TECHNOLOGY AND NATURE
Part Two

Synthetic Biology: The Assault on the Realm of Life

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"For living beings will indeed be produced in the laboratory from that which has no life."
Rudolf Steiner, 1917.[1]

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The First Synthetic Organism

Last year (May 2010), a defining moment in biology was reached with the purported creation of the first ever synthetic life-form. The organism – a humble single cell bacterium – was designed by scientists of the J. Craig Venter Institute in Rockville, Maryland, U.S.A., whose founder – Craig Venter – became famous in 2000 when he successfully mapped the human genome (i.e. the complete genetic make-up of a member of the species). The synthetic organism created by his team was based on the genome of the tiny bacterium *Mycoplasma mycoides*, whose DNA was sequenced and the information stored digitally on computer. The digitised code was the information source for chemically synthesising short strands (the so-called "base sequences") of the bacterium's DNA, something that many companies using DNA synthesis machines can now do relatively inexpensively. From one such company, Venter's team ordered more than a thousand base sequences, which were then painstakingly reassembled piece by piece in the laboratory until the whole genome of the bacterium was artificially reconstructed.

Apart from a few fresh strands of DNA, added as a "watermark", the genome was an exact, computer-generated replica of *Mycoplasma mycoides*. The way Venter subsequently explained it to the world's media was:

> "We made it by starting with digital code in the computer. We built the DNA chromosome from scratch from four bottles of chemicals… It is the

> first species on the planet to have its parent be a computer."[2]

It is important, however, to understand that the synthetic genome did not in itself amount to an actual organism. The chemically synthesised genome had to be inserted into the already existing cell of a different species of bacterium, *M. capricolum,* which had been stripped of both its DNA and its immune response enzymes so that it was to all intents and purposes an empty bio-receptacle. In order to reproduce itself, the cell had no alternative but to draw on the synthetic genome inserted into it, and so its progeny had the characteristics of *Mycoplasma mycoides.*[3]

In line with many biologists engaged with engineering new life-forms, Venter sees living organisms as self-replicating machines best described in the language of computer technology. The microbial cell is thought of as "hardware" while the DNA inserted into it is "software", i.e. the equivalent of a computer programme:

> "It's pretty stunning when you just replace the DNA software in the cell. The cell instantly starts reading that new software, starts making a whole different set of proteins, and in a short while all the characteristics of the first species disappear and a new species emerges."[4]

A few months after this breakthrough, Richard Dawkins interviewed Venter on BBC Radio 4 and asked him to explain the principles of his method for creating synthetic organisms. Venter, with his penchant for explaining things in simple bold outline, described his method as

follows: you begin by taking "the software of life", namely the four letters of the genetic code, A, C, G, and T (which represent the chemical compounds of DNA: adenine, cytosine, guanine and thymine), and you put it into the computer. There it is converted into ones and zeros, so that all the genetic information is digitised. Then it can be transferred to a microbial cell where one can "boot it up" (a rather ugly phrase normally applied to the activation of operating systems in computers).

Audibly pleased with this description, Dawkins interjects:

> "I love that phrase 'boot it up'. The whole of life consists of bites of digital information. Before that, people would have thought that life was some kind of throbbing, oozing, vibrant, separate kind of substance, and now we know it's just like computer information, and you're demonstrating that."

Just like computer information? Dawkins clarifies:

> "Digital computers provide the central metaphor not just for genomics but for the whole of biology… 'Metaphor' is too weak a word. Life does not just depend on information technology; life *is* information technology."[5]

The Assault on the Realm of Life

Dawkins has a remarkable aptitude for making pronouncements that resonate with the collective psyche, and at some level, perhaps many people will feel that he here expresses a profound truth. Living as we do in the

digital age, in which digital technologies permeate every aspect of our lives, and in which disconnection from the natural world has become the new norm, the statement that "life *is* information technology" certainly carries a powerful resonance far beyond the confines of synthetic biology. The statement succinctly sums up how many of us, especially those adjusted to urban environments, have come to regard the pulse of life. The extent to which this is the case indicates the degree to which the reductionist philosophical paradigm that underlies the digital revolution is implicitly affirmed in lifestyle and attitude. Our embrace of the technologies of the digital revolution has inevitably, but for the most part unconsciously, drawn us into an ever more dangerous collusion with this underlying paradigm. And yet a sense of profound discomfort may also accompany digital technology's breach of the inner sanctum of the living organism. And if it is possible to suffer this discomfort sufficiently consciously, we may also come to see that it offers a chance to wake up to what is going on not only in the field of synthetic biology but also at a much more intimate level in our own habits of thinking. We shall return to this later.

One of the most important recent advances in biology is genome sequencing, with which the creation of synthetic genomes is closely interlinked, for it provides the data bank in which relevant strands of DNA can be identified. Since Craig Venter sequenced the human genome back in 2000, the speed at which genomes can be sequenced has, thanks both to more efficient automation of sequencing and to the expansion of the data-processing capacity of

computers, vastly increased and is now *thousands* of times faster today than in 2000.[6] As Venter commented last year, "It took ten years of international effort costing billions of dollars to sequence the first human genome. Today, this can be done in a day, in a single machine for just a few thousand dollars."[7]

Human genome sequencing continues apace. This year (2011), the "1000 Genome Project" has so far produced highly accurate assembled sequences of over a thousand individual human beings. This is an ongoing project that aims to sequence more and more people from different countries around the world in forthcoming years.[8] What it really amounts to is the compilation of a massive electronic database of DNA sequences. So far the 1000 Genome Project database comprises *eight trillion* DNA base pairs of sequence data – and this is just human DNA. The genomes of other species are of course also being sequenced. In 2009, for example, the "Genome 10K Project" was launched with the aim of sequencing the genomes of 10,000 different vertebrate species.[9] This will be a major addition to already existing databases of genomes of many plants and animals that have been sequenced over the last two decades.

The massive drive to "digitise biology" has aroused enormous excitement, because DNA is regarded by so many as holding the secret of life. Digitisation promises to deliver the essence of life into human hands through the medium of the computer. Just consider that the synthetic genome created by Craig Venter's team last year consisted of a million base pairs of DNA. It has been

estimated that working with the technologies available as recently as the early 1970s, this would have taken 90,000 years to create![10] In other words, without contemporary computing power, it would have been impossible to do it. Through its ability to digitise DNA sequences, the computer has also apparently vindicated the *philosophical assumption* that the smallest parts of an organism determine the whole, and therefore knowledge of the parts gives us knowledge (and control) of the whole. Thus biology has become increasingly diverted away from the living apprehension of living creatures to the manipulation of an aspect of the organism that has now proved susceptible to being translated into digital code.

With the advent of synthetic biology, this reductionist philosophical assumption acquires life-denying menace, as we have seen in Richard Dawkins' statement that life *is* information technology. It is both life-denying and at the same time it shuts off the path of inner development, for at the foundation of synthetic biology is the belief that the livingness of an organism resides in a domain to which digital technology has given us special access. The computer, which could be understood as a machine that simply multiplies the power of analytical thinking, appears to prove that any idea that we need to develop a higher kind of thinking in order to grasp the organism as a living whole is redundant. For the realm of life has surrendered its secrets to us precisely through our directing attention *away* from the wholeness of the living organism to the vast quantity of data that constitutes the sequenced genome. Or at least, so it is argued.

As the focus of attention has shifted more and more towards the molecular composition of the cell, the motivation of the researcher has also been subtly turned away from understanding for its own sake towards the kind of understanding that will lead to the ability to manipulate and control. For synthetic biologists, biology is not so much a science concerned with the qualitative understanding of living organisms, as a technology concerned with gaining control over the organic realm through treating it as if it consisted of inanimate parts. Robert Carlson, who has worked in the field for many years, regards a living organism as a "composable system" no different from an automobile or a computer, and therefore "the measure of understanding in biology should be the ability to build biological systems. That is, only when we can build a system that quantitatively behaves as predicted should we say we understand it."[11]

For Carlson, the very definition of understanding has become interwoven with the ability to engineer, a fact reflected in the title of his book: *Biology is Technology*. The aim of synthetic biology, then, is to overwhelm the realm of life with the force of quantitative thinking, in order to deliver it as captive into the hands of the technological mentality. And this mentality, which sees the whole as merely a complex assembly of parts (i.e. as a mechanism), regards its view of life as vindicated just because it is able to set about reconstructing from these parts new wholes. Thus biology is now in the process of re-conceiving itself as no more than a form of

engineering, and the way is opened to a massive and systematic assault on the realm of life.

The Beginning of a New Industry

In the early years of the last decade (i.e. the early 2000s), a group of synthetic biologists founded the BioFab (short for "Biological Fabrication") Group, the aim of which was to promote the engineering of new biological systems that would be assembled from standardised parts. These component parts (referred to as "BioBricks") would consist of strands of DNA, each designed to reliably perform a specific function. They would, like standardised electronic components, have clear specifications and be readily compatible with other molecular components in the construction of "genetic circuits" (conceived as analogous to electronic circuits). To this end the group established a Registry of Standard Biological Parts. It is both an online catalogue and a physical repository of standardised, interchangeable parts (i.e. DNA sequences) that can be used to design and build "genetic machines". By 2010, the Registry had accumulated more than five thousand standardised parts, from which custom-built life forms could supposedly be assembled.[12]

With their eyes firmly set on the production of new synthetic organisms, the BioFab group sought to adopt an industrial model, similar to that followed in the electronics industry. This would involve separating the design process (done on the computer screen) from the fabrication process of actually assembling DNA

fragments into larger molecules. It would also require greater specialisation, through using a so-called "abstraction hierarchy", which would allow researchers to work independently of each other on different aspects of the same project, as is done in the design and manufacture of semiconductors. In this way, biology would develop the "foundational technologies that make the design and construction of engineered biological systems easier".[13]

In 2006, the BioFab group published a manifesto in the *Scientific American*, entitled "Engineering Life". In it they emphasised that their aim was to change the way biologists thought about living organisms, in particular through "encouraging biologists to think more like engineers". They envisaged that bio-engineers would "imagine increasingly complex devices" and "use powerful engineering tools, such as computer-aided design, to manage that complexity".[14] While the development of design and fabrication technologies was seen as vital, the manifesto nevertheless rightly emphasised that:

> "Bio fab is more than a collection of speedier synthesis technologies. It is a *way of thinking* about existing biological machines and of constructing new ones, which borrows both language and methodology from engineering."[15]

This "way of thinking" requires that we consciously dismiss any residual belief that living organisms have an innate unity in favour of the view that they are merely an assembly of genetic components (strands of DNA) that

are susceptible of digitisation in the computer and can then be outputted as standardised components to perform as reliably as any transistor, oscillator or switch in the electronics industry. To this end, computer software has been developed that simplifies the whole procedure by allowing the bio-engineer to design genetic parts through "dragging and dropping" (i.e. selecting and moving) DNA sequences virtually so that they fuse together on screen. Instructions can then be fed to a liquid-handling robot that executes various reactions and assembles each genetic component, as it is needed.[16] Thus the bio-engineer works from the virtual world into the real. The computer, which in contemporary society has become the source not only of information but also of every kind of sellable product, now acquires the additional role of becoming the source of life. Echoing the words of Craig Venter, Drew Endy, a prominent synthetic biologist and founder member of the BioFab Group, summarised the approach as follows:

> "You program in whatever you want to build, and that machine [a DNA synthesiser] will stitch the genetic material together from scratch. This is the recipe: you take information and the raw chemicals and compile genetic material. Just sit down at your laptop and type the letters and out comes your organism."[17]

While this may be a simplified description of actual procedure, it is nevertheless an accurate characterisation of the way of thinking that underlies the synthetic biology mindset, not least because it so thinly conceals the blatant ambition that shapes it: to by-pass nature in

order to create new life-forms "from scratch". For example, it promises to produce new drugs far more simply and cheaply than at present by treating cells as biological factories that can be made to churn out the desired compound. According to Jay Keasling, the scientist-cum-entrepreneur who has designed a new microbe to produce the anti-malarial drug, synthetic artemisinin:

> "We ought to be able to make any compound produced by a plant inside a microbe. We ought to have all these metabolic pathways. You need this drug: O.K., we pull this piece, this part, and this one off the shelf. You put them into a microbe, and two weeks later out comes your product."[18]

Apart from new drugs, synthetic biology promises to be able to engineer microbes that will manufacture on an industrial scale new bio-fuels and deal with the problem of global warming by absorbing carbon dioxide from the atmosphere. According to Craig Venter, both these possibilities could be realised within ten years.[19] Thus we are led to believe that some of the most pressing problems of the world will shortly be solved by this new technology. With such promises, it is not surprising that synthetic biology has attracted multi-million dollar funding – in the case of Keasling's synthetic artemesinin, $42.6 million from the Bill and Melinda Gates Foundation. Other projects have drawn funding from both venture capitalists and government organisations, such as the United States Department of Defence's DARPA (Defence Advanced Research Projects Agency),

and The National Science Foundation, which underwrites the work of BioFab.[20]

For several years now, one of the most high profile events of the synthetic biology scene has been the annual International Genetically Engineered Machine (iGEM) competition, aimed at undergraduate students, and held in November. Using components from the Registry of Standard Biological Parts, more than a hundred teams of students from all over the world both design new components that are added to the Registry, and also manufacture new "biological systems" through the manipulation of genetic material. It is a competition that also has attracted interest (and funding) from multinationals like Monsanto and Merck as well as established grant-awarding bodies like the Welcome Trust.[21]

An example of the kind of project submitted is the contribution of undergraduates from the University of Cambridge to last year's competition (2010). The team took modified genetic material from fireflies and from a luminescent marine bacterium and inserted it into the *E. Coli* bacterium. They found that a volume of the subsequent bacterial culture about the size of a wine bottle gave off enough light to read by. They also found a way to engineer standardised strands of DNA that would help future researchers to work towards their long-term goal of fabricating bioluminescent trees that would glow in the dark, as an alternative to street lights.[22] This purely utilitarian manipulation of genetic material torn from its natural context is typical of iGEM entries and well

illustrates the contempt for the natural order that underpins this biotechnology.

Inherent Problems

Despite rapid advances, synthetic biology has not progressed without having to contend with problems. It is a telling fact that only a few of the iGEM projects actually work as designed.[23] One reason is that there have been considerable difficulties with "standardising" biological parts. Of the 5,000 on the Registry of Standard Biological Parts, 3,500 have yet to be independently confirmed, and a large number of parts have either failed to work or have been reported as problematic.[24] While these figures may be regarded as no more than "teething problems", they also point to inherent difficulties in an approach to living organisms that systematically ignores an organism's wholeness. Bio-engineers may carry out very precise analytical and surgical procedures, but the results may nevertheless very often be unpredictable because, once laboratory procedures end and the organism begins to function independently, a new factor – the organic entity as such – comes into play.[25]

It is now well-established that segments of DNA that are described as performing a specific function within a given organism may perform a quite different function within another organism. For example, experimental results have repeatedly shown that the same gene in a mouse and in a human will have a quite different effect.[26] Even within the same species, the same gene will have different effects from individual to individual because, as

biologist Mae-Wan Ho observes, "the gene itself has no well-defined continuity or boundaries, the expression of each gene being ultimately dependent on, and entangled with, every other gene in the genome."[27] This means that the attempt to compile a database of standardised biological parts that are shorn of any relationship to an actual organism will be bound to run up against the challenge of reliably predicting how a specified part will behave – both at the chromosomal level and within the wider context of the functioning of the whole organism.

Most biologists have long recognised that the simplistic model of genetic determinism, in which a specific DNA sequence is regarded as determining a specific function or character trait, simply does not correspond to biological reality. Just as every living organism is influenced by the environmental context to which it belongs, so do genes belong within the context of the organism of which they are a part. The so-called "central dogma" of molecular biology set out by Francis Crick in 1958, which sees genetic information as a uni-directional flow from DNA to messenger RNA to protein synthesis, ending up with a specific function or trait in the organism, was already having to face evidence in the 1960s that showed the picture to be far more complex. Through the 1970s and 1980s more and more evidence accumulated that totally undermined the simplistic central dogma.[28]

This evidence showed that the precise sequence of amino acids in a cell (from which proteins are synthesised) depends on influences from the greater context of the

cellular and physiological state of the organism as well as from the environment in which it lives, all of which can lead to modifications in its DNA. The flow of information, in other words, is not just uni-directional, but subject to complex interactions within the whole organism, and between the organism and the environment. A cell's enzymes (the proteins that catalyse metabolic processes in the organism), for example, are capable of actively manipulating DNA so as to modify its information content, a fact that has led several biologists to question not only the mechanistic approach of genetic determinism but also the very existence of genes.[29] Likewise, environmental factors such as fertilizers have been shown to induce inheritable changes in the DNA of plants like flax, maize, pea and broad bean.[30] This is too vast a subject to go into here, but one thing is certain, and that is that the original "central dogma" formulated by Francis Crick in 1958 has been shown over and over again to be untenable.[31]

What Kind of Life is Synthetic?

This is not to say that synthetic biologists are unaware of these problems, but rather that their core allegiance is to this discredited and simplistic model. A question that therefore presents itself is: what kind of organisms *are* they going to be able to create? One indication comes from the mental framework within which the bio-engineers are conducting their research. They are technicians, not nature lovers. Many of them did not even train as biologists but as engineers, and they approach organisms as they would approach any engineered

system in need of optimising for human benefit.[32] It is taken for granted that "biological machines" have no value other than their utility for us: they have no being, no essence, other than the genetic sequence that has so haplessly succumbed to digitisation. "When we look at cells as machines," Craig Venter once commented, "it makes it very straightforward in the future to design them for very unique utilities."[33] And so they set about programming them as one would program a computer. What we must expect to see more of in the future, then, are organisms that have been debased to the level of machines.

While at the present time synthetic biologists are predominantly working with single cell organisms, their ambition is to build up towards the fabrication of increasingly complex multi-cellular organisms.[34] Given the thoroughly mechanistic approach of the discipline, one must suppose that these organisms, made of standardised parts and designed and constructed on the model of electronics components, will have an existence that is intermediate between a natural living organism and a mechanism. One sign that this is the way things are likely to go is the fact that fabricated synthetic networks are increasingly being established *in isolation* from the rest of the living cell.[35] Meanwhile, work is progressing towards building an artificial "protocell" that will contain and express synthetic DNA as flexibly as a computer stores document files and runs computer programmes.[36] In order to get round the problems of gene entanglement and the fluidity and unpredictability that are part and parcel of what makes a living organism alive, synthetic

biology seems almost bound to edge its way towards producing a new kind of hybrid cyber-organism, half-electronic and half-living.

A New Step in Consciousness

By the late eighteenth century, after roughly two hundred years of attempting to understand nature in mechanistic terms, it had become apparent to many sensitive thinkers and poets, such as Goethe and Coleridge, that a new step in human consciousness needed to be taken. To continue to follow the path of a purely mechanistic science that proceeded on the basis of an objectifying view of the world would lead humanity further and further away from the spiritual and creative powers within nature. The step that needed to be taken was one which would lead to an awareness of the all-pervasive yet non-sense-perceptible energies that work into and inform the realm of life, referred to in the Middle Ages as *Natura naturans*, literally "Nature naturing" as distinct from the finished sense-perceptible forms of "Nature natured" or *Natura naturata.*[37]

Both Coleridge and Goethe saw that in order to come to such an awareness, it was necessary to move beyond the objectifying, analytical way of thinking to one that was more empathetic and holistic. Analytical thinking, referred to in the German idealist philosophy of the time as *Verstand*, is good at sorting information, good at problem-solving, and generally very useful to us, but it does not give us insight into living processes. This is because it renders things understandable by breaking

them down into their constituent parts rather than seeing things in their wholeness. German idealist philosophers, notably Hegel, placed great emphasis on a higher kind of thinking, referred to as *Vernunft*, which functions at a different level from the analytical mind with its all too precise yet fixed and lifeless concepts.[38] The *Vernunft* thinks into and embraces the growth, flux and metamorphosis that characterise the development of living things.

For Goethe and Coleridge, this distinction between the two kinds of thinking was enormously significant. Revisiting Aristotle's idea of the entelechy – the non-physical form-giving agency that strives to realise itself in the developing organism – Goethe saw that only a more mobile thinking attuned to the living whole would enable us to grasp it.[39] With analytical thinking alone we cannot lay hold of the form-giving and self-organising principle, which infuses and "in-forms" the parts, and so we will neither interpret the parts correctly nor see the true relationship of the parts to the whole. Goethe put it as follows:

> "The power of the Godhead permeates what is living, not what is dead; it is present in that which is in process of becoming and that which transforms itself, not in that which has become and has congealed in its form. Hence *Vernunft,* in its affinity with the divine principle, is concerned with what is evolving and developing, whereas *Verstand* deals with what has become formed and congealed, in order to put it to use."[40]

The thinking of the *Vernunft* is for most of us a possibility that as yet remains undeveloped. But in allowing it to remain undeveloped, we become the unwitting accomplices of the purely technological approach to nature. We collude by default in the reductionist paradigm that cleverly presents to us an alluring and seductive fantasy of living the "digital life" and, falling under its spell, we find that we all too easily give our consent to the view that *life itself* is but digital because that is the reality in which we live. If we continue to neglect to take the step that Goethe, Coleridge, Hegel and others saw as so necessary, we will have failed one of the most important challenges of modern times, which is to defend the realm of life from the rapidly intensifying assault of the forces of death, which we ourselves have unleashed upon the world through an untransformed thinking.

This untransformed thinking of the technological mentality perpetuates a view of the world in which utility (i.e. *usefulness to us*) has become an absolute value displacing all others. The question that synthetic biology should lead us to ask, then, is not so much whether or not it will work, but rather whether we are to give our assent to a way of seeing that places utility above truth. According to Hegel, the truth of a living organism resides in its outer reality corresponding to its inner idea or formative principle.[41] To force organisms to conform to our utilitarian designs by treating them as no more than biological machines is to extend over creation a tyranny of falsehood, in which the inner meaning of an organism

is replaced by an alien meaning imposed upon it by an external will.

Synthetic biology may "work", just as the factory farming of animals could be said to work (although it brings with it a host of other problems). But when we allow the living organism to be reconceived as a machine that exists to be manipulated and improved for our benefit, we then allow the moral integrity of the whole culture to be undermined. For not only is the creature degraded but so also is our own perceptive faculty abused, having become corrupted by purely utilitarian values that, as Hegel would say, are infected with falsity. If a culture serves untruth, then it becomes ever more difficult for it to serve what is beautiful and good.

Because it so seriously compromises both the natural integrity of the organism and the moral integrity of the human being, synthetic biology – while promising to be the panacea that solves the world's health and energy problems and to get rid of global warming, etc. – is likely to produce far more problems (both ecological and moral) than it solves. If, on a collective level, synthetic biology threatens fundamental values, the onus is on each of us as individuals to throw off the influence of the purely technological thinking that has become so pervasive in today's world. Otherwise we all remain complicit in what is unfolding in the laboratories of today's bio-engineers. Somehow we need to find the strength to exert that extra moral, imaginative and cognitive effort needed to grow into a new relationship to the realm of life; to find a way of perceiving and

knowing, which both enables us to apprehend the livingness of living organisms and at one and the same time to affirm fundamental human values.

Notes

[1] Rudolf Steiner, "Humankind and the Extra-earthly". Berlin, March 13th, 1917. Reproduced in Rudolf Steiner, *Cosmic and Human Metamorphoses* (Great Barrington, MA: Steinerbooks, 2004), p.122.
[2] "How scientists made artificial life", BBC news, 20 May, 2010.
[3] See Elizabeth Pennisi, "Synthetic Genome Brings New Life to Bacterium" in *Science,* 238 (21 May, 2010), pp.958-959 for a summary of the procedure followed. For a withering critique of Venter's claims see Mae-Wan Ho, "Synthetic Life? Not By a Long Shot" in *Science in Society,* 47 (Autumn 2010).
[4] Quoted in Ian Sample, "Synthetic life breakthrough could be worth over a trillion dollars", *Guardian*, 21 May, 2010.
[5] *The Age of the Genome,* Part 4, BBC Radio 4, 14th July, 2010.
[6] Mae-Wan Ho, "Reams of Data and No Progress in Sight", *Science in Society*, 48 (Autumn 2010), p.23.
[7] Craig Venter, "Multiple Personal Genomes Await", *Nature* 464 (April, 2010), pp.276–277.
[8] 1000Genomes Project Press Release, 21 June, 2010: "1000 Genomes Project Releases Data from Pilot Projects on Path to Providing Database for 2,500 Human Genomes", p.3. Available at http://www.1000genomes.org.
[9] J. Hered, "Genome 10K: A Proposal to Obtain Whole-Genome Sequence for 10,000 Vertebrate Species", *Journal of Heredity* (2009), vol.100 (6), pp.659–674.

[10] ETC Group, *Extreme Genetic Engineering: An Introduction to Synthetic Biology* (ETC Group, 2007), p.7. Available from http://www.etcgroup.org.
[11] Robert H. Carlson, *Biology is Technology: The Promise, Peril, and New Business of Engineering Life* (Cambridge, MA: Harvard University Press, 2010), p.15.
[12] Jon Mooallem, "Do-It-Yourself Engineering", *New York Times,* 10 February, 2010. See also The BioFab Group, "Engineering Life", *Scientific American*, 294:6 (June, 2006), p.51.
[13] Drew Endy, "Foundations for Engineering Biology", *Nature*, 438, (2005), pp.449–453. See also The BioFab Group, *op. cit.*, p.48.
[14] The BioFab Group, *op. cit.,* p.46.
[15] The BioFab Group, *op. cit.,* p.49.
[16] Jon Mooallem, *op. cit*.
[17] Drew Endy, quoted in Michael Specter, "A Life of its Own: Where will synthetic biology lead us?", *The New Yorker*, 28 September, 2009.
[18] Jay Keasling, quoted in Michael Specter, *op. cit.*
[19] *The Age of the Genome,* Part 4, BBC Radio 4, 14th July, 2010.
[20] For Bill and Melinda Gates Foundation, see Michael Specter, *op. cit*. For DARPA and the NSF, see Gaymon Bennett, "What is a Part?", *BioFab Human Practices Report 1.0,* (2010). Available from the BioFab website: www.biofab.org.
[21] Jon Mooallem, *op. cit.* See also the Welcome Trust website, http://www.wellcome.ac.uk.
[22] Frank Swain, "Glowing Trees Could Light up City Streets", *New Scientist*, 2788 (25 Nov, 2010).

[23] C.D. Smolke, "Building Outside of the Box: iGEM and the BioBricks Foundation", *Nature Biotechnology* 27 (12), 2009, pp.1099–1102.
[24] Roberta Kwok, "Five Hard Truths for Synthetic Biology" *Nature* 463 (2010), p.288.
[25] Craig Holdrege, *A Question of Genes* (Edinburgh: Floris Books, 1996), p.112.
[26] Holdrege, *op. cit.,* p.81.
[27] Mae-Wan Ho, *Genetic Engineering – Dream or Nightmare?* (Bath: Gateway Books, 1998), p.104.
[28] *Ibid*, chapter 8.
[29] Craig Holdrege and Steve Talbott, *Beyond Biotechnology* (Lexington: University Press of Kentucky, 2010), chapter 6. See also Mae-Wan Ho, "The Death of the Central Dogma", *Science in Society* 24 (Winter 2004), p.4, and other articles in this issue.
[30] Mae-Wan Ho, *Genetic Engineering – Dream or Nightmare?*, p.115f.
[31] The reader is referred to Craig Holdrege, *A Question of Genes* (Edinburgh: Floris Books, 1996), Craig Holdrege and Steve Talbott, *Beyond Biotechnology* (Lexington: University Press of Kentucky, 2010), Mae-Wan Ho, *Genetic Engineering – Dream or Nightmare?* (Bath: Gateway Books, 1998), and Mae-Wan Ho, *Living with the Fluid Genome* (London: Institute of Science in Society, 2003).
[32] See Drew Endy, *op. cit.*, p.449–453.
[33] Craig Venter in conversation with Richard Dawkins, "Life: A Gene-Centric View", Munich, January, 2008. Transcript available from www.edge.org.

[34] According to Drew Endy, "There is no technical barrier to synthesising plants and animals; it will happen as soon as anyone pays for it." Quoted in ETC Group, *Extreme Genetic Engineering: An Introduction to Synthetic Biology*, p.7.
[35] Roberta Kwok, *op. cit.,* p.289.
[36] ETC Group, *op. cit.*, p.11.
[37] For a history of the distinction between *Natura naturans* and *Natura naturata*, see Olga Wiejers, "Contribution á l'histoire des termes *natura naturans* et *natura naturata* jusque' á Spinoza", *Vivarium* 16.1 (1978), pp.70–80. For the importance of the distinction in Coleridge's thought, see Owen Barfield, *What Coleridge Thought* (San Rafael, CA: Barfield Press, 1971), Chapter 2.
[38] Thus Rudolf Steiner, *Goethe's Conception of the World* (London: Anthroposophical Publishing Company, 1928), p.182, described Hegel as "the philosopher of the Goethean world-conception".
[39] See Goethe's essay "The Purpose is Set Forth" (1817) reproduced in Jeremy Naydler, *Goethe on Science* (Edinburgh: Floris, 1996), pp.48-50, in which the German word *Bildung* corresponds to Aristotle's *entelecheia.* See also Rudolf Steiner, *Goethe the Scientist* (New York: Anthroposophic Press, 1950), p.60 for Goethe's understanding of the entelechy.
[40] Goethe in conversation with Eckermann, 13th February, 1829, translated by H.G. Weigand, in Naydler, *op. cit.*, p.51.

[41] Hegel, *Encyclopaedia of the Philosophical Sciences, Part One: Logic* (Oxford: Oxford University Press, 1975), §213.