# *Consequentialism and the Synthetic Biology Problem*

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**Abstract:** This article analyzes the ethics of synthetic biology (synbio) from a consequentialist perspective, examining potential effects on food and agriculture, and on medicine, fuel, and the advancement of science. The issues of biosafety and biosecurity are also examined. A consequentialist analysis offers an essential road map to policymakers and regulators as to how to deal with synbio. Additionally, the article discusses the limitations of consequentialism as a tool for analysing synbioethics. Is it possible to predict, with any degree of plausibility, what the consequences of synthetic biology will be in 50 years, or in 100, or in 500? Synbio may take humanity to a place of radical departure from what is known or knowable.

**Keywords:** synthetic biology (synbio); consequentialism; biosafety; biosecurity; ethics

> If the painter wishes to see features that would enrapture him, and if he wishes to see monstrous things… he is their lord and god… In fact, therefore, whatever there is in the universe through essence, presence or imagination… he has to find it in his mind and thus in his hands.
>
> Leonardo da Vinci[1]

## Introduction

In this article, I will evaluate the ethics of synthetic biology (synbio) from a consequentialist perspective. Rather than examine the ethics of its subfields individually, I will evaluate synbio ethics under some likely applications of its different research areas, as that is a more intuitive approach.[2] Therefore, I will examine its potential effects on the advancement of science per se; and on agriculture, medicine, and fuel. I will also discuss biosecurity (the danger of deliberate malevolent use) and biosafety (the danger of accidental damage to the environment by, for example, accidental release of a synthetic organism).[3] These latter two are the most commonly discussed in the relatively (and surprisingly) sparse literature that exists on the subject. The relative lack of debate on synbio is surprising, because if the field succeeds, it seems likely to lead to a change in human civilization as significant as the industrial or, indeed, the Copernican revolution. In the words of Craig Venter: "there's not a single aspect of human life that doesn't have the potential to be totally transformed."[4]

This study yields essential insights into the ethics of synthetic biology. It also raises a question: is a consequentialist approach adequate for examining the ethics of humanity creating life? Synbio may present challenges to consequentialism unlike anything that has preceded it. Although consequences can rarely be predicted to a high degree of certainty, the uncertainties introduced by synbio may be so great as to lead one to ask whether consequentialist analysis is meaningful beyond a very limited time horizon.

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## Effects on Agriculture

Some recent research hints at synbio's potential for revolutionizing the food supply. A Dutch scientist, Mark Post, has manufactured synthetic beef by removing stem cells from cow muscle and using them to create synthetic beef protein.[5] This technology, although in its infancy, indicates where a mature synbio may lead: it may be feasible to synthesize food. Several companies aim to have synthetic beef, pork, and poultry in the shops by 2021.[6] This has the potential to end world hunger, alleviate much animal suffering, reduce environmental degradation, and minimize the land use needed for farming (hugely important in an era in which population increase requires ever more land for food cultivation and habitation). Throughout history, food shortages and famines have been frequent. Could synbio help? Or make things worse? There is great promise, but there are also potential negatives.

One such negative is that nature may not respond to synthetic organisms being placed in its midst in a manner that is convenient to humans. An example: studies have shown that several weed species in the United States have become immune to a major weed killer, Roundup. This is significant, because many crops have been genetically engineered to depend for their survival on the use of this weed killer, but between 2007 and 2011, there has been a fivefold increase in weeds that are Roundup resistant.[7]

Genetic variation in the weed population meant that although most were killed by Roundup, a few outliers were not; these survived repeated application of the weed killer, and passed their advantageous genes onto their offspring, resulting in the evolution of weeds that were Roundup resistant. Numerous species of weed have now evolved such resistance. Some of these species make agriculture more difficult; for example, pigweed can grow to the thickness of a baseball bat, and put a combine harvester out of action; giant ragweed can grow to more than 10 feet high. This problem has not arisen in Europe, however, as genetically modified (GM) crops are not generally in use there.[8]

GM plants that are genetically resistant to more than one weed killer are now being developed; only those weeds that evolve immunity to both weed killers being able to survive, something that is far more difficult to do.[9] Therefore, there is a battle here between human ingenuity and evolution. Which will win in the long term? Biochemistry professor William Reville observes that: "It is only to be expected that natural selection would give a good account of itself in any contest. After all this is the mechanism that powered biological evolution from the first simple life form that arose on Earth almost four billion years ago to the myriad species of life that today colonise every environmental niche on Earth."[10,11] The long-term consequences of this particular battle could, instead of advancing agriculture, be very damaging for it.

There are other potential problems. For example, synthetic food may not be as efficient as natural food. The underlying science is very complex, and more is unknown than is known; for example, research has shown that a GM crop yield is smaller than that of natural plants. GM soya was found to produce 10% less yield than natural soya. Investigation showed that this may have been caused by the engineered soya being less efficient at taking up manganese from the ground.[12] Could such factors affect nutritional value?

Another potential problem is the convergence of current intellectual property laws with synbio. The prospect of achieving fortunes from patented food encourages corporations to invest heavily in such research, thus speeding up the science.[13,14] However, some companies have shown troubling attitudes. Robert Fraley, a former chief technology officer of Monsanto has been quoted as saying: "What you are seeing is not just a consolidation of seed companies, it is really a consolidation of the entire food chain."[15] Was the company seriously considering cornering the world market on seeds, the basis of plant life? In the same statement, Fraley also said: "Since water is as central to food production as seed is, and without water life is not possible, Monsanto is now trying to establish its control over water."[16]

There is potential for cartels and monopolistic abuses to arise. Famine occurs with natural farming, because of factors such as weather, disease, and political issues, but there may be more danger if the process becomes synthetic. For example, GM technology (developed using classical genetic engineering, not synbio) is used to create seeds that produce infertile plants; farmers using them need to buy new seeds every year. This technique is referred to as *terminator technology*.[17,18] Plants that yield infertile seeds could be dangerous; natural plants have been affected through the normal reproductive process, by GM seeds being carried in the wind.[19] Therefore, this technology poses a possible threat to the world food supply.[20] Also, Monsanto has been aggressive in enforcing its ownership rights over genetically modified seeds. It has sued some inadvertent recipients of its wind-borne seeds for using them without a license.[21]

Such scenarios may increase with the advent of synbio. It was said at the height of nineteenth century capitalism that some businesspeople would obtain ownership over the world's air supply if they could, and sell it at vast profits, letting those who could not afford it die (reference unavailable). There is potential for a version of this scenario to become real if synthetic production of food becomes the dominant mode. In recent years, investment banks and other financiers have speculated on food prices to the tune of hundreds of billions of euros, following deregulation of the agricultural commodities futures markets. This has caused price fluctuations and food riots in some countries;[22,23] if food production becomes largely synthetic, under patent, this could become more extreme.

On balance, successful synbio research on food and agriculture may offer both the promise of solving many of the world's food supply problems, and the danger of creating monopolies that threaten it. There is also the possibility for catastrophe as a result of error and unknown consequences. There are currently enough resources to feed the world; however, there is not always the will to distribute those resources justly. The creation of synthetic food may not, therefore, solve the problems of food supply, and could make it worse. Advances in synbio are unlikely to be a panacea here, and wise regulation is needed.

### Effects on Medicine

At this early stage of the research, it is difficult to say with certainty how synbio will affect medicine. It seems likely, however, that synbio will revolutionize it, if the science advances to an appropriate level. Some potential benefits in the near to medium term can be reasonably predicted, based on current research. For example, new drugs may be developed. Artemisinin, an antimalarial drug, is the most successful product of synthetic biology so far.[24] Also, gene therapy shows promise;[25,26] for example, treatments have been developed through which sight loss has been reversed.[27] Researchers are examining whether gene therapy can be used to replace painkillers.[28] CRISPR-Cas9 seems to have potential to take medicine to a new level;[29] synbio may allow it to flourish far beyond that.

Some examples are as follows: various laboratories, from those in universities to small startups, are currently attempting to engineer rudimentary biological tissue; skin for surgery, for example.[30] A bioprinter has been developed that can "print" some human tissue, with space for blood to flow.[31] A synthetic ear has been "printed"; the "ink" included cells from humans, rabbits, mice, and rats. It was grafted onto a mouse's back; it lived, and grew.[32] Applications could include the growth of organs for transplant. Synthetic sperm, created from stem cells, has been used to breed mice.[33] A research team is attempting to grow human organs inside pigs, to be used in transplants.[34] Artificial blood vessels have been engineered.[35] Synthetic bones have also been made, and successfully transplanted into pigs; human trials are hoped for.[36] A synthetic stingray, made from a mix of living tissue and inert materials, has been built; the feat made the front cover of *Science*. Its creators are calling it an "artificial animal" and a "bio-inspired swimming robot." It is genetically programmed to swim toward light. Its creators hope to build on it to create replacement human body parts, particularly hearts.[37,38]

An even more sophisticated approach to engineering biological parts is to design DNA that will express them in vivo. A May 2016 scientific meeting proposed a next stage in DNA synthesis: the Human Genome Project 2, which aims to write synthetic human genomes. Originally called HGP2: The Human Genome Synthesis Project, its name was changed to the less evocative HGP-Write: Testing Large Synthetic Genomes in Cells. The aim is to write a complete human genome within 10 years.[39] If this succeeds, the next logical phase would seem to be the design of human genomes.

Harvard's George Church, one of synbio's founding fathers and an organizer of the meeting, has noted that such advances could eliminate heritable diseases from the gene pool.[40] He stated that the meeting was about improving DNA synthesis in general, for all creatures, not just humans. Questioning the ethics of the project, another synbio pioneer, Drew Endy, asked: "Would it be OK, for example, to sequence and then synthesise Einstein's genome?"[41]

If it succeeds, and progresses to the design level, it seems plausible that it will advance medicine significantly. But could it be used for other purposes, including eugenics? Jennifer Doudna, one of CRISPR's co-discoverers, has been quoted, (in a different context, that of her own research): "Prof Doudna told me of a nightmare she had where she was led into a dark room where a man was seated with his back to her. She said: "When he turned, I realised with horror that it was Hitler and I was being expected to discuss this technology with him and he eagerly wanting to use it."[42]

A biological computer has been built inside a cell by Massachusetts Institute of Technology (MIT) scientists: an early prototype of a "living computer," built from cells.[43] Research into developing DNA as a digital storage medium is also ongoing. The concept is that the 1s and 0s of binary code are converted into the DNA bases of ACTG; then read back when necessary. DNA as old as 700,000 years of age has been found in nature; therefore, the longevity of such storage may be vastly greater than current methods of digital and paper. Also, the space needed to store data with DNA is a tiny fraction of current methods.[44] Research is also ongoing into the barcoding of life, converting information from DNA into machine-readable barcodes that allow life forms to be uniquely identified.[45] Such technology could be used to improve health and make life more convenient, but authoritarian governments could use it to enforce hitherto unknown levels of monitoring and control.

Research into the "machine-life interface" is ongoing. Simple artificial (electronic) eyes have been manufactured.[46] They allow blind patients to see large objects in a very rudimentary way.[47] Mimicking a human eye to any degree of sophistication is currently impossible technologically as, among other issues, its complexity and its number of interconnections cannot be replicated electronically. Such problems may be solvable to a far higher degree if future artificial eyes are made from biological materials.

Brain–computer interfaces permit electrical signals from the brain to be harnessed to control electronic devices.[48] Robotics researcher Kevin Warwick has implanted his own body with a silicon chip transponder. In a "smart" building, with appropriate detectors, doors were opened for him and devices greeted him by name as he walked around. He could also operate devices, at a distance, by thought.[49,50]

Artificial limbs are now being developed that can be controlled by a patient's brain or thoughts, giving basic artificial limb use to amputees.[51] A neural bionic device has been developed that effectively allows transmission of thoughts, and can be delivered to the brain without surgery, via blood vessels.[52,53] Also, a prosthetic hand that has a rudimentary sense of feeling has been made, "extending sensation to… machines."[54] Research of this type could restore movement to paralyzed people.[55,56,57,58] Another project, Neural Engineering System Design (NESD), aims to develop a device to convert the electrochemical activity of the brain into binary code; thoughts could be uploaded to/downloaded from computers.[59,60] Another aims to utilize the peripheral nervous system to enhance the brain's learning ability;[61] and also to cure diseases and improve the healing process.[62] Also, implants are being developed that enhance the senses, and add extra senses.[63]

Such research could both enhance and be enhanced by research into artificial intelligence (AI); for example, a recent AI project, in its earliest stages, is attempting to program morality into computers.[64,65,66,67] DARPA (Defense Advanced Research Projects Agency),[68] the scientific research wing of the United States military, recently held a competition to encourage hackers to build an AI that could monitor computer systems for problems such as bugs and attacks, and fix those problems itself, without human intervention.[69] Critics have pointed out that a consequence of this, ultimately, could be a malevolent AI, which could pose a threat to humanity.[70]

A significant portion of the above research, and synbio research in general, has been developed or financed by DARPA. The projects, and so many others, could radically enhance medicine (and society in general), but DARPA's raison d'etre is, of course, military. Other DARPA research is attempting to develop exoskeletons that enhance soldiers' abilities to see, hear, move, shoot, and communicate, as well as protecting against conventional, biological, and chemical attacks. These technologies could lead to the creation of supersoldiers;[71] they could also be a step towards transhumanism. DARPA's Eric Eisenstadt is quoted as saying: "Imagine a time when the human brain has its own wireless modem so that instead of acting on thoughts, warfighters have thoughts that act."[72] Electrically transmitting thoughts that override free will could potentially be applied beyond the military.[73]

Most of the research described here has been announced within the last 7 months, at the time of writing (between January and July 2016); although much of it is at an early, exploratory stage, the science appears to be advancing very rapidly. The technological developments described have mostly been developed without input from synbio, but as synbio advances, and dovetails with these technologies, they could advance each other to a far higher level.

On balance, synbio appears to offer tremendous potential benefits to medicine; it has the potential to revolutionize it, greatly alleviating human suffering, saving and enhancing countless lives, and being almost biblical in its ability to heal the sick. Although disasters do occur in medicine, the overall benefits of medical research and clinical practice have greatly improved human well-being, and a well-directed synbio has the potential to take medicine to a new level of development, probably to heights that cannot currently be imagined. But there are significant potential dangers.

## Effects on Fuel Production

> The fuel of the future is going to come from fruit like that sumach out by the road, or from apples weeds, sawdust – almost anything… There's enough alcohol in one year's yield of an acre of potatoes to drive the machinery necessary to cultivate the fields for 100 years.
>
> Henry Ford, 1925[74]

Several research institutes are attempting to create biofuels using synthetic biology.[75] Biofuels are derived from biomass (i.e., plants, algae, fungi, municipal waste);[76,77] unlike fossil fuels, they are a renewable energy resource.[78,79] Fossil fuel reserves are diminishing, and when they run out, civilization could revert to that of an earlier era unless a replacement is found. The transition could be traumatic. In addition, fossil fuels are a source of climate change, another potential threat to humanity; replacing them with greener fuels could play a significant part in reducing it. This research may have the potential, without exaggeration, to save our current civilization.

However, ethical problems have been identified with current methods of biofuel production. A 2011 report by the Nuffield Council on Bioethics concluded that that current biofuel production policies in the United Kingdom and Europe are unethical.[80,81] A 2010 study from the ETC Group (Action Group on Erosion, Technology, and Concentration) reached a similar conclusion.[82] It is ethically questionable whether land normally used to produce food should be given over to produce fuel, in a world where food shortages occur: the food versus fuel debate. Should food be taken from the poor to provide transport for the relatively well off?[83] Biofuel production may also cause environmental damage. MIT research scientist Ahmed Ghoniem has stated: "If fossil fuels were to be replaced by biofuels in the transportation sector, the need for land, water, fertilizers, etc., would rise significantly, and the associated ecological impact could be devastating, let alone its impact on food prices."[84]

Synbio could help to solve such problems. For example, it may allow new types of crops, specially designed to maximize efficient biofuel production, to be designed at the DNA level. Also, metabolic engineering could be used to engineer organisms that produce biofuels.[85] Also, some biofuel crops may enable degraded land to recover.[86] Research into bioluminescence is also underway; some plants and insects (such as some fungi, fireflies, and deep sea fish) glow in the dark. If the biochemical mechanisms can be understood and replicated synthetically, light could be generated without fuel (from trees, for example).[87] (A crowdfunded synbio project aims to engineer and sell synthetic glowing plants.)[88]

At present, approximately 86 percent of the world's biomass, on land and sea, is not being used for commercial products. Synbio offers the potential for a far greater proportion of it to be utilized.[89] Synbio may also promise a higher level of economic development via the creation of more skilled, better-paid jobs. On the other hand, some of the world's least productive land is utilized by poor farmers; using it for synthetic biofuels could destroy their livelihoods.[90] However, synbio itself could damage the environment. An example: if bacteria are engineered to convert biomass plant waste (e.g., stalks) into fuel, there may be ecological problems if these are not returned to the soil.[91]

Patenting of various underlying biological processes may prevent fuels from being developed by other, more efficient competitors, holding back the science. A small number of corporations could effectively corner the world's fuel supply, potentially leading to very high prices; instead of owning some oilfields, they could come to own oil itself. Such patenting may also inhibit or shut down research in neighbouring areas.

Sir John Beddington, former chief scientific advisor to the British government, has observed that a perfect storm may be facing humanity by the mid-twenty-first century; namely, a population increase of approximately 50 percent; a consequent increase in demand for food, water, energy, and land; and climate change, which may be destructive to agriculture and the food supply.[92,93] It seems reasonable that research into synthetic biofuels may be a significant part of any scientific solutions, and it seems to be an ethical imperative that such research is conducted, but it is not without its dangers.[94] In the words of Achim Steiner (Executive Director of the United Nations [UN] Environmental Programme [UNEP] and Under-Secretary General of the UN): "Biofuels are neither a panacea nor a pariah but like all technologies they represent both opportunities and challenges."[95]

### Effects on the Advancement of Science

At first glance, it appears that synthetic biology's potential effects on science, in themselves, are likely to be positive. The Nobel prize-winning physicist Richard Feynman summarized much of his scientific thinking with: "what I cannot create, I do not understand."[96,97] Biology is extremely complex, and biological knowledge is still quite primitive compared with that in other scientific disciplines. A leading researcher has stated that its current state compares with the state of physics knowledge in the seventeenth century.[98] Undoubtedly, advances in synthetic biology, "building" life, will help to advance the overall field of biology, adding significantly to human knowledge. Consequent advances in derivative fields such as medicine, agriculture, and fuel production are likely to result, as was discussed.

However, negative outcomes from synbio, and even negative perceptions, pose dangers (see subsequent **Biosafety** and **Biosecurity** sections). The present era is marked by a rising scepticism against scientific thinking, ranging from indifference to hostility.[99] Such scepticism is not a majority view—yet—but it could become so.

A disaster, or worse, multiple disasters, in synbio research are likely to increase anti-science feelings; in the worst case, to a degree that may greatly undermine science.

It is worth describing, briefly, the main sources of anti-science rhetoric, to put this in context. Anti-science feeling tends to be strongest in the United States, the world center of scientific research. It occurs most significantly in certain groups on both the academic left and the political right.

On the left, in a movement that reached its heyday in the 1990s and provided, to an extent, an intellectual foundation for current conservative attacks on science, some philosophers and social scientists rejected the very idea that there is such a thing as a scientifically observable reality that can be objectively studied; instead positing a subjectivist approach to truth.[100] Such challenges occurred in the postmodern context, in which the grand narratives of Western society had largely collapsed, to be replaced by greater individualism, greater freedom from restraints such as social class, and a diminishment of universally held perspectives.[101] Narratives, including scientific and religious world views, may remain, but allegiance to them is not universal.[102] In this context, there are many who argue that science is a mere social construct, without inherent truth. A type of culture war took place in the 1990s; one of its most significant figures was physicist Alan Sokal.[103] He issued an open invitation to those who denied the objective truths of science: "Anyone who believes that the laws of physics are mere social conventions is invited to try transgressing those conventions from the windows of my apartment. I live on the twenty-first floor."[104]

Many are not persuaded by such a statement. I once attended a history of science seminar at Harvard University. I was amazed at the confidence with which faculty and graduate students asserted that scientific discoveries do not represent any kind of truth. One of the most famous attacks on the integrity of science was quoted with approval: feminist philosopher Sandra Harding's claim that Newton's *Principia* could be referred to as "Newton's rape manual," as scientific study violated nature just as rape violates a woman.[105] (Her book in which this was argued won an award from the American Sociological Association.)[106] At this meeting, a defense of science would have been equivalent to heresy or blasphemy among a Medieval Christian group. In conversations with Ivy League students, undergraduate and graduate (in various disciplines including science), I have been told that science's discoveries are not and cannot be objectively true; also that science is inherently misogynistic, this latter view being "proved" by the existence of "offensive" terminology such as "big bang." The damage that such attitudes, held at the highest levels of academia, could do to science should not be underestimated. Such attitudes could become seriously problematic if those who hold them come to influence government policy on science, including its funding.

At the present time, the most notable opposition to science is from the political right in the United States. Opposition to evolution has become increasingly common, usually on religious grounds. There is also strong opposition to scientific consensus on human-made global warming.[107] Here, scientific analysis is frequently rejected, without any scientific counterarguments being offered, or any intellectual engagement at all. Chris Mooney, author of the *Republican War on Science*,[108] proposes several reasons for conservative hostility to science. First, conservatism tends to value the preservation of society's status quo, and is threatened by the inherent subversiveness of science, which constantly generates new ideas and technologies, and is based on the search for truth, without deference to authority. This conflict has occurred repeatedly in history, the Galileo and Darwin controversies being good examples.[109] In the United States, a certain political mix can be added to this: the influence of corporate interests and the religious right, combined with a distrust of big government, on which much of science is dependent for funding.[110] In addition, anti-intellectualism is common among many present-day United States conservatives; and science could be seen as the pinnacle of intellectualism.

Although anti-science sentiment is strongest in the United States, it is not unique to that country; such sentiments are arising in Europe and elsewhere.[111] In this intellectual environment, the rise of synbio could pose problems for the entire enterprise of science. A number of disasters caused by synbio could lead to an increased turning away from science in Western culture. Even without disasters, an improper public presentation of it—media stories about "Frankenstein science," for example—could be very damaging.[112] Even the mere existence of synbio could cause problems when it becomes more widely known. When Craig Venter published the details of his Synthia creation, a large number of hostile comments arose on internet forums.[113] Synbio, probably science's greatest advance and its creative peak, has the potential to lead to a further diminution in respect for science.

The scientific era comprises a relatively small portion of human history. In the worst case, synbio gone wrong could be a step towards its end. Is that too extreme? One would hope so, but the threat appears real. Richard Dawkins has noted that on a visit to a London bookshop, he saw three times as many books on crystals, fortune telling, and fairies as he did on science. He observed that: "The enlightenment is under threat. So is reason. So is truth. So is science."[114] Paul Nurse, winner of the Nobel Prize in Physiology or Medicine, and former president of the Royal Society, wrote: "It is time to reject political movements that reject science and take us back into the dark rather than forward into a more enlightened future."[115]

It is not only scientists who are raising this concern. Pope Emeritus Benedict XVI has also written on the issue:

> today…we are witnessing an upsurge of ideologies that deny *in toto* the very value of development, viewing it as radically anti-human and merely a source of degradation. This leads to a rejection, not only of the distorted and unjust way in which progress is sometimes directed, but also of scientific discoveries themselves, which, if well used, could serve as an opportunity of growth for all. The idea of a world without development indicates a lack of trust in man and in God. It is…a serious mistake to undervalue human capacity to exercise control over the deviations of development or to overlook the fact that man is constitutionally oriented towards "being more."[116]

The Islamic world points to how a scientific era can come to an end. It was once pre-eminent in world science (from the eighth to the fifteenth centuries), and some ideas that were developed there still influence modern science.[117] Various causes have been posited for its scientific decline, including financial and political deterioration of the culture, the rise of a new religious paradigm that saw scientific enquiry as inimical to faith, and the ever-increasing relative power of the West.[118] The decline of science in the Islamic world had far-reaching effects on its society, which last to the present era. What happened there is proof that continuing scientific pre-eminence cannot be taken for granted.

Another relevant issue is the economic environment in which synbio exists. Traditionally, scientific advances have been shared openly via peer-reviewed journals, status being obtained in the profession by the quality and number of discoveries and publications. A different scenario has now arisen, however, in which many discoveries are being patented, and scientific knowledge is being privatized. It is within this environment that synbio is coming into being, and patents are being applied for on many foundational discoveries.[119] Synbio in itself is neutral on such issues, and there is also a significant open source movement within it, which maintains traditional scientific values. However, if the profit-driven approach comes to predominate—which seems to be the case—then the success of a nascent synbio in such an environment could lead to an erosion of scientific values, spreading throughout the sciences. It could corrupt science to its core.

On balance, synbio appears to potentially have both positive and negative effects on science per se. Positives could be revolutionary in scope; as could negatives.

## Biosafety

Synbio is seen by its practitioners as an engineering discipline rather than a biological one.[120] Failure—such as structural or electronic—is an integral part of engineering. All materials and devices have a limited life-span; in the words of a textbook on engineering failure: "it is not a question of whether the device will fail, but when."[121] Courses on failure analysis and risk in engineering are taught in undergraduate engineering degree programs, and there are graduate degrees in the subject.[122]

A famous engineering failure was that of the Tacoma Narrows Bridge, Washington state, in 1940. At the time, it was the third largest suspension bridge in the world. A few months after opening, a high wind caused it to resonate wildly until it collapsed. Dramatic videos can be seen online. It is a textbook case, mentioned in standard undergraduate engineering and physics books.[123] Its designer, Leon Moisseiff, an engineer at the top of his profession, who also worked on the design of the Golden Gate and Manhattan Bridges,[124] said that he did not understand why it collapsed, because it was built in accordance with engineering rules. He was attempting to build the world's slenderest suspension bridge, however, and changing the design parameters slightly meant that the standard rules were no longer adequate.[125]

Biological organisms also fail: they experience sickness, injury, and, ultimately, death. Scientific knowledge of many of the processes that cause failure is incomplete. Such failures are likely to be more common in synthetically designed organisms; the current state of knowledge in biological science means that it is very difficult to design and accurately predict the properties of novel organisms.[126] Biology is orders of magnitude more complex than civil engineering. Small changes in a biological system can have cascading, unpredictable effects throughout densely interconnected biological networks. Microbiological processes are usually stochastic (random, probabilistic) in nature. This results from internal processes—thermal, spatial, and temporal fluctuations at the molecular level—and external ones, such as changes in nutrients, temperature, or pressure.[127] For example, genetic mutations and gene expression are stochastic; the same genetic code in the same chemical environment can result in very different expression, because of random variations.[128] Such differing expressions could be beneficial, neutral, or toxic. The mechanisms underlying mutation in genomes are not understood.[129]

Biological systems' stochastic nature is not necessarily an inherent obstacle to biological design. Nevertheless, when added to biology's inherent complexity, and the large number of scientific unknowns, it makes biological design far more challenging than that of standard engineering. Engineering curricula offer failure prevention and analysis as part of their syllabi, as mentioned, yet failures still occur. Synthetic biologists are aware of this, and will endeavor to eliminate or minimize failure, just as engineers do in their designs. For example, Craig Venter's "synthetic cell," Synthia, was designed with the intention that it could not survive outside the laboratory.[130] Nevertheless, it seems plausible that failures will occur, and reasonably frequently.

Regarding biological unknowns, until recently, 97 percent of DNA was referred to as "junk DNA" by scientists, as it appeared to have no function.[131] It is now known that much of it has important functions, such as regulating genes, although its functions are not fully known.[132,133] Introducing changes at the DNA level when there is such a large degree of unknowability may result in unpredictable outcomes. Given that there are so many potential unknowns in this research, the question arises: is synbio too big a risk? Monsters could be created inadvertently, at the microbial level or higher.

Also, it is possible that some newly created organism could be accidentally released into the environment. It may have the ability to replicate, evolve, and affect the course of evolution of other organisms with which it interacts. There may be no consequences to such a release; however, on the other hand, significant ecological damage could be caused. A worst case scenario has been proposed, adapted from Eric Drexler's description of Gray Goo in nanotechnology; here, self-replicating robots continuously build copies of themselves, filling the earth and killing all life in the process.[134] A "green goo" version of this has been postulated for new biotech creations gone out of control.[135,136] Drexler, regarded as the 'father of nanotechnology,' describes Gray Goo as follows:

> If the first replicator could assemble a copy of itself in one thousand seconds, the two replicators could then build two more in the next thousand seconds, the four build another four, and the eight build another eight. At the end of ten hours, there are not thirty-six new replicators, but over 68 billion. In less than a day, they would weigh a ton; in less than two days, they would outweigh the Earth; in another four hours, they would exceed the mass of the Sun and all the planets combined.[137]

It is an apocalyptic scenario, albeit an extreme worst case.[138,139,140] In short, potential dangers appear to be so great regarding biosafety that questions arise as to whether synbio can be considered ethical per se. This is the case even without human error and accidents (which can never be disregarded).

## Biosecurity

One of the first publications in synthetic biology was written for DARPA.[141] At the Synthetic Biology 6.0 conference in 2013, virtually all the presentations that

I attended had DARPA as one of their sponsors. It is no surprise that military researchers are among the first to recognize the potential of synthetic biology. Warfare appears to be intrinsic to human nature, and with that instinct to fight comes the drive to develop more powerful weapons than potential enemies.

Biological weapons have a long pedigree. Their design frequently reveals great ingenuity, and dates back to humanity's earliest history.[142] Synbio offers the probability of taking them to a new level. Some dangerous pathogens have already been "written" synthetically, including the 1918 Spanish flu virus.[143] A synthetic polio virus has also been built, using mail-order chemicals.[144]

It is feasible that Ebola, or similarly deadly viruses, could be synthesized and released.[145] Currently there are no laws against doing this, nor is it illegal to produce, advertise, and sell kits containing all the relevant materials, and detailed instructions on how to do it.[146] Sequences of the various Ebola genomes (and many other pathogens) are freely available on the Internet.[147] Also, these online sequences could be altered to make the virus more deadly. Scientists have done this for mousepox.[148]

This scenario is all the more troubling because biological weapons, like nuclear weapons, have up to now largely been the preserve of a few governments. Their production can be monitored to an extent. But when synbio reaches a certain level of maturity, it will almost certainly be possible for all governments, along with terrorist groups, criminals, and any interested individuals, to make their own bioweapons. All synbio research, including the most beneficial, has the potential to advance the field to a place where "people's bioweapons" will be achievable: the dual-use dilemma.

Already, an amateur biohacking culture has developed, analogous to the hacker culture in computing. Amateurs can experiment with creating their own synthetic organisms. Online biohacking forums exist.[149] Biohacker collectives are emerging, spaces where amateurs can learn, and advance the science.[150,151,152] In 2009, a "BioBrick assembly kit" was created for purchase, to enable hobbyists to build synbio devices; it costs, at the time of writing, US $261.[153] It is likely to become ever easier for people to create genomes of their own design. Most people currently involved in the biohacker culture are technically oriented, as were the early computing pioneers, but as the technology becomes more widespread and more easily usable, it may become as ubiquitous as the Internet.

A significant proportion of modern computer technology had its genesis in the homes and garages of young hackers in Silicon Valley in the 1970s; the term *garage hacking* was used to describe their activities. The first Apple computer was created by Steve Jobs and Steve Wozniak in Jobs's garage.[154] Google was developed in a garage, as were the first Hewlett Packard devices. Bill Gates was also a garage hacker; he has said that if he were starting today, he would hack biological materials: "Creating artificial life with DNA synthesis. That's sort of the equivalent of machine-language programming …If you want to change the world in some big way, that's where you should start—biological molecules."[155] He said synbio needs: "the same type of crazy fanaticism of youthful genius and naïveté that drove the PC industry—and can have the same impact on the human condition."[156] Biohacking is now at a similar place that computing was in the 1970s. The activities of hackers of that era changed the world; synthetic biology may do the same.

In the earliest days of computer hacking, there were no negative uses. Over time, pranks began to be played, eventually evolving to full-scale criminality.[157]

The same evolution seems likely to occur in biohacking, as it evolves from being an underground techie movement into society's mainstream. Although computer hacking and virus creation can be very destructive, they pale in comparison with the potential destructive power of synbio. In the words of, Marcus Wohlsen, author of a book on biohacking: "This is one important way in which home brew biotech departs from… more traditional hacking. A cook experimenting in the kitchen could end up with a fallen soufflé. A computer builder with a soldering iron could end up with burnt fingers and a useless box of metal. A biohacker who is either careless and unlucky or brilliant and evil could someday theoretically unleash a swine flu variant that resists all treatment by known antivirals and has no off switch."[158]

In worst case scenarios, synbio could produce something as deadly, or more deadly, than the atomic bomb, in multiple variants, to be possessed by anyone who wishes. A 2003 CIA report, *The Darker Bioweapons Future*,[159] concluded that a significant bioweapons threat is likely to come into existence, and that "the world's most frightening weapons"[160] could be created. They observed that the pace of biological research is so great, and the increase in knowledge so vast, that "the resulting diversity of new [biowarfare] agents could enable such a broad range of attack scenarios that it would be virtually impossible to anticipate and defend against… As a result, there could be a considerable time-lag in developing effective biodefense measures."[161] A report from the Carnegie Corporation of New York states: "Compared with nuclear and chemical weapons of mass destruction, biological weapons are in some ways the most dangerous; they are easy to produce and their ingredients are readily available and equally useable for harmful or benign purposes. That's why they have been referred to as "the poor man's atom bomb."[162] A 2008 United States bipartisan Congressional report, *World at Risk*, stated that an attack with a weapon of mass destruction on the United States is likely within a few years, and that such a weapon is most likely to be a bioweapon.[163]

At speeches in Prague in 2009, and Seoul in 2012, President Barack Obama said that he wanted to secure the world's nuclear materials, to prevent nuclear terrorism; and, ultimately, to rid the world of nuclear weapons.[164,165] However, largely unnoticed, in the background, synbio is advancing, which may enable rogue governments, criminals, terrorists, psychopaths, and emotionally disturbed people to create weapons of mass destruction. Which raises the question: can it be wise or ethical to allow such a branch of science to advance, knowing that it could lead to such scenarios?

### Can a Consequentialist Support Synthetic Biology?

Journalist Fintan O'Toole has expanded upon Donald Rumsfeld's known knowns, known unknowns, and unknown unknowns, to write of *unknown knowns*: "the stuff we know but choose not to know."[166] His examples include the fact that there was corruption in the financial system during the boom, and abuse in the Catholic Church. Ignoring these unknown knowns eventually led to catastrophe in these areas.

Synthetic biology also has its unknown knowns, as described: the fact that its dangers are so great. The potential dangers are clear; however, the research is still going ahead, and without much in the way of regulatory oversight. Reasons for this include the fact that potential positives are great, and could result in benefits for humanity that could be, in best-case scenarios, revolutionary. Also, scientific fame could be achieved by leading practitioners, and there is potential for great wealth. In addition, there is a *laissez-faire* tendency in regulation. The dangers are known, but the research presses ahead regardless, without significant steps being taken to safeguard against them. The dual-use nature of synbio means that the most beneficial advances also have the potential to be used negatively. In between the most extreme potential outcomes, synbio offers myriad opportunities and dangers. Ethically, it differs from other fields of science and technology in that the potential for both benefits and harms seems to be much greater.

O'Toole notes that denial and wilful ignorance can be "comforting and congenial," and quotes T.S. Eliot on such a psychological approach: "human kind/Cannot bear very much reality."[167] Denial and wilful ignorance in the ethical evaluation of synbio could, in worst case scenarios, result in the greatest disasters ever experienced by humanity. The issues here are not particularly complex: synbio, if it succeeds, and remains on its current path, will almost certainly allow members of the public to become creative using biological materials. This creative power will include the ability to create biological weapons, including weapons of mass destruction. A future Columbine, or something much worse, may be carried out with such weapons. Once this particular Pandora's box is opened, there is unlikely to be a means of shutting it.

The legend of *Faust*, which has been retold in various literary works since the sixteenth century, (by various writers such as Philip Marlowe, Johann Wolfgang von Goethe, and Thomas Mann) tells the story of a man who sold his soul to the devil in return for knowledge. He obtained the knowledge he desired; but at the price (in most versions of the tale) of eternal destruction in hell. The question must be asked: Was it worth it? A similar question can be asked of synbio: Are the possible benefits worth the possible risks? Undoubtedly, synbio may lead to great scientific advances, including great therapeutic advances, but this could be a Faustian bargain, as its destructive potential is so great.

Balancing the potential benefits against the potential negatives, it is reasonable to conclude that a consequentialist cannot support synthetic biology. That may change if adequate regulations can be developed that permit the beneficial side of the research to flourish, while minimizing hazardous applications. Proper regulation of this field is an ethical imperative, and such regulations will need to go beyond the imposition of sanctions. In the case of computer hacking and viruses, enforcement takes place after a criminal event occurs. Such an approach will be of little use in the case of malevolent synbio creations. Regulation needs to ensure that the chances of worst case scenarios occurring are minimal. Regulation would need to be worldwide in scope, and obtaining agreement from all governments may be challenging. Also, do-it-yourself biology/biohacking by individuals may be impossible to detect. Even in laboratories, malevolent research is unlikely to be distinguishable from legitimate research in all cases. This would be difficult, if not impossible, to monitor. It is possible that the banning of certain information from public view may be necessary to achieve public safety.

In devising appropriate regulations, policymakers must be mindful of the dangers posed by synbio. They must also bear in mind the potential benefits that could be lost through overzealous regulation. In the words of John Harris: "How do we assess the loss of life/loss of benefit when beneficial/life saving measures are delayed through caution? Caution is not necessarily beneficial or even cautious" (personal communication). This is the essential dilemma of synbio ethics. As mentioned, the potential dangers are so great, at present, that they outweigh any potential benefits. The challenge for regulators is to tip the balance.[168]

### Is a Consequentialist Analysis Adequate?

> By 'uncertain' knowledge, let me explain, I do not mean merely to distinguish what is known for certain from what is only probable… there is no scientific basis on which to form any calculable probability whatever. We simply do not know.
>
> John Maynard Keynes[169]

It is clear that synbio offers a complex web of potential benefits and dangers, and a consequentialist study is useful in attempting to unravel it. It offers an essential road map to policymakers and regulators, in a way that other ethical theories, such as deontology or virtue ethics, seem unlikely to. But is this analysis adequate? Scientific research tends to be applied in ways that are frequently impossible to predict. For example, early pioneers in research into electricity could not have foreseen its applications to uses as diverse as the Internet, mass air travel, space travel, MRI scans, and mobile phones. Synbio, if it succeeds, may revolutionize human life to a far greater degree. But in what ways will it do this? Can we predict, with any plausibility, how it will be used in 50 years? In 100? In 500?

To attempt to answer the question, consider an intelligent observer at the following event:

> But if (and oh! what a big if!) we could conceive in some warm little pond, with all sorts of ammonia and phosphoric salts, light, heat, electricity, etc., present, that a protein compound was chemically formed ready to undergo still more complex changes.
>
> Charles Darwin[170]

The quote is a description, by Charles Darwin, of the origin of life. It should not be taken as scientific truth, as scientific origins of life are still not yet known.[171] However, it is a good enough description for our purposes. Imagine that an intelligent observer was at that event, the coming together of certain chemicals, or whatever form the origin of life took. Could they have predicted that the earliest protein compounds would, over eons, evolve into the uncountable myriad life forms on earth? Could they have predicted the vast array of bacteria; of swarming insects; or of birds, fish, or animals? Or could they have predicted humanity, with all its achievements and failings: its technology, art, philosophy, architecture, warfare, poetry, religions, and romance, as well as its propensity for both good and evil? If they came from a place and culture in which none of these things existed, it would be obvious that they could not.

If synbio succeeds, we may now be at a point comparable to the earliest days of life on Earth, in terms of evolutionary change, and it will be as difficult for us to predict the outcomes as it would have been for an observer at the beginning of life on Earth.

Of what use is consequentialism in this scenario? What uses will scientists make of synbio, over decades and centuries? Or healthcare professionals, armies, dictators, and the general public? Has synbio rendered consequentialist analysis useless, placing a limit beyond which it cannot go? Possibly, but objections can be made to this. First, it could be argued that synbio is not equivalent to the first emergence of life. It is already known how life has developed and evolved; therefore, it will be possible to make educated guesses about where synbio may lead. Against this, synbio is already showing a tendency to merge with robotics, computer science, and nanotechnology, which may create a world that is currently unimaginable. It is unlikely to be predictable, in any meaningful way, therefore, where this may lead.

It could also be argued that synbio, as it is now, could be analyzed with consequentialist thought; then, when the landscape of scientific advance changes, it could be analyzed again. This could be done continuously as the landscape keeps changing. Bit by bit, a consequentialist analysis of synbio could be built, reaching an adequate analysis over time. However, at the extremes, synbio may ultimately result in a paradise on Earth, or it could lead to a type of Hell. By the time such outcomes become clear, it may be impossible to reverse course.

It appears, then, that synbio poses the ultimate challenge to consequentialism, defining a boundary for it. This is an area where meaningful consequentialist analysis becomes impossible, the extreme case that renders it useless. Ultimate consequences cannot be predicted, or ethical evaluations made; we are staring into a void. This is not to say that consequentialist analyses must always be able to predict the future. The future is not usually predictable to an accurate degree. However, consequentialism is perceived to be valid because the future, or a number of posited alternative futures, can be usually predicted up to a point. But this is not so in the case of synbio. It takes humanity to a place of radical departure from what is knowable. Perhaps this is as it should be; synthetic biology is such a great step that it may, if it succeeds, change *everything,* including our attitudes to nature and to life, as well as the very nature of life itself; as well as attitudes to God, and the foundations of philosophy and ethics.

Although the philosophical literature abounds with critiques of consequentialism, regarding the difficulty of predicting consequences in a meaningful way, the advent of synbio proves this fact, independently of whether or not the previous literature existed. It offers something akin to empirical evidence: a scientific proof of consequentialism's limitations.

## Conclusion

Two major conclusions can be reached from this analysis. First, synbio offers great potential benefits and great potential dangers. The dangers of serious destruction are so great that they appear to outweigh any potential benefits, no matter how great those benefits may be. Unless and until the dangers can be minimized, it seems that synbio research is unethical, and cannot be supported by consequentialist thinkers.

Second, a consequentialist analysis is invaluable in determining the immediate potential benefits and dangers of synbio and in giving guidance to ethicists and policymakers as to how to respond in the short term. However, paradoxically, it is of no value in determining whether synbio is ultimately ethical and whether humanity should take this step. Consequentialism fails in a scenario such as this, where consequences cannot be predicted in any meaningful way beyond the short term. If a topic as important as synbio cannot be dealt with meaningfully by consequentialism, then the usefulness, and indeed the validity, of the theory comes into question. If consequentialism fails in this important and testing scenario, then it must be questioned whether it is valid in any scenario. It appears to be flawed at its conceptual roots. It may occasionally yield answers that may appear logically sound and correctly argued, but are wrong, because the underlying theory itself is wrong.

In this, it may be comparable with scientific theories that have been overthrown; for example Newton's theory of gravitation, which was superseded by Einstein's general theory of relativity. Although frequently yielding correct answers, Newton's theory will also give wrong answers in certain circumstances, because it is not a completely correct description of the universe. Paralleling this, this analysis suggests that consequentialism is not a fully correct description of the "moral universe," although it may offer useful approximate guidance in some cases.

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