop innovative tools and services for the UK synthetic biology industry, and can include companies of any size, rather than just small and medium-sized enterprises (SMEs).

Policy makers should monitor these competitions, which help to reveal trends in the development of synthetic biology. In particular, the iGEM competition is now truly global. Several countries have stressed the need for international communication and exchanges, and iGEM has been a springboard for globalisation. Moreover, the iGEM community has a history of involving students and the public. Public engagement, from an early stage and as a continuous process, should be made a major goal in the development of the field.

The following chapters of this report draw attention to emerging policy-related areas that will be important for the future development of synthetic biology: current and potential applications, the required research infrastructure, investment, the intellectual policy issues and regulation. A final chapter describes various countries' development of technology roadmaps.

Chapter 2 sets the scene. It describes how synthetic biology arose in the United States, following a rapid rise in research grant funding due to the rise in interest in biofuels. The life sciences research community has embraced synthetic biology, and some applications are appearing, with many more being researched. Many early applications, and some of those that reached the market earliest, are related to bio-based production of fuels and chemicals. The platform tools of synthetic biology are emerging from these applications.

There are also many health-care applications, from new drug design to tissue engineering and diagnostics. In particular, synthetic biology promises to transform medicine and health care in developing and poor countries, which have health-care problems different from those in developed countries. Many recent projects of the Bill and Melinda Gates Foundation (see Annex A) reflect this. For example, malaria is very difficult to control in poor countries, while developed countries are barely touched by it. In developed countries, the re-emergence of many bacterial scourges in the form of multi-drug resistant strains, such as the multi-drug-resistant tuberculosis that appeared in New York City in the early 1990s, requires new approaches to antibiotic discovery and development.

Agriculture is another area of great promise. The strides made in agricultural productivity and efficiency in the developed countries are now slowing. Some of the greater effects of synthetic biology in this area are likely to be felt in developing countries. The more obvious relate to increasingly "efficient" plants that have, for example, a higher yield or produce less CO_2. Agriculture would be revolutionised if plants can be engineered to fix their own nitrogen; this would free agriculture from synthetic nitrogenous fertilizers and significantly decouple it from the fossil fuel industry. Disease resistance in crops has always been an issue, especially in industrialised monocultures where disease can destroy whole crops over very large territories. With an expected nine billion people on the planet by 2050, food security is one of the Grand Challenges. Inextricably linked to it is water security: humans are expected to appropriate 70-90% of the planet's fresh water by 2025, most of it for agriculture. Synthetic biology's potential to address the Grand Challenges of climate change, energy security, food and water security and health care means that it is likely to shape the research and political agendas of the life sciences in this century.

In terms of research infrastructure needs, Chapter 3 shows that many of the issues are those that apply to any emerging technology: research subsidies and international co-operation. At this point the most important technical barrier to synthetic biology is the speed, cost and accuracy of DNA synthesis of long sequences (i.e. writing the code). Rapid progress has been made, but there is still a large gap between the cost of synthesis and sequencing. There will be a landmark shift in the way many laboratories work when commercial gene synthesis is on par with synthesis of synthetic oligonucleotides, with similar costs and turn-around time. Much of the laborious work currently done to manipulate DNA will be phased out of routine use. Several companies appear to be poised to make significant breakthroughs in the high-throughput, automated production of DNA sequences at lower cost and higher accuracy than currently available, with a turn-around time in the range of 5-12 days.

Another important challenge arises from the success achieved in DNA sequencing, i.e. reading the code. So much sequence is being generated that the bottleneck has shifted from its creation to its storage. With the huge advances in DNA sequencing made from the mid-2000s, the capacity to store the information arises. With the number of new DNA sequencers entering service, the storage issue can only become more serious.

As public and private investments in synthetic biology increase (Chapter 4) and the first products appear, two policy areas are vitally concerned: intellectual property (Chapter 5) and governance (Chapter 6). The biotechnology industry has been characterised as one that files many technically complex patents. Evidence links the possession of IP in the biotechnology

industry to success in attracting investment. For synthetic biology, the most important IP issues that have arisen are:

- The tension between the need for openness, especially concerning DNA parts and the ability to communicate in the academic world, and the need for IP protection in order for companies to be able to appropriate the returns to their investment.
- Freedom to operate (FTO) and transaction costs, specifically the costs involved in guaranteeing FTO, and the costs associated with material transfer agreements (MTAs). In a device that might contain several hundred parts, the cost of appropriating FTO could be excessive.
- The complexity of the patent landscape and potential problems raised by broad, prophetic patents.
- The need for patent clearing houses, organised by a third party, to accept the registration of synthetic biology inventions, both sequence and functional claims, as a potential solution to some IP challenges.
- The likely expansion of the IP landscape to involve forms of IP such as trademarks, copyright and protection of databases.

However, communications from some national and international patent offices suggest that synthetic biology does not create fundamentally new challenges that would overwhelm the IP system. It would be a mistake to give the impression that these challenges are insurmountable.

In terms of regulation, several decades of regulating genetically modified organisms (GMOs) have positive and negative implications for synthetic biology. On the positive side, there is no need to start from scratch; a huge amount of experience has been gained. To date, synthetic biology regulation is covered by GMO regulation. Scientists in the field seem to think that there is no need for massive modification of the current system. The biosafety issues appear to be the same, except that the multidisciplinary nature of synthetic biology creates a need for greater awareness and training of stakeholders who are new to the field, such as engineers who are not familiar with biosafety procedures or the growing body of amateur scientists for whom the field may be a mystery.

DNA synthesis and biosecurity is a more serious concern. Two issues differ from GM biosecurity concerns:

- DNA can be readily designed in one location, constructed in a second and delivered to a third. The use of the finished material is therefore not under the control of its originators.
- Synthesis might provide an effective way to obtain specific pathogens for the purpose of causing harm, thereby circumnavigating national or international approaches to biosecurity. Currently, however, it would be much easier to modify an existing pathogen than to try to create a pathogen through synthetic biology.

Many agree on the need for a screening process for synthetic DNA manufacture and sale. The main aspects deserving consideration for control are: sequence screening for select agents to avoid synthesis of known pathogens or toxin-related DNA; customer screening to avoid shipment to dubious clients; and licensing of equipment and substances required for the synthesis of oligonucleotides.

One of the greatest challenges facing those who develop regulations will be to weigh the costs and benefits of rules and to develop an effective enforcement system. A government role at the international level will be necessary, and harmonisation among countries will be important. Otherwise, potential violators of biosecurity regulations may simply transfer their design and construction activities to a less regulated country. Chapter 6 summarises how regulatory interaction between governments, synthesis companies and customers might be achieved.

Regulation is intimately related to public opinion and acceptance. In the on-going debate about whether or not there is already enough regulation, it is worth re-emphasising that GM concerns have been much more of an issue in Europe than in other regions. It is not a significant issue in much of Asia, the Americas or some of the OECD partner economies. The negative reaction to GM technology is not gradually disappearing in Europe as was expected, although there are recent signs of a change in attitude in some countries. There is a possibility that Europe might undertake break-through research in synthetic biology but be unable to move to capacity building or wealth creation if its results cannot be deployed. The growing support in Europe for the idea of a future bioeconomy creates a quandary: many bioeconomy strategies and blueprints rely on synthetic biology as a platform technology but if public opinion rejects synthetic biology it will be difficult to achieve the desired bioeconomy. Public engagement must therefore start early and be maintained. GM has a sterling safety record, but that has not made it attractive to some publics. A new way of communicating the risks and benefits is needed. Aside from objections relating to release to the environment and biosecurity, other societal concerns include the distribution of benefits, and ethical and religious concerns.

The extreme youth of synthetic biology means that there is not a great deal of policy specifically directed to it. Chapter 7 looks at some of the roadmaps and policies that are being developed in a few countries. There are no real surprises: issues of early technology development such as education, R&D infrastructure, research funding and public engagement all feature. Some countries are more proactive than others. China is positioning itself to be a leader in the field and is developing policy on several fronts. The main point for governments is that the potential benefits of synthetic biology are greatest once it moves out of the laboratory. If its aspirations to bring engineering to the life sciences and enable a new future for manufacturing are to be realised, this can only be achieved in a globalised economy through international agreement and harmonisation. This is not a task for the private sector but for governments. The OECD, through its members and global outreach, would be well placed to act as the forum for co-ordination.

Notes

1. http://syntheticbiology.org/Graduate.html.
2. www.princeton.edu/integratedscience/curriculum.
3. http://igem.org/Main_Page.
4. BioBrick standard biological parts are DNA sequences of defined structure and function that share a common interface and are designed to be composed and incorporated into living cells such as *E. coli* to construct new biological systems.
5. www.bio.davidson.edu/GCAT.
6. http://synbioconsulting.com/igem-synthetic-biology-map/.
7. http://biomod.net/about-biomod.
8. http://openwetware.org/wiki/CAGEN.
9. http://gen9bio.com/g-prize/.

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