Synthetic Biology Perceptions: Aligning the Public View with Scientific Fact

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Executive Summary: Synthetic biology is a burgeoning field of research that separates itself from its predecessor, traditional genetic modification of organisms, by applying regimented engineering processes to the field of biology to recombine, and even create entirely new genetic code. This report focuses on the current public perception of the aforementioned subject, why these perceptions are the way they are, and how to better align consumer knowledge with scientific consensus. Synthetic biology is a difficult technology to explain to the general public because of a combination of scientific and psychological factors. Consequently, many consumers fall prey to sensationalist thinking and other misinformation that can unreasonably bias them for or against related products. To combat such problems, this report outlines three major efforts that should be taken by the synthetic biology community to rectify any informational inaccuracies and allow the entire American populace to make educated decisions about further development of this field. These proposed movements are to start including the basic concepts of genetic manipulation into the school system at a much younger age, to institute a dedicated governmental agency to assume sole regulatory responsibility for all genetically modified products, and to provide informal, voluntary educational opportunities for adults in the form of games, competitions, and other more personally engaging endeavors. With the proper implementation, it is believed that these options could make a significant impact on overall synthetic biology literacy, facilitating better, more informed decision making across the country.

I. Synbio: Definition and Current Perspectives

Synthetic biology, or synbio for short, is a pioneering technology that represents the next evolution of genetic manipulation. Previously, researchers were limited to what they could find in nature and relied on a trial and error system to slowly assemble functions that they desired from genes that already exist. Synthetic biology is the transition of this field into a new realm dominated by strict engineering principles and intentional, human-designed elements. Scientists are now able to construct genes from scratch with specific functions and store them in a database of reproducible parts, much like a machinist can choose between a standardized set of nuts and bolts. As such, this technology has progressed to the point where old guess and check practices have finally given way to sound rules and reliable governing principles. In this way, synthetic biology is to traditional Genetically Modified Organisms (GMOs) as modern materials science is to a medieval blacksmith's heuristic rules.

Of course, with such an improvement in design capacity, there also comes an increase in potential for societal, environmental, and industrial impact. To begin with, there are substantial benefits that could be reaped from a greater mastery of the biology that surrounds us. Two prominent examples under production right now are the microbial mass production of Artemisinin, a critical precursor to antimalarial drugs, and the photosynthetic production of advanced biofuels using nothing but air and sunlight ("How it Works" 2014; Sawyer 2011). Technologies such as these have the ability to completely redefine their respective industries, yet come with commensurate risks as well. First, many think that the intentional abuse or accidental misuse of this technology could lead to the release of custom engineered bioweapons into the general population. Second, many believe that a simple miscalculation in the long term effects of a new organism could wreak havoc to the natural environment, possibly destroying some previously stable ecosystems entirely. Third, some see this technology as a morally problematic direction to take, believing that it violates basic human rights, the natural order of the world, and/or religious imperatives against the role of creating life. Though difficult, it is up to the next generation of scientists, industrialists, and policy makers to reconcile such dangers with the aforementioned potential to solve many seemingly intractable global crises.

One of the most critical first steps for accomplishing such a complex task is to make sure that all of the players involved are equipped with correct, up to date, and useful information about the subject material itself. Genetic manipulation has long carried with it a broad range of scientific, philosophical, and religious stigmas, and to move forward it is necessary to tackle those perceptions head on. Some of the fears around this technology are well founded, while others stem primarily from a lack of pertinent education and scientific understanding (Konnikova 2013). Consequently, the objective of this research is twofold. First, an analysis is performed, primarily based on past experience with traditional genetic manipulation technology, to identify and determine the causes behind the prevailing opinions that dominate the perception of this field. Second, this report seeks to extrapolate several key directions that scientific, governmental, and corporate experts should take to help ensure that everyone has access to the most up to date information and to allay some of the concerns involved.

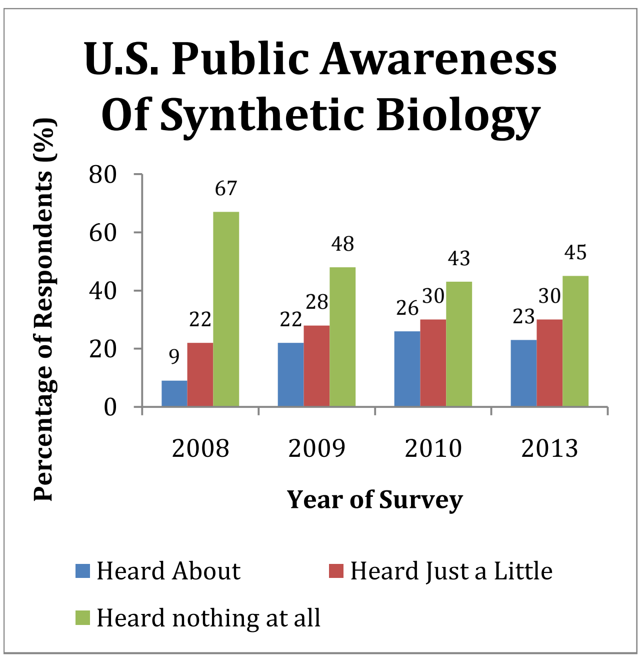

FIGURE 1: Public Awareness of Synthetic Biology. Responses to the question, "How much have you heard about synthetic biology?" show that awareness has improved over the last several years but gains have slowed and public knowledge remains low (Data from "Awareness and Impressions" 2013).

As the situation stands right now, there are several prominent realities when it comes to the public's views on synbio. First, there is a general lack of awareness. According to a report conducted by Hart Research Associates on behalf of the Woodrow Wilson Center, only 23% of adults have heard either a lot or some about synthetic biology ("Awareness and Impressions" 2013). Though there was initially a dramatic improvement from 9% to 22% between 2008 and 2009, this growth has recently plateaued, as demonstrated in Figure 1 ("Awareness and Impressions" 2013).

The next major issue is a sense of hesitance concerning the adoption of these products as a regular part of life. Without a market, there is very little drive for innovation and if the average citizen has a negative view of the subject, that view could stymie major developments for years to come. Most prominent was a tendency towards ambivalence concerning synthetic biology (Pauwels 2013a). Statements made by participants in the survey and in associated focus groups were dominated by caveats, cautionary additions, and other such equivocations. Such a skeptical view towards adopting or promoting synbio is also reflected by the fact that, based on initial impression, a 40% plurality of people thought that the risks and benefits of the technology were about equal, while only 18% percent thought that the benefits would outweigh the risks ("Awareness and Impressions" 2013).

Another aspect of public perception is the change in views of people as they are given an introduction to the actual risks and benefits of the technology. With only a very brief introduction, people's fear of the dangers seems to escalate much faster than their appreciation of the potential gains ("Awareness and

Impressions" 2013). The subsection of data shown in Figure 2 demonstrates how the public opinion shifts more towards the negative side as it is educated on the matter.

Though not a direct contradiction, some data also suggest that the more educated a given person is, the more likely he or she is to be accepting of synthetic biology advances ("Awareness and Impressions" 2013). Other demographic imbalances show dramatically decreased support for synthetic biology among women as opposed to men and much less support from weekly church goers as opposed to those who attend less often ("Awareness and Impressions"). Finally, there are racial and socio-economic differences as well, with white, middle to upper class Americans showing the most support and lower income Hispanics the least ("Awareness and Impressions" 2013).

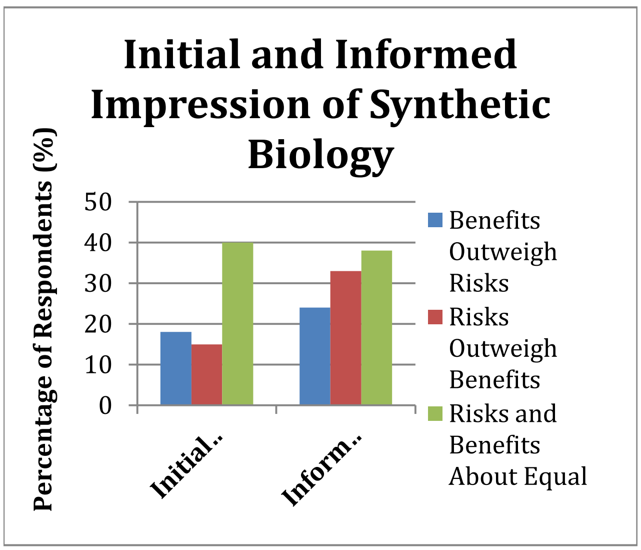

FIGURE 2: Initial and Informed Impression of Synthetic Biology. Perceptions shift negatively with a rudimentary knowledge of pros and cons (Data from "Awareness and Impressions").

II. Confusion, Dread, and Metaphors

After reviewing the aforementioned survey data, the next step is to attempt to better understand current public perception of synthetic biology. As past experience with nuclear, stem cell, and traditional GMO technology has shown us, public opinion is a critical component of the evolution of any new technology. To properly address this, however, one must first understand the motivations behind the views of the people concerned.

Psychologist Paul Slovic, who has been studying the perception of risk since the 1950s, has identified three major factors that can cause people to deviate from a logical, analytical view of a given situation (Slovik 1979). These are the degree of familiarity, the level of dread, and the number of people that could be affected by the issue. Unfortunately, synthetic biology is on the extreme negative of all three of those criteria (Konnikova 2013).

Considering the first of these elements, the current ambivalence discussed above stems from a general lack of familiarity. This deficit occurs on two fronts, however, for not only does most of the populace know very little about synthetic biology, but it is also such a nascent field that it is difficult for researchers to provide them with static, factual information. There has been a great deal of evidence to suggest that materials produced by genetically modified organisms are not inherently more dangerous than those produced by traditional breeding techniques, but there is also no way to prove, incontrovertibly, that this is the case (Nicolia et al. 2014). Compounding this ambiguity is the complex nature of synbio itself. Based on a large body of esoteric molecular biology, this is a field that is largely inscrutable, at an in-depth level, to the average citizen.

That being said, such a dearth of concrete knowledge should not inherently skew public perception one way or the other. Consumers commonly accept many products with internal processes they do not understand. At the same time, lack of scientific comprehension opens up pertinent decision making to the whims of instinct rather than analytical objectivity. In the same vein, that deficit does not contaminate the issue in and of itself; it simply allows unfounded, and sometimes even completely fallacious, points to hold an unreasonable amount of sway (Sherer 2012).

In the case of genetic manipulation, past experience with GMOs has shown that such an opening is ripe for the entrance of dread, Slovic's second risk factor for irrational analysis. One of the aspects that make biological products seem uniquely dangerous is their ability to self-propagate and evolve. Most people do not see how one can simply turn off bacteria in the same manner as an electrical system and that perceived resilience raises the stakes in many people's minds (Wright, Stan, & Ellis 2013). Furthermore, this theme has been recurring in public media for decades, making it seem all the more inevitable in the public eye. It is easy to vilify scientists, who remain a small, little-understood minority, for overconfidence induced catastrophe and that message has been perpetuated extensively through movie themes ranging from *Rise of the Planet of the Apes* to *Jurassic Park*.

In reference to Slovic's final factor on the perception of risk, the scope and impact of GMO applications is immense. These products make up approximately 2.5% of the American GDP and some estimates claim that eighty percent of packaged food in the United States contains genetically modified products (Carlson 2014; Doering 2014). Synbio is set to expand into many major industries over the course of the next several years, and this is a trend only likely to extend further in the future. People are beginning to see genetically modified products in the news more and more, yet lack a reliable way of actually determining if a given organism is a GMO. The combination of ubiquity and ambiguity is exactly the scenario needed to round out the extensiveness aspect of Slovic's three areas of concern.

Another contributing factor to the confusion that surrounds this field is the combination of vocabulary and metaphors commonly used to describe it. Linguistic choice has a powerful effect in framing a given situation, and once that framework is established in a person's mind, it usually has a strong impact on his or her overall perceptions (Entman 1993; Thibodeau & Boroditzky 2011). This effect was demonstrated in a simple experiment where participants were randomly given one of two different descriptions of synthetic biology, one using the word construct and the other using the word create. Despite the two words meaning the exact same thing in this context, the change in vocabulary resulted in significant differences in overall opinion of the subject material (Pearson et al. 2011).

Synthetic biology is still at such a nascent stage that scientists and the public alike do not always know exactly how to describe it. Metaphors, such as referring to DNA as the "software of life," are very useful in communicating ideas between disciplines or to the layperson, but in making such a characterization there is often critical information about the mechanics of the processes involved that is lost (Pauwels 2013b). This is not as much of an issue when discussion occurs among scientists, who must be careful to keep track of that subtlety, but it creates problems when used outside the laboratory (Pauwels 2013b). Eleonore Pauwels, a researcher at the Woodrow Wilson Center, points out that in using the more convenient linguistic option to explain such complex matters, it actually, "widens rather than closes the gap between scientific realities and the expectations of policy-makers and the public" (Pauwels 2013b). Consequently, it is critical that researchers and consumers alike take care with the language that they are using and regularly check that it is indicative of the current state of affairs.

III. The Right Information for the Right People

Given the high stakes involved and difficult informational issues just discussed, it is critical that appropriate actions are taken to prepare the public for this nascent technology so that consumers are able to make educated, logical decisions about synthetic biology products. In compiling the work of a variety of analysts on the subjects of synthetic biology, GMOs, and pioneering technology in general, there have emerged three main efforts that seem most likely to be effective in addressing some of the primary concerns of this emerging field. These potential policy options are a redesign of early education efforts, implementation of a governmental regulation body specifically for genetic modification practices, and a push for voluntary, adult education opportunities.

Each of the proposed plans will be analyzed according to a similar metric. First the overall structure and implementation details will be described. Then four areas that must be addressed for the overall solution to be effective are analyzed. These are: the cost of implementation, overall political feasibility, percentage of the population impacted, and the time required to affect a meaningful impact.

IV. Starting Young

Beginning with the revamping of early education efforts, it will be helpful to the overall discussion of genetically modified products to provide a better introduction to the concepts of genetics and gene manipulation in schools before the university level. This effort must involve everyone, down to elementary school teachers, and counts on reliable access to engaging, impartial instruction in the subject area as well as the addition of this subject material to the required tested curriculum.

As of right now, the Standards of Learning (SOLs) from the Department of Education include only a slight introduction to the concept of genetics at all, and do not even address its intentional, human manipulation there of ("Standards of Learning Assessments" 2010). With the introduction of this subject material into the basic grade school curriculum, students will have a much better faculty for forming educated, well-informed opinions from a reliable source of information. For this reason, the basic concepts of GMOs and how they work should be included in the SOL tests which, though still controversial in many ways, will at least require teachers to introduce the topic and teach from a regimented set of information. This gives the government some power in ensuring that children are provided factually accurate information at some point in their careers. The students may still deem the field too dangerous to pursue, but they will be able to do so from a standardized scientific perspective.

Some may believe that it is unrealistic for such a complex set of principles to be taught in the earlier grades of schooling, but with proper integration that is not the case (Child 2013). There are myriad simple activities, such as "Toothpick Fish," a game where toothpicks are used to represent fish color alleles and contrived scenarios represent selective pressures, which can make the overall concepts of genetic changes quite accessible even for very young individuals (Brown et al. 2001). Furthermore, these efforts can be scaled effectively as time goes on, incorporating hands-on exposure throughout the academic process. There are already kits available online that can supply and facilitate very basic genetic modification for an entire middle school class ("pGLO" 2014). Such lessons should become a mainstay of the biology curriculum because it is through that kind of youthful experimentation that children will grow to become experienced and rational adults.

Another important educational aspect that commonly is not addressed sufficiently is a general understanding of the scientific research process (Schmidt et al. 2014). This is not a procedure generally taught until later in an academic career, yet it is critical in digesting the vast amounts of scientific data that is now available. This is a complex, iterative process, and the amount of contradiction and ambiguity that can emerge before a new consensus is reached often creates confusion for those who have not actively participated in it before ("Understanding Scientific Studies" 2008). If the goal is a more reasoned review of scientific research by a non-expert citizen, then it is critical to include more education about the details of what different results can mean before students have left the required high school stage.

Tying the above options into the proposed metric, we begin by addressing the overall feasibility of such shifts in public education efforts. Unfortunately, it will be quite difficult to affect changes to the basic content of the US public school system. Even now, there is still conflict about the issue of teaching evolution in schools, which is a commonly accepted, thoroughly corroborated theory that does not even impact everyday life (Davis 2000; "Science Textbook Statement" 2007). Conversely, genetic manipulation technology results in tangible products that people eat, drink, and even breathe, making its addition as an accepted part of the curriculum even more controversial.

Concerning the time required for these motions to make an impact, this option also encounters problems. The proposed changes to the education system will require years, even decades, to make a meaningful impact as they are focused primarily on younger school children. This is a potent way to affect lasting change, but one that has an inherent time delay. Though this policy option should be very helpful in preparing the next generation of American citizens for synthetic biology, it will be years before those children become the primary decision makers of the country, and for that reason, there must be other, more immediately effective movements made as well.

The same problem applies in terms of overall scope, as it leaves out the adult populace that is not commonly involved in the American school system. In addition, according to the Council for American Private Education, one in ten American children in grades pre-kindergarten through twelve attend private schools ("Facts and Studies" 2012). While attempting to include genetic engineering in the national standard for grade school education may sway the degree of its inclusion in these institutions somewhat, it is ultimately up to those schools whether or not to actually teach it. Considering that 80.2% of private schools have some form of religious affiliation and, according to the statistics from the

Hart Research Association, those with higher expressed levels of religiosity are far less likely to support synthetic biology research, there could be a major barrier to including the private demographic in this educational reform ("Awareness and Impressions" 2013; "Facts and Studies" 2012). Despite this, sweeping changes to public school curriculum would still impact 90% of American schoolchildren, making for a fairly expansive policy option ("Facts and Studies" 2012). Finally, as with all plans, the financial cost must also be weighed. As these options are considered with nationwide impact in mind, here we speak mostly of federal funding and, consequently, tax dollars. Given the limited amount of time available in a given school year, it will be impossible to include this new information without it replacing some aspect of the older curriculum. Consequently, the total funding required for such instruction should remain roughly the same to previous financial allocations. There is the possibility of some conversion costs stemming from teacher training or revamping of lab activities, but those would be minimal given the basic nature of the material being taught.

Just as an example calculation, this report considers the implementation of pGLO, one of the most basic genetic manipulation experiments that can be performed, on a nationwide scale. As of the 2010-2011 school year, there were 67,086 public, primary schools in the United States and to provide each of them with one pGLO genetic modification kit (only $89.00 for schools) would cost a total of $5.971 million ("Fast Facts" 2013; "pGLO" 2014). This would allow, assuming they are each used by a single grade, roughly 3.7 million students to experiment with genetic modification technology (Bauman & Davis 2013). Of course, such a rough estimate is not perfect, as it would require classes over thirty-two students to double up and would require some materials to be restocked each year, but it does show that there are easy, relatively cheap options to be implemented around this subject.

V. Regulatory Overhaul

The next policy option is to establish a new institution, be it under an existing agency or a new regulatory body, which is specifically mandated with the regulation of all genetically modified products and responsible research. The J. Craig Venter Institute, a recognized leader in the synthetic biology field, recently published a report that claims such an action is not actually necessary at this juncture as the current regulatory framework of the US government is sufficient to handle most near-term applications of synthetic biology (Carter, Rodemeyer, Garfinkel & Friedman 2014). Despite this lack of immediate emergency, however, there are still significant benefits to be gained from implementing such an action right now.

The current regulatory system for GMOs is improvised and convoluted in nature (Carter, Rodemeyer, Garfinkel & Friedman 2014). There are multiple government agencies, particularly the FDA, EPA, and USDA, that each have the authority and capacity to regulate different sectors of the genetic modification industry (Carter, Rodemeyer, Garfinkel & Friedman 2014). Their laws combine to form a complex web that, while mostly comprehensive for the time being, is inconsistent and ad hoc in its regulatory power. While creating a new, more focused regulatory body is not entirely pertinent to the informational accuracy received by the public, it will help allay related fears and eliminate some of the confusion regarding this particular aspect of GMOs. Many respondents listed regulation as one of their chief concerns when it came to the continued pursuit of synthetic biology, and so if the goal is to create an environment that facilitates reasoned discourse on the topic, it seems reasonable to eliminate this more reconcilable element from the points of contention ("Perceptions of Synthetic Biology" 2014).

An example of the improvised nature, mentioned above, of these laws can be seen in the authority of the Animal and Plant Health Inspection Service in the USDA (Carter, Rodemeyer, Garfinkel & Friedman 2014). Its legal purview stems from the right to control plant pests, which only extends over genetically engineered crops because the USDA decided that any flora that had been engineered using a known plant pest as a recipient, source or donor organism, or as an agent to deliver such genetic modifications should be considered a "presumptive plant pest" (Carter, Rodemeyer, Garfinkel & Friedman 2014). Consequently, their regulatory power is heavily dependent on the actual production technique, integrating plant pest DNA into the genetic code or using those plant pests to augment said code (Carter, Rodemeyer, Garfinkel & Friedman, 2014). Without that specific pest component, APHIS loses its authority, something that could easily occur with synbio derived transformation methods that do not rely on plant pests (Carter, Rodemeyer, Garfinkel & Friedman 2014). At that point, a new adaptation would have to be made and the current laws further contorted to include technology that they simply were not originally designed for. Though United States policy on the regulation of genetic modification has traditionally focused on the final product instead of the production method, this example shows how tiny details in the techniques used can still have a significant impact on the regulatory process as a whole.

In fact, the porous nature of the current system is already emerging as a problem in the cases of glowing plants and fish. The first of these two products narrowly escapes regulation by APHIS because the gene transformations used are performed with a gene gun instead of the older method of using a plant pest as a vector (Krichevsky 2012). Regulation of the latter product was simply deemed unnecessary by the FDA with the explanation, “Because tropical aquarium fish are not used for food purposes, they pose no threat to the food supply. There is no evidence that these genetically engineered zebra danio fish pose any more threat to the environment than their unmodified counterparts, which have long been widely sold in the United States. In the absence of a clear risk to the public health, the FDA finds no reason to regulate these particular fish” (Bratspies 2006). Perceived governmental neglect in both cases was greeted with an uproar by environmental activists who were deeply concerned about the precedent that these actions set for later, more threatening inventions (Bratspies 2006).

Not only do situations such as these indicate a need for systemic future changes, but the public itself has also expressed a continual cry for greater regulation and, with it, increased transparency (“Perceptions of Synthetic Biology” 2014). The average consumer needs to be able to trust the regulatory body that is in place and it is critical that he or she understands that body to be able to put faith in it (Konnikova 2013). Yes, the current system works, but it took experts from the J. Craig Venter Institute two years of research to fully parse out the pertinent details and put them together for a coherent report (Carter 2014). A layperson probably does not have the time or interest to even read that 57 page document, much less perform such scrutiny themselves. Affecting the transition to a single, focused body of experts would not only make it much easier to accommodate for future changes in the rapidly evolving field, but would also provide a tangible government presence that the average citizen can understand, look to for help, and trust.

The actual political feasibility of implementing these new regulatory actions is difficult to determine. On the one hand, both supporters and detractors of synthetic biology technology seem to evince interest in greater levels of knowledge and inspection going into this field (“Perceptions of Synthetic Biology” 2014). Such a body would publicly address the public criticism of the technology while simultaneously providing increased regulation that the more skeptical demographics have sought. As such, there may be enough of a common cause on both sides of the argument to achieve what would likely be a momentous regulatory shift.

The closest precedent to creating an entirely new regulatory agency can be seen in the Nuclear Regulatory Commission (NRC) and the Atomic Energy Commission (AEC) before that. While not a perfect comparison, there is a critical lesson to be learned from the failure of the latter institution and its subsequent replacement by the former (“About NRC” 2014). It is critical that such a body restrict itself to the regulatory side of affairs. The AEC fell apart due to a confusing mix of goals where it was simultaneously charged with publicizing the good and restricting the bad aspects of the then pioneering technology (“About NRC” 2014). This sent a mixed message to the public that quickly broke down what trust could have been established and set nuclear power adoption back decades (“About NRC” 2014). For this option to be both feasible and effective in the case of genetic modification, it is imperative that the new body limit its goals to a strictly regulatory direction.

Another factor closely linked to the aforementioned feasibility is the financial cost involved, addressing the second evaluative criteria. Again using the Nuclear Regulatory Commission, which currently operates on roughly one billion dollars per year, as a comparable body in size, role, and scope, it is easy to see that this could be a costly option, likely detracting from its general support (“Congressional Budget Justification” 2012). This burden could potentially be mitigated, or possibly even eliminated, by requiring companies to pay for the regulation, still by federal inspectors, of their genetically modified products as long as this does not result in a loss of scientific integrity or untenable financial burdens on smaller companies. Given these mitigating factors, the financial cost of implementing such a policy change should not be prohibitive in the long term.

In terms of overall scope, this policy option does well. Regulatory confusion would drop, loopholes close immediately, and the entire public would have an obvious, culpable entity at which to direct their attention. While this does not address public awareness directly, it does provide a much more scrutable lens on the regulatory processes involved and thereby increase nation-wide comprehension and, consequently, engagement.

Additionally, assuming that it was successfully implemented and funded, the benefits of such an agency would be felt almost immediately. There may be some time required for the resulting body to establish its legitimacy, but there is enough federal precedent in similar areas, like the FDA, EPA, or NRC, to establish the necessary trust. One respondent in the previously mentioned Hart focus group stated, matter of factly, "Oversight seems to me to be the kind of like one of the main things the government is for, I mean, on our behalf, as the people" ("Perceptions of Synthetic Biology" 2014). People want regulation to take place; they just do not know what the appropriate manifestation might be. Once that is provided, it is likely that they will quickly adopt it wholeheartedly into the GMO debate.

VI. Voluntary Opportunities and Adult Education

Moving to the final proposed action, this report also recommends making an effort to support the informal engagement of adults in the field of synthetic biology. While it may be impossible to force older demographics into learning a new topic, the same goal could be achieved by incentivizing that result to the point where it still occurs on a voluntary basis. To accomplish this, there must be synbio opportunities that are fun, appealing, have a low barrier to entry, and yet still contain reliable educational material. This is not so much a federal policy option as it is a direction that should be promoted by, and for, the entire industry.

Several examples of ideas that meet those requirements are already gaining traction. First, the iGEM competition, standing for International Genetically Engineered Machine, provides a venue for high school, undergraduate, and graduate level teams to engineer and publicize their own synbio products ("Synthetic Biology Based on Standard Parts" 2014). There are various different prizes to be won and the organizers focus on rewarding factors such as rigorous documentation and safe environmental practices as well as the more traditional metrics like creativity and potential for societal gain ("Synthetic Biology Based on Standard Parts" 2014). Through this kind of well-developed educational program, it is much easier to get the next generation of young adults involved in the field and, even more importantly, show them that this is something to take seriously, but also be excited about. This is an endeavor that should not only be supported, but hopefully even expanded upon in the future.

Second, there is growing participation in do-it-yourself (DIY) biology laboratories. These labs are public venues for average citizens, not associated with any university or company research, to experiment with genetic modification technology and run experiments of their own. This group of involved citizens, who are statistically much more educated than the average American, provides a convenient avenue to provide solid, scientific exposure to the general public in a casual and non-institutionalized manner (Gruskin et al. 2013). Considering it their duty to engage local communities and spread knowledge about the field, such a facility is ideal for bringing up to date, personalized information to the adult public. People involved in this movement are also continually demonstrating a desire for regimented, safe practices that is critical in ensuring their ability to continue working and inspiring trust in those that they seek to teach ("Biosafety Advisory" 2014). Given this interest and the potential to make great gains in public awareness, it is important that government regulation works in collaboration with these private endeavors to establish a system that benefits both sides and is sustainable in the long term.

Another direction that deserves continued investment and support is the idea of synthetic biology gamification (Schmidt et al. 2014). This movement is based around the idea that games have several attributes that make them ideal for teaching the public about complex, interconnected issues. Games are accessible, fun, easily scalable, and provide excellent, real time feedback (Tucker 2012). Katie Salen and Eric Zimmerman phrase it in their book, *Rules of Play,* "Inside a game, what constitutes it, is a system: a group of interaction, interrelated, or interdependent elements that come together to create a complex whole" (Zimmerman & Salen 2003). A prime example of how this can be applied to synthetic biology is seen in the game Hero.Coli, produced by a small team at the Parisian Center for Research and Interdisciplinarity ("Hero.Coli" 2014). This game uses an artistic, visual interface and adventure based gameplay mechanics to allow users to discover for themselves the various benefits and dangers of synbio technology ("Hero.Coli" 2014). Though not technically a policy in its own right, it is still recommended that organizations, governmental or private, pursue such avenues for informal public engagement wherever possible.

Of course, there are many more educational approaches to take than the three examples mentioned above, these are simply three that could lead the way in terms of both efficacy and sustainability. This proposed process of informal education should be one of the more feasible options to implement given its diverse and decentralized nature. Most of the options available are either small-scale or private in nature, and for this reason, there is little opportunity for political objections to come into play in the actual inception of a given program.

Similar reasoning indicates that the financial cost should be fairly low as well. All three examples rely on small development teams, private funding, or both, meaning that the federal government should have little to no financial involvement. There must still be some interplay of these startup endeavors and government regulation, particularly if a new agency is being implemented as discussed previously, but that should not require monetary investment so much as a robust and continual dialogue.

The scope of programs such as these is inherently limited by their voluntary nature. No matter how fun a game is or how rich the rewards for a competition, there will still be plenty of people who have no interest in the area. In this situation, those people that care about the topic the least are likely going to be the ones with the smallest amount of actual information to draw on. Consequently, such voluntary educational efforts will be effective in distributing knowledge to those who are particularly curious or who have an interest in the field of synthetic biology already, but they may have a problem reaching the rest of the population. Considering that only 23% of people surveyed in the Hart report claim that they have heard at least some about synbio, there could be serious limitations on the scope of such adult education programs ("Awareness and Impressions" 2013).

Lastly, the time required to affect change with such measures is very difficult to determine. It is possible to measure the rate at which a given app is downloaded or a game is purchased, or the number of registered DIY Bio members, but that is hardly an accurate measure of the actual impact on public awareness. The decentralized nature of these kinds of public awareness options should allow them to spread very quickly, whether it is over the internet or across local communities, but the speed at which they are absorbed is entirely dependent on the application itself and the target demographic. Consequently, the overall time required to take effect varies dramatically and can only be classified as average.

V. Past, Present, and Future

The takeaway messages from this report are varied, though deeply interconnected, in nature. First, the current public perception of synthetic biology as a stand-alone field is almost non-existent. People do not know much about synbio and, while a problem in its own right, this creates a fantastic opportunity to approach the issue of public opinion in a directed and proactive manner. At the same time, what consumers know is often colored by a combination of media sensationalism, confusing definitions, and several deep seated psychological factors. For this reason, it is critical that efforts are made now to align overall public perception with scientific fact so as to ensure that everyone is properly equipped to make their own educated decisions about the pros and cons of this technology.

In promoting such an increased level of public knowledge, there are several avenues that are most likely to have a meaningful impact in the near future. First, there must be a change in the education system to begin providing students with information on genetic manipulation and synthetic biology concepts at a much younger age. This will prepare the next generation of consumers with unbiased and well established data upon which they can make their own decisions.

Second, a revamp of the current regulatory facilities for genetically modified products should occur with the goal of combining all current efforts under one roof. This would most likely entail an entirely new regulatory body that would serve as the governmental face for oversight of this controversial issue. Though also streamlining the process significantly and closing dangerous loopholes, this action would serve an equally valuable function by making the system more easily scrutable, thereby increasing overall public comprehension.

Lastly, efforts should be made by scientists, activists, industrialists, and even concerned citizens to help provide voluntary, adult education opportunities. These actions could take any number of forms, but they should all focus on providing fun, engaging methods of personalizing the field of synthetic biology and encouraging people of all demographics to become involved. Though contingent on proper implementation, such a movement could make significant gains in improving the general synbio literacy of consumers around the nation.

Each of these proposed directions has its own set of advantages and drawbacks, but taken as a whole, they will likely be able to affect real change in overall public awareness of synthetic biology. People simply do not know that much about this still nascent field of study, and it is the duty of its proponents to change that. Everyone is entitled to, and should, make their own decisions on what the appropriate future looks like for such a controversial technology, but it is critical that they are able to do so from an unbiased, well-educated perspective. That well-informed point of view is the ultimate goal of this research and, though a long road still remains to be traveled, it is a mission that can be achieved with a well-planned, coordinated effort from around the country and, eventually, even the globe.

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