

# Synthetic Biology: Origin, Scope, and Ethics

By JOACHIM BOLDT

Synthetic biology looks poised to change the world in which we live in a manner that parallels the transformation brought about by synthetic chemistry a century ago. Within a few decades, products generated by synthetic biology could become as commonplace an element of our everyday lives as those from the chemical industry that shape all facets of our lives today—frequently in ways that are no longer consciously perceived. Like chemistry previously, biology—the study of life—is on the verge of generating technically realisable knowledge.<sup>1</sup> The potential applications are manifold, ranging from microbes that can detect and curb pathogenic mutations in the human body to bacteria that neutralise harmful substances or generate energy.

And yet synthetic biology—unlike chemistry—is involved in the technical alteration of animate nature. Building on recent advances in genetic science and technology, synthetic biology aims to understand the molecular fundamentals of the metabolic and reproductive functions of simple single-cell organisms precisely. It thereby seeks to enable us thoroughly to manipulate and rearrange existing organisms in a standardised manner, and to equip them with characteristics that do not occur in nature.

It is hardly surprising that this technology provokes heated response. Colloquially, the term “life,” (even when it is artificially constructed) is not merely a descriptive but invariably also a normative concept. Vitality—being alive—is the nucleus of that which, with wider cultural reference, implies worthiness of protection, at the very latest when living things display evidence of pain perception and simple forms of awareness; moreover, vitality frequently means unpredictability and individualism. Finally, we often associate vitality with some sense of an inherent right to exist.

The creation of life in the laboratory counts as one of the literary and culturally pivotal codes for the goals of modern humanity, both in the form of the ideal and the “writing on the wall”. The

latest advances within the research impetus of synthetic biology, which has been developed with zeal in recent years, give rise to expectations that there will soon be more news from this code. This is particularly the case since one of the objectives of this sub-discipline of biology is precisely to produce microbial forms of life with properties that do not occur in nature. In the wake of such research, old ethical and philosophical issues, expectations and anxieties arise again in acute new forms.

## ORIGINS

The first isolated references to the term “synthetic biology” can be identified as early as the beginning of the 20th century. For instance, the French medical scientist and biologist Stéphane Leduc published a book in 1912 entitled “La Biologie Synthétique”.<sup>2</sup> In this volume, Leduc maintained that, besides the method of analysis, fact compilation and classification, there also existed in science a synthetic method that attempts to reproduce observed phenomena in a rule-governed and reproducible manner. According to Leduc, a science can only develop in its entirety if this second method is acknowledged and employed. In his era of biology, Leduc felt that the consistent implementation of this scheme of the controlled reproduction of observations was missing, and he advocated such an application. It can thus be said that the conviction—according to which the task of theory is primarily to deliver knowledge that enables the object of theoretical reflection to be controlled and utilised—is transferred to the area of living things in Leduc’s first attempts. Knowledge, and therefore also biological knowledge, can only accurately be called such if it enables objects to be controlled and applied practically, since knowledge is only confirmed in this manner. This, at least, is one way in which this assumption, central to the modern natural sciences, can be stated.

In 1911, the biologist Jacques Loeb, who lectured in Germany and the USA, formulated his hypotheses in a similar fashion:

[It] must be emphasised that modern biology is a purely experimental science, the results of which can take only one of two possible forms: either we succeed in controlling a life phenomenon to the extent that we can evoke the

same whenever we wish (for example, muscle twitches or the chemical stimulation of the development of certain mammals' eggs); or else we manage to identify the numerical connection between an experimental condition and the biological result (such as in the Mendelian law).<sup>3</sup>

The prerequisite of this natural science-based understanding of biology is that the phenomena of living things can be completely reduced to simple powers and laws that govern the organism and whose modes of action can be clearly predicted. Applied to the question of how life can evolve, this assumption must lead to the requirement that living things must be artificially producible. Entirely in this spirit and typically for his era,<sup>4</sup> in 1906 Jaques Loeb declared “abiogenesis”—the creation of life from inanimate material—to be an objective of biology.<sup>5</sup> John Butler Burke, an English biologist, also believed that there must be a transition from that deemed inanimate to that considered animate; he describes the experimental production of “animalcules” as a task of biology.<sup>6</sup>

These early scientific/programmatic approaches to “synthetic”—i.e. “assembling” or “producing”—biology illustrate the fact that the technical realisation of each body of knowledge is not a contingent ingredient in that knowledge understood to be natural science, but rather a constitutive part of this research. The reproducible application is the confirmation of the findings gained from analysis, and hence not only the result but simultaneously the catalyst of research. In this general sense, synthetic biology is not “merely” a branch of biological research alongside many others, but is an essential element of science-based biology. Its existence is an expression of the fact that biology has established itself as a programmatic natural science, and moreover complies methodologically with the respective requirements.

This orientation towards the replication and recreation of nature, which makes the ability to control living things the central research objective and the central test for knowledge advancement, is also described in later literature as the “engineering science viewpoint” or the “engineering science ideal”.<sup>7</sup>

At the level of intra- and intercellular molecular processes, this scheme could only be developed systematically after the discovery of the DNA double helix. Following this milestone, the term “synthetic biology” was also swiftly applied again in this area of molecular biology, where its meaning was used analogously to that found at the beginning of the century. Thus, in 1974 the Polish-American geneticist and molecular biologist, Waclaw Szybalski, wrote in terms that sound almost prophetic from today's perspective: “Up to now we are working on the descriptive phase of molecular biology. [...] But the real challenge will start when we enter the synthetic biology phase of research in our field. We will then devise new control elements and add these new modules to the existing genomes or build up wholly new genomes. This would be a field with the unlimited expansion potential and hardly any limitations to building “new better control circuits” and [...] finally other “synthetic” organisms [...]”<sup>8</sup>

Four years later, in 1978, marking the occasion of the awarding of the Nobel prize in Physiology and Medicine, Szybalski and Skalka wrote an editorial in the journal *Gene* that displayed a very similar set of assumptions. The pair proclaimed the dawn of a new era in biology:

The work on restriction nucleases not only permits us

easily to construct recombinant DNA molecules and to analyze individual genes but also has led us into the new era of ‘synthetic biology’ where not only existing genes are described and analyzed but also new gene arrangements can be constructed and evaluated.<sup>9</sup>

The final step on the road toward current developments involves endeavors to establish the field of “synthetic biology”, which commenced at around the year 2000. In continuation of the molecular biological research approach described by Szybalski, a group of American researchers defined synthetic biology as a scientific activity that aims to analyse the interactions of complex cellular processes at the molecular level and to test these analyses by modelling and replicating the processes and structures, and to make them technically utilizable. Thanks to a close connection between biology and engineering science, an attempt is therefore made at conducting genetic engineering, previously characterised as being “manual”, in a more systematic manner and on a greater scale—despite its analytical foundation and its synthetic realisation.<sup>10</sup>

This more recent approach in establishing the discipline of synthetic biology has been inspired and supported by the increase in knowledge in the area of systems biology on the one hand, and on the other, and primarily, by the quick-paced development of electronics, rapidly improving sequencing technology and the possibilities offered by DNA synthesis, which is becoming increasingly cheaper and more accessible.<sup>11</sup> Gene sequences no longer need to be synthesised in the laboratory by the scientists themselves, but can be ordered via e-mail from specialist companies and dispatched by mail. Prices for sequencing a base pair are constantly decreasing, while the length of the gene sequences that can be synthesised is increasing.<sup>12</sup> It is impossible to forecast an end to this development. One thing is clear, though. With these technical and economic foundations there are also greater possibilities for more easily testing hypotheses about how the molecular building blocks of simple organisms function with regard to their application and reproduction. Accordingly, the possibilities for replicating or recreating gene sequences and genomes have also burgeoned.

#### SYNTHETIC BIOLOGY'S SCOPE OF RESEARCH

With regard to current research within the field of synthetic biology, a distinction can be drawn between two ways in which attempts are being made to achieve the overarching research objectives. Some approaches aspire to produce a single-cell organism or a cell in the laboratory from scratch, from non-living molecules. Other approaches attempt to minimise the genome of an existing bacterium to such an extent that the organism is only left with the above basic properties of life, with no further specific abilities. The aim of “hollowing out” existing bacteria, in other words, is, if possible, to leave the organism with only those genes that ensure the organism's metabolism and fertility—and that are capable of mutating. According to the basis from which the minimal cell or minimal organism is set to be developed, the two main directions of research can be separated into “top-down” and “bottom-up” or “*in-vivo*” and “*in-vitro*” approaches of synthetic biology.

The advanced idea of the *top-down approach* is to add genome sequences, assembled as the need arises, to the engineered minimal organism so that it can perform precisely defined tasks. The basic organism would act as a “chassis”, to which the desired func-

tions are added.<sup>13</sup> In this context, the genomes are often called the “software”, while the remaining structures of the organism are described as “hardware”. Following genetic essentialism (which is a disputed perspective outside of the field of synthetic biology), it can be said that the aim of the top-down approach is to equip the hardware of a cell with new, tailor-made software, designed to control it.

On the other hand, the aim of the *de novo* production of a so-called minimal cell in the laboratory, the paradigmatic case of the *bottom-up approach*, is to assemble a basic form of life from simple parts. In doing so, no existing organism is used and altered *in vivo*. Instead, an organism or, in general, a biological system is created *in vitro* from scratch. This second approach can in turn be subdivided into those approaches that deploy already existing biological building blocks to assemble the artificial or “synthetic” cell, and those approaches that attempt to develop a kind of “protocell” (or cell analogue, rather than actual cell) and which set out with chemical precursors.<sup>14</sup> The typical feature of these two research approaches is that they do not only comprise the pure replica of natural cells, but also envisage the construction of cells whose mechanisms for realising the functions of life are very different from naturally occurring cells. Where the latter is the case, reference is also made to engineering an “orthogonal” nature. In this context, and following the parlance of information science, “orthogonal” means biological systems whose basic structures are so dissimilar to those occurring in nature that they can only interact with them to a very limited extent, if at all.

The top-down (or *in-vivo*) and bottom-up (or *in-vitro*) approaches are typically associated with two differing research interests and research traditions. While the *in-vivo* approach is primarily oriented towards technical application and easily tolerates an engineering-based access to modularisation and standardisation, the *in-vitro* approach is more akin to fundamental research that aims to explain and reconstruct the origin and basic functions of life. The foundation and driving force behind this research is the question of how the origin of life can be explained and reproduced in the course of natural history. Nonetheless, this approach is also related to issues of application within the context of synthetic biology. It cannot be ruled out that an *in-vitro* created cell analogue may turn out to be more suitable than a minimal bacterium as a basis for technical realizations.

Although this classification of the research landscape of synthetic biology is useful in obtaining an initial overview, it must nevertheless be emphasised that a range of research approaches exist that cannot be neatly fit into this classification scheme. This is particularly the case for all types of research that deal with the analysis and the replication and regeneration of metabolic processes and cellular signal structures. In these cases, research involves analysing and replicating how cellular constituents in which the genome is embedded function. These studies will in all likelihood have to be counted among the *in-vivo* approaches, which also follow the top-down procedure in that—in analysis and synthesis—they seek to split up complex biological structures into easily describable sub-areas. However, this type of investigation does not generally aim to engineer a minimal bacterium; in this respect, this kind of research distances itself from the top-down procedure, which is otherwise frequently deemed typical for *in-vivo* approaches.

This difference can also be illustrated with regard to the use of the imagery of hardware and software in the minimal bacterium project. Inquiry into understanding metabolic pathways and signal transmission mechanisms cannot be focussed on the conception of the genome as the software of the cell and the remaining biological cell structures as the hardware due to the fact that it becomes clear from such imagery that these remaining structures are also integrally involved in the behaviour that an organism ultimately has. Moreover, these structures can also be used to control the behavior of organisms in a similar fashion to the genome. It is not improbable that this kind of research into cell functions, “beside the genome,” will also lead to technologically far-reaching developments. Synthetic biology as a whole is thus more complex than what can readily be portrayed in the media, which already tends to reinforce genomic reductionism and to focus on the major projects of the bottom-up and top-down models that can be conveyed more succinctly.

Finally, a further area of research exists within synthetic biology that is slightly out of line with the top-down and bottom-up framework. This area of research involves the attempt to create genetic structures that are not founded on the same material basis as those occurring in nature. There are thus approaches to supplement the four natural base pairs of the genome with additional base pairs, and other research is being carried out that goes one step further and tries to create genomes that function completely independently of the four base pairs of natural life. In the first instance, such approaches belong to the *in-vitro* field of synthetic biology since the synthetic genomes are assembled from simple building blocks. They therefore blend in, and are partly also a direct element of research within the context of engineering a minimal cell. However, it is also conceivable that non-natural genomes can be used in natural cells and organisms—in other words, to deploy them *in-vivo*.

#### SPECIFIC CHARACTERISTICS

In order to grasp the specific ethical and philosophical challenges of a newly emerging direction of research, it is essential to ascertain in precise terms how this science differs from already existing areas of science. What, in other words, is novel about synthetic biology?

Application-oriented sciences—to which synthetic biology belongs—are generally subdivided into “enabling technologies,” (which create the prerequisites for realising the respective research), “basic development technologies,” and “applied technologies.” In the case of synthetic biology, the technological prerequisites mainly include gene synthesis technologies, the possibilities of which are constantly expanding. The field of research consisting of *in-vivo* and *in-vitro* approaches and the research surrounding these paradigmatic cores form the area of basic development. The applied technologies include all technical applications that are conceivably associated with synthetic biology. Out of these three areas, the technological prerequisites and the basic development are primarily of interest when exploring the question of what is novel about synthetic biology.

As our brief tour of the history of the subject has already demonstrated, synthetic biology is not a topic that has emerged “out of the blue”. On the whole, there are continuities and mechanisms

internal to science that have facilitated the emergence of today's synthetic biology; moreover, in miniature there are also many specific points of contact to existing areas of research. The main points of contact are gene technology and systems biology, as well as engineering science, information technology, and nanotechnology. Due to these manifold references, some commentators consider synthetic biology to be almost a prime example of the much-evoked "converging sciences".<sup>15</sup> In particular, the vicinity to genetic engineering leads to the justified critical question of what is actually novel about synthetic biology and, concurrently, whether this science implies new ethical challenges.

In the first instance, this question can only be answered using quantitative references: In the area of technological prerequisites, the capabilities of gene synthesis are increasing up to the ability to synthesise entire genomes. In the area of basic development, depending on the research direction, the aim is not simply to replace or modify individual gene sequences of an existing organism but to insert a whole synthesised genome into a genetically minimised bacterium. As we have already seen, research is also being carried out into replicating metabolic cell processes and signal transmission mechanisms, and supplementing the "alphabet of life"—comprising four different organic bases—with other bases, or else completely replacing them and incorporating non-natural amino acids into synthetic organisms.

For this reason, there has been a noticeable extension of that which is technically manipulable and controllable. With the synthesis of larger genomes and the advent of also being able to handle large gene fragments, it is no longer only individual, short DNA segments, but also entire genomes that come into practical reach.<sup>16</sup> For instance, scientists recently managed to synthesise the entire genome of *Mycoplasma genitalium*, a DNA structure with over 580,000 building blocks—a significant difference to the classic gene technological synthesising of a plasmid with 5,000 elements.<sup>17</sup> Gene technological research, such as transplanting parts of the human immune system to mice in order to produce human antibodies<sup>18</sup> and implanting beta carotene synthesis into rice<sup>19</sup>, are being continued and quantitatively expanded in this manner. Furthermore, as already mentioned, the genome is being expanded with novel starting materials and recreated in research into synthetic biology. In addition, other molecular cell structures beside the genome are being replicated, making them controllable.

In the ethics of technology there is a meaningful distinction to be made between quantitative and qualitative change; change in degree and change in kind. Quantitative change extends the scope of pre-existing human power and control; qualitative change ushers in a new kind or dimension of power and control. Taken individually, new characteristics of synthetic biology appear to represent a quantitative rather than qualitative advance. However, when viewed on the whole it can be maintained that synthetic biology opens a new field of research and technology from a qualitative perspective, even if it is impossible to define where the transition from quantity to qual-

ity lies exactly.

The crucial element of this transition is that the focus on the organism to be explored and controlled is changing. The basis of gene technological manipulations is an existing organism with properties that are of keen interest to humans. These existing properties are then optimised by genetic engineering to make them economically exploitable. However, the perspective of synthetic biology is no longer necessarily oriented towards existing organisms. Since, for synthetic biology, the entire genome and the whole molecular structure of single-cell organisms are technically configurable, therefore existing organisms and existing properties are ultimately only incidental examples of what can be assembled from the building blocks of nature. If scientists seek an organism to serve certain interests, the ideal of synthetic biology is specifically to design and engineer these organisms according to these interests.

In the case of synthetic biology, therefore, the phenomenon of single-cell life—or indeed of life at the cellular level—is made accessible to human manipulation and design never seen before. While genetic engineering was linked to already existing forms of life and the exchange of single gene sequences, synthetic biology goes about creating and engineering forms of life that are largely detached from nature. Hand-in-hand with a manufacturing process that, according to ambition, will be characterised by computer simulation and construction, modularisation and standardisation, synthetic biology will henceforth initiate a change in perspectives from genetically engineered manipulation to synthetic creation, which can be fairly described as a qualitative leap.

This leap can be illustrated using the example of a scientific competition that has developed with the emergence of the latest initiatives at establishing synthetic biology: the "international Genetically Engineered Machines" competition (iGEM) was initiated by the Massachusetts Institute of Technology in 2003. In 2009, 112 teams and a total of app. 1200 participants entered the competition.<sup>20</sup> In it, young scientists and students design and develop DNA-based biological circuits, proteins with non-natural properties or artificial cell-cell communication or signal transduction processes.

A requirement for participation is that the genetic modules engineered for the competition have to possess compatible terminals to facilitate the quick assembly of various modules. Furthermore, these modules must be deposited in a material bank, the so-called "BioBricks" database. Not only contestants can access this database—other interested parties can also access it and contribute towards its expansion.<sup>21</sup>

This material bank is to be used as a building set geared towards simplifying and accelerating the future development of increasingly complex synthetic biological systems. Genetic building blocks will no longer be manipulated and replaced ad hoc in individual cases, as is the convention in genetic engineering, but rather will be specifically developed and made accessible in the form of standardised building blocks (it is no coincidence that they have been christened "BioBricks" analogous to Lego bricks) to perform specific tasks.

In this way, the iGEM competition highlights two central concepts on which synthetic biology is founded. On the one hand, the great extent to which synthetic biology is replacing the old gene

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technological method of improving that which already exists becomes apparent through the creation of new things—phenomena which are to fulfil precisely defined tasks that no known natural organism can even remotely achieve. On the other hand, it becomes clear how much the interference of synthetic biology in nature relies on the modularisation and compatibility of the generated biological systems.

#### SOME ETHICAL REMARKS

Ethical reflection on synthetic biology has so far mostly been concerned with issues of biosafety and biosecurity.<sup>22</sup> These topics are indispensable if one is concerned about short- or medium-term legal or political regulations. Nonetheless, in order to get a hold on ethically relevant hidden dynamics of the research agenda, a complementary, more general approach to ethical issues is essential.<sup>23</sup> Given the specific historical and systematic background of synthetic biology described above, a number of relevant issues can be discerned, all of them hinging on the way in which synthetic biology approaches the phenomenon of life.

Synthetic biology fits an ideal of scientific progress in which scientific explanations of the behaviour of complex entities are based on explanations of the behaviour of those entities' parts. If one is to find an explanation of the actions and reactions of an organism, one is led to look for explanations in terms of patterns of actions and reactions of the molecular make-up of the organism. In this way, synthetic biology follows genetic engineering's epistemology, apparently giving further credentials to its aspirations by adding the ability of creation to genetic engineering's manipulative abilities.

This explanatory strategy stands in contrast to explanations that refer to an organism's perceptions of and attempts to accommodate to its environment, since in this latter case states of the organism as a whole are taken to be able to influence processes at cellular or molecular level. Taking human beings as an example, the contrast is obvious. One may explain the behaviour of a human being by referring to genetic determinants or, alternatively, to his or her perceptions and intentions. While the former knowledge can be used as a tool to identify Archimedean points of behaviour manipulation, the latter kind of knowledge is the prerequisite of the ability to talk to and understand the person as a whole person and to ascribe inherent value to it.

Now, if the organism is a single cell, one may assume that the two perspectives converge. After all, what can the ability to "talk to a cell" conceivably mean besides being able to manipulate cellular features? This is the reason why metaphors of signalling and sensing, often used in molecular biology without recognizing the tension between these concepts and bottom-up explanations, can be understood as containing a core of truth, although they are often criticized as misleading. Making use of molecular processes inside a single cell organism may be seen as a way of "talking" to the organism in this special case.

Nonetheless, the perspective of "talking" basically draws one's attention in other directions than does the bottom-up outlook, even in the case of single cell organisms. For example, if a cell is understood as sensing and transmitting information, the influence of the environment on processes inside the cell becomes a natural part of explanation of what the cell does, yet, when working within the bottom-up paradigm, the cellular environment appears to be a subordinate factor of influence. Accordingly, the bottom-up paradigm favors research on genetics and tends to construe the influence of genetic processes on the organism as deterministic, whereas the "responsive organism outlook" stresses the organism's ability to accommodate to its surroundings, including the ability to remake itself in this process.

It is commonly supposed that in moving upward from simple to ever more complex forms of life genetic bottom-up explanations give way to "responsive organism" explanations, necessitated by emerging phenomena such as sensitivity, consciousness, rationality etc. It is important to note, though, that no matter how complex a form of life is, it is always possible to maintain the ideal of a bottom-up explanation. Unexpected behaviour that may seem to renounce this ideal can always be explained away by referring to the complexity of causes and effects involved, a complexity that is not yet accounted for, but will in the future be accessible in terms of bottom-up explanations.

Moreover, it is difficult to see how "responsive organism" explanations are to be based on bottom-up explanations, given that the explanatory principles involved stand in stark contrast to each other. To invoke "emergence" as a solution to this problem is simply to invoke an explanatory "deus ex machina". Hence, if one wants to allow "responsive organism" explanations to play a role in explaining behaviour at all, one has to use this scheme right from the start, in accounts of even the simplest forms of life.

Now, this does not mean that bottom-up explanations are generally useless and ought to be avoided. For one thing, in the case of simple forms of life, the languages of the two schemes may overlap to a certain degree. For another, the bottom-up outlook can always serve as a tool for any inquiry that is aiming at effectively controlling and manipulating processes. It does mean, though, that in accepting the general validity of the "responsive organism" perspective one ought to be attentive to the one-sidedness of bottom-up explanations even in the case of simple forms of life. One should also be attentive to the ethical limits the "responsive organism" outlook imposes on bottom-up explanations if applied to higher organisms—especially, of course, to human beings.

Everything that has been said so far applies almost equally to genetic engineering and synthetic biology. Therefore, in order to delineate specific ethical aspects of synthetic biology, one has to take a further step and look at synthetic biology's special features, i.e., first and foremost, the appeal to creation and, to a lesser degree, the role of engineering principles such as modularization and standardization.

Creation, from the point of view of synthetic biology, amounts

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to being able to put together basic cellular parts, thus building a novel entity that exhibits all the characteristics of life. This is true both of *in-vivo* and *in-vitro* approaches. As an obvious first remark, it is important to note that this kind of creative activity is not “*creatio ex nihilo*”, creation from nothing.<sup>24</sup> In other words, synthetic biology’s creations cannot unqualifiedly be compared to the act of creation that theology commonly attributes exclusively to God—claims to this effect both by scientists and by synthetic biology’s critics notwithstanding. Even if it became possible, following a bottom-up approach, to build a living cell entirely from non-living complex molecules, this still would have to count as creation by way of refined combination of given parts. One may say that in this scenario, too, scientists do not create life from scratch but supply necessary and sufficient conditions for matter to actualize its potential to form living organisms.

Now, while the assertion to be able to create life from scratch surely must count as hyperbolic, it seems to be true that synthetic biology is a more creative activity than genetic engineering has been before. The aim and the success of the iGEM competition bear witness to the fact that synthetic biology carries with it a new level of aspiration, if not yet achievement. Whereas genetic engineering had its focus on optimizations of existing organisms (the benchmark being societal or consumer needs and preferences), synthetic biology gives free play to fantasy and imagination. Potentially, synthetic biology takes us beyond nature. “Nature 2.0”, i.e. nature with novel functions or even an orthogonal system of life, is not pure speculation any more.

From an ethical perspective, the shift of perspectives is significant, since the results of the creative activity in question gain life of their own. Synthetic organisms interact with the environment and evolve just like natural organisms, which means that their future is to a large extent unpredictable. At the same time, the engineering ideal of synthetic biology suggests quite the opposite, namely a product that, since it can be created, can be understood and explained in all the details of its functioning. Condensed to a catchword, synthetic biology reconstructs and creates organisms as machine-like entities, while nonetheless as a matter of fact having to cope with all the uncertainties and idiosyncrasies of evolving life.

From this perspective it does not come as a surprise that in the cultural imagination closely connected to synthetic biology’s aim of creation of life are the stories of Frankenstein’s creature and Faust’s Homunculus. Both stories may be taken to exemplify, among many other aspects, the gap between the highest accomplishment that science can aspire to, namely the creation of living organisms and essential autonomy of these organisms, which turns them into independent rivals and, in the case of Frankenstein, victims of their creators. In other words, Frankenstein and Faust are not always misguided associations of a scientifically under-educated public. Rather, these cultural narratives and cautionary tales can help us to stay aware of the limits of the general explanatory framework synthetic biology employs and to the necessity of sober multi-disciplinary risk assessment.

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## CONCLUSION

Synthetic Biology is a rapidly developing new field of biological research. Its aims to analyze intra- and intercellular processes and to use this knowledge in order to build hitherto unknown single-cell life forms. Thus, the shift from analysis to synthesis to which chemistry has been subject in the early 20th century is now about to become reality in biology.

In the case of chemistry, this shift has had a massive influence on the economy and society as a whole. It does not come as a surprise, then, that the rise of synthetic biology is accompanied by high-flying expectations: possible applications range from decisive advances in cancer therapy to microorganisms that degrade remedies and fuel-producing bacteria.

At the same time, the development of the research field is met by a growing number of critical voices. Under the heading of “biosafety”, social scientists, ethicists and philosophers discuss topics concerning the unintended harmful effects of synthetic organisms to humans and the environment, and further attention is paid to possible cases of intended misuse—so-called “biosecurity” concerns. Taking a step back, it becomes possible in addition to focus on some general ethical implications of synthetic biology’s endeavor.

First, calling an object alive is deeply connected, both historically and systematically, with the conviction that the object in question is to be valued as a (more or less) autonomous agent, a status that artifacts do not share. As a consequence, the way in which newly created organisms are conceptualized has an ethical impact on how life in general is understood and valued. When describing microorganisms and their signalling pathways, synthetic biology researchers often invoke computer metaphors of “hardware” and “software” as well as mechanical metaphors of “brick” and “chassis”. Keeping in mind the difficulties of defining life and the normative dimension of the concept of life, it is important, though, not to prematurely conflate the concepts of “life” and “machine” in synthetic biology research.

Second, even though it is not correct to claim that synthetic biology attempts to create life “from scratch,” synthetic biology does comprise a perspective of creation rather than manipulation. From point of view of creation, one does not have to settle for smoothing out nature’s shortcomings but can engineer a nature without shortcomings from scratch. Using the abilities of nature through cultivation, manipulation or even exploitation differs from reinventing nature. Assuming all appropriate safety measures are in place, doing so might be justifiable in many specific cases. Nonetheless, taken as a general approach, it might lead to an overestimation of how well we understand nature’s processes and our own needs and interests and of how best to achieve them.

Following up on this last point, it becomes possible to connect ethical reflections on life and creation with down-to-earth questions of biosafety and biosecurity. For example, given the ability to create single new forms of life, the degree to which we believe in our ability to understand and calculate nature’s processes will increase, while at the same time our actual knowledge of complex interactions of different kinds of organisms in their habitat might not have expanded at all. As a consequence, the core characteristics—ethically speaking—of synthetic biology present a challenge to regulations and treatises originally developed to deal with risks and cases of misuse regarding genetic engineering.

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