Biomimetic Chemistry and Synthetic Biology: A Two-way Traffic Across the Borders

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Abstract: Crossing the boundaries – between nature and artifact and between inanimate and living matter – is a major feature of the convergence between nanotechnology and biotechnology. This paper points to two symmetric ways of crossing the boundaries: chemists mimicking nature's structures and processes, and synthetic biologists mimicking synthetic chemists with biological materials. However to what extent are they symmetrical and do they converge toward a common view of life and machines? The question is addressed in a historical perspective. Both biomimetic chemistry and synthetic biology can be described as descendants of an ambitious program developed by Stéphane Leduc who coined the phrase 'synthetic biology' in the early twentieth century. The main intention of this genealogy is to emphasize that although making life in a test tube is a recurrent project there are subtle nuances in the underlying metaphysical assumptions. This comparison is meant to contribute to a better understanding of the cultural issues at stake in the convergence between nano and biotechnologies. It suggests that the demarcation line between life and inanimate matter remains a hot issue, and that all traffics across the borders do not proceed from the same metaphysical assumptions.

Keywords: *synthetic biology, nature versus artifact, self-assembly, reductionism, vitalism*.

1. Introduction

Crossing the boundaries – between nature and artifact and between inanimate and living matter – is a major feature of the convergence between nanotechnology and biotechnology for those concerned with their cultural dimensions. This paper points to two symmetric ways of crossing the boundaries: chemists mimicking nature's structures and processes, and synthetic biologists mimicking synthetic chemists with biological materials.

Despite the revolutionary claims of champions of nanotechnology and synthetic biology, it is not useless to trace the genealogy of their programs.

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There is a long tradition of boundary crossing in the history of chemistry. Medieval alchemists were condemned by the reigning scholastic culture because they subverted the order of nature in their attempts at making artificial gold and in a few cases to make life in a test-tube. Their nineteenth-century heirs, who celebrated Wölher's synthesis of urea as the death of the metaphysical belief in the vital force, proudly claimed that there was no vital force and that consequently chemists were able to artificially produce living materials.[1] On the other hand, from Descartes to Jacques Monod the history of life science displays similar denials of any demarcation and that living organisms are mechanical or chemical machineries.[2]

In pointing to the antecedents of today's philosophical claims I do not mean that the current programs in nanotechnology and biotechnology are simply re-enacting old paradigms. On the contrary, the genealogy is valuable precisely because it helps identifying significant differences in the ways of crossing boundaries. Certainly each century had its lot of unbound Prometheus. Far from being an exceptional attitude, *hubris* – the defiance of the gods, which provided the etymology for hybrids, *i.e.* mixtures of two species – seems to co-evolve with science and technology. However as the circumstances that repeatedly prompt such ambitions change the achievements may have a quite different impact on culture.

2. A Common Ancestor

'Synthetic biology' is a phrase coined in the early twentieth century by Stéphane-Armand Nicolas Leduc, a French medical doctor who developed a biophysical theory of life along with biophysical therapies. As he became an expert in the art of growing a variety of life-like shapes – such as trees, mushrooms or shells – out of solutions of carbonates, phosphates, silicates, nitrates or chlorides, he ambitioned to expand the domain of physical chemistry, a new science studying electrolytic and colloid solutions and the kinetics of reactions.

2.1 Leduc's ambitious program

Leduc's program of 'synthetic biology' was exposed in his book *Théorie physico-chimique de la vie et génération spontanée* and further developed in *La Biologie synthétique*.[3] It consisted in imitating the forms, colors, textures, and movements of living organisms by osmotic growths. It is of special interest for the purpose of this paper because it was both synthetic and biomimetic. "The task of synthetic biology, he wrote, is the recognition of those physico-chemical conditions which can produce forms and structures analogous to those of living beings" (Leduc 1910, p. xv).

Leduc belonged to the anti-vitalist movement. His ambition was to account for the phenomena of life with the properties of colloid liquids: Not only a crude solution of mineral compounds generates buds, stems, roots, branches without the presence of organic ferment, but also these life-like forms are analogous to living organisms in their fine structures, as they present colonies of microscopic vesicles separated by osmotic membranes. Leduc went on claiming that they also display analogous functions, such as rhythmic and periodic movements, nutrition,[4] and even a selective choice among the substances available in the surrounding medium. Leduc was so fascinated by the analogies between the mineral shapes grown in his test-tubes and living organisms that he boldly concluded (Leduc 1910, p. 3):

> Since then, we are totally unable to define the exact boundary which separates life from the physical phenomena of nature, we may fairly conclude that no such separation exists.

All living organisms are transformers of energy, chemical transformers of matter and transformers of forms. Life originated in liquids and spontaneous generation is the corollary of the theory of evolution.

2.2. Naïve reductionism?

At first glance, Leduc's conclusions inspired by a crude and naïve reductionism seem almost absurd. Analogy is not identity. Consequently Leduc's inference from the spectacular forms grown in inorganic solutions to the existence of spontaneous generation is clearly invalid. Leduc's synthetic biology thus can be considered as a vestige of a time when chemists were confident enough in the power of their discipline to believe that they could provide explanations for the origin of life.

However this *prima facie* judgment rests on a superficial understanding of Leduc's program. Indeed Leduc was not naïve enough to mistake his life-like shapes for genuine living organisms. He presumably knew that mimicry is not a process of identification and that imitation presupposes the difference between the model and the copy. His claim is better understood as the expression of 'methodological reductionism'. The synthesis of life-like structures by osmotic diffusion provided him with a model for investigating the forces at work in morphogenesis. Just as contemporary biologists use drosophila or mice as animal models for exploring the mechanisms of human diseases, Leduc used osmotic growths as a concrete model, an *analogon* for exploring the power of physical and chemical forces. He used his osmotic growths to identify the most basic conditions of life that he identified as "the contact between an alimentary liquid and a cell" (Leduc 1910, p. xiv). He did not mean that life could be reduced to any chemical element:

> Life is not a substance but a mechanical phenomenon: it is a dynamic and kinetic transference of energy determined by physico-chemical reactions. […] It is the grouping of physical reactions and their mode of association and succession, their harmony in fact, which constitute life. […] The problem in the synthesis of life is the proper attuning and harmonizing of these physical phenomena. [Leduc 1910, p. 158]

2.3 Still Life

Nevertheless Leduc's epistemic strategy presupposes that there is no sharp division between chemical and biological phenomena. He clearly assumed the *continuity* between inanimate and living matter both in time and space.[5] The ingredients of living beings thus flow from the mineral to the vegetable and the animal realms. This grand vision of a cosmic cycle reminiscent of eighteenth-century views of the economy of nature, lead Leduc to the conclusion that:

> Life is but a phase in the animation of mineral matter; all matter can be said to have in itself the essence of life, *potential* in the mineral, *actual* in the animal and the vegetable. The flux and reflux of matter is alternate and incessant, from the mineral world to the living, and back again from the living to the mineral world. [Leduc 1910, p. 148]

Leduc thus admitted an inner spontaneity in matter, that life could emerge from the forces and properties intrinsic in matter. Since he used the Aristotelian categories of 'potential' and 'actual' let us label his metaphysical view 'Aristotelian emergence', although it rather belongs to the materialistic tradition initiated by Diderot and Maupertuis.

Thus, Leduc's 'synthetic biology' was more a biomimetic practice than the synthesis of artificial life. His program relying on the assumption that there is no demarcation between the realms of nature consisted in the production of inanimate *analoga* of living organisms. Just as artists paint still lives, inorganic matter creates a still life. Nature is the artist, Leduc is just a mediator who helps nature in her performance. Leduc's synthetic biology rests on a dynamic model of living organisms based on the physico-chemical properties of liquids. It is dynamic in two respects: i) life is a *dunamis,* a potential inherent in all matter; ii) living organisms are open systems interacting with their environment.

3. Copying the Book of Nature

Leduc's bold attempt was the origin of a bolder and more influential essay by Wentworth D'Arcy Thompson. The British zoologist shared with Leduc a fascination for biological forms. In his publication *On Growth and Forms* he applied mathematics, in a quest for the principles unifying the diversity of life. In identifying the physical and geometrical principles at work in the morphogenesis of biominerals, he assumed that organisms are as much the products of physics as of natural selection. Both Leduc and D'Arcy Thompson intended to explain life with the resources of physics and chemistry and to debunk all vestiges of vital force and design. The harmonious and optimal forms of living bodies do not testify for a supernatural design, they result for the interplay of natural laws.

3.1 A passion for biomimerals

Although this metaphysical claim is not what caught the attention of today's biomimetic chemists, they share with D'Arcy Thompson a passion for shells and biominerals. They marvel at the optimally shaped forms of biomaterials, they admire the complex hierarchical structure of shells, teeth, bones, diatoms, which are composites made of inorganic compounds (mainly silica) and biomolecules. The aim is to understand the basic principles of the formation of their subtle and rather enigmatic structures.

Biomaterials became a source of inspiration for materials scientists in the 1980s and prompted collaborations between chemists, engineers, and biologists. A new research field labeled 'Biomimetics' emerged with journals and conferences, which even became a subject taught in engineering schools and a subject for textbooks. Mekmet Sarikaya and Ilhan Aksai defined biomimetics:

> Biomimetics is the study of biological structures, their function, and their synthetic pathways, in order to stimulate and develop these ideas into synthetic systems similar to those found in biological systems. [Sarikaya & Aksay 1995, p. xi]

This branch of chemistry has been recently renamed 'nanochemistry' because biomimetic processes are bottom-up syntheses performed at a few nanometers length-scale. In many respects it can be described as a modern and pragmatic counterpart of Leduc's phantasmagoria. Unlike Leduc's chemistry, nanochemistry is aimed at making things, preferably useful things. Like Leduc, however, today chemists are synthesizing a variety of shapes of silica such as nanospheres, naocylinders, and nanotubes. For this purpose they retain a major lesson from nature, which conjugates inorganics and organics in the making of biomaterials. Nature uses templates, *i.e.* scaffolds that direct the inorganic structure formation. The use of soft moulds to shape hard materials is a key to achieve the synthesis of inorganic materials with all sorts of curved shapes.[6] Chemists came to realize that templating can be a dynamical process. Coordination chemistry also combines inorganic and organic components in order to synthesize supramolecular materials assembled by molecular recognition.[7]

Biomimetic chemists also share Leduc's passion for the fine structure of biomaterials. Their synthetic products just as their natural models are defined as systems rather than as devices or machines. They are characterized by their hierarchical structures, which qualify them for being more than materials out of which larger objects can be built. Rather, they are complete systems.

Hierarchical structures include at least four different levels held together by specific surface interactions. The multilevel structure is organized according to a set of purposes or performances to achieve.

3.2 Molecules at work

Self-assembly is the third major lesson that nanochemists learnt from biology. Just as ribosome and virus form spontaneously in a medium containing the appropriate elements, chemists are trying to get molecules arrange themselves into ordered functioning entities. It is extremely advantageous for operating at the nanoscale where our traditional manufacturing processes cannot work. Thanks to a variety of weak intermolecular forces – hydrogen, Van der Waals, coordination, and so forth – molecules self-assemble into structures and properties not found in the individual components. Jean-Marie Lehn who developed bio-inspired self-assembly strategies in supramolecular chemistry moved on to a program of 'dynamic combinatorial chemistry', which emphasizes another lesson taken from nature. Supramolecular chemists recognize that isolated molecules do not behave like interacting molecules. 'A glass of water is not like a water molecule' as Lehn often remarks.

Thus two key words – composite and collective – summarize the major lessons that nature taught to chemists. Without renouncing their quest for purity, they are mainly interested in composite and hybrid structures – displaying various properties and performing multiple functions. Rather than dealing with a single molecule and shaping materials atom by atom, they deal with crowds of molecules in rather messy environments.

How shall we describe their synthetic strategy? Occasionally chemists use the phrase 'we self-assemble molecules'. This paradoxical sentence stresses the ambiguity of their strategy: while the 'self' in self-assembly suggests that the process is going on with no human involvement, the subject 'they' suggests that they are actors of the process. In fact, they just initiate the process of self-assembly by securing the necessary agencies and appropriate conditions. One would hardly dare say that they ‘engineer’ structures or machines. Rather they design a kit of molecules to be self-assembled, with the expectation of controlling the end products. Their art of synthesis consists in taking advantage of the interactions between molecules and of their dynamics, just as the conductor taking advantage of the interactions of music instruments in a symphony orchestra.

Biomimetic strategies rely on the same basic convictions that inspired Leduc and D’Arcy Thompson: that physical and chemical forces can explain the stuff living organisms are made of. Biomimetic chemists echo Leduc’s claims about the continuity between inanimate and living matter. For instance, Jean Marie Lehn and George Whitesides never concealed that the ultimate goal of their chemical investigations was to understand how self-organization generates living organisms that are able to reflect on their own origin. For this purpose, they are trying to map the bonding forces and principles at work at all length-scales, from the self-assembly of molecules up to the self-assembly of materials.[8] Their concern with self-assembly at all scales leads to the clear recognition of two sorts of emergence: on the one hand, like Leduc, they assume that there is an inner potential intrinsic in matter (‘Aristotelian emergence’), which may result in structures and properties not found in the individual constituents. However, they locate this inner potential in the relations between molecules rather than within each molecule. It is a ‘transindividual emergence’. On the other hand, they assume a more modern notion of emergence, more familiar to evolutionary biologists, which connects the production of novel properties to structural complexity. The hierarchy of structures at different length-scales exhibits unique properties that are not found in the individual components and suggests that the system is made on purpose.

3.3 Nature, an insuperable engineer?

What is the status of the exquisite biomimetic structures modeled on nature’s ones? They obviously belong to the category of artifacts, they are typical ‘materials by design’. However apart from a few examples, most biomimetic structures are more laboratory curiosities than useful materials. As Philip Ball (2007) noted: “Such structures can be valuable but they are rather literal mimics – to put it harshly, they simply plagiarise nature”. Although the idea that nature provides elegant solutions to technological problems is deeply rooted in biomimetic chemistry, practical purposes are more an excuse than a real priority. Just as Leduc’s beautiful osmotic growths, a number of biomimetic structures are material models for exploring nature’s process of biomineralization. Morphosynthesis in general is meant to provide an insight in morphogenesis. Nanochemistry is the continuation of a long tradition of synthetic chemistry driven by cognitive purposes. The same could be said of many nanomachines designed by supramolecular chemists such as rotaxanes, catenanes, or other nanorotors, and nanopropellers. They are not meant for performing useful tasks. Many of them were initially synthetic challenges and only after they had been synthesized, it turned out that they could be useful when it was realized that similar structures already existed in nature.[9]

Although materials scientists claim that nature is an insuperable engineer, biomimetics leads to the clear recognition that despite surprising similarities human technology and nature's production rely on diverging principles. The specifications and the requirements are very dissimilar for bioproducts and manufactured products both at the macroscale and at the nanoscale. The diverging principles have been pointed out by Stephen Vogel who emphasized that human technology is far less constrained than biological evolution which is a blind process using soft materials rather than stiff structures with no central control (Vogel 1998). At the nanolevel, Richard Jones noted similar divergences in his reply to Eric Drexler's techno-utopia of a molecular manufacture: living cells are populated with soft machines wandering around with Brownian motions and making things through trials and errors (Jones 2004).

In brief, life has been a heuristic paradigm for chemistry over the past decades. It seems that the more chemists are working in this paradigm, the more they acknowledge the distance between the model and their copies. In exploring the potentials of self-assembly for synthesizing technological *analoga* of biomaterials, they better identify the laws that preside over the construction of biostructures and at the same time they better realize the distance between human manufactures and nature's creatures.

4. From Reading to Writing

Although Leduc coined the phrase 'synthetic biology' no one today would claim that he was a precursor. His advocacy of spontaneous generation clearly belongs to the prehistory of molecular biology. Today synthetic biologists know that there is no life without genes, which direct the development of cells according to a program encoded in their molecules. Over the past sixty years molecular biologists have been deciphering the code and reading the messages. Now it's time to move from reading to writing.

4.1 Commercial and philosophical ambitions

This is the grandiose program publicized by John Craig Venter, the former NIH biologist who together with Francis Collins announced the mapping of the Human Genome in 2000. Venter, who is famous for his determination for making business out of genomics,[10] contributes to the publicity and visibility of synthetic biology.[11] In October 2007, after filing a patent, he boldly declared to *The Guardian* that he had built a synthetic chromosome out of laboratory chemicals, and he commented the news saying that it was

> a very important philosophical step in the history of our species. We are going from reading our genetic code to the ability to write it. That gives us the hypothetical ability to do things never contemplated before.[12]

Indeed Venter is a controversial scientist who is inclined to hyperbolic claims meant to direct funding in his business ventures. Not all the proponents of synthetic biology are inclined to hype and commercial ventures. Some of them even suggest that there is a 'European way' of conducting synthetic biology. Protein design, modeling and bioengineering were synthetic biology '*avant la lettre*'.[13] However the close association of cognitive, technological, and commercial aspects is a major feature that synthetic biology shares with nanotechnology. The first Conference held in 2004 defined the goal of synthetic biology as "understanding and utilizing life's diverse solutions to process information, materials and energy".[14] In this respect, contemporary synthetic biology and its project of re-engineering life out of synthetic genomes would rather be the heir of another early-twentieth-century visionary, Jacob Loeb who developed an ambitious project for controlling and reshaping life in 1911 (Pauly 1987).

Venter's project of making a minimal bacteria genome exemplifies another feature of synthetic biology: it is a 'Big Science'. This painstaking synthesis was an expensive project requiring the cooperation of dozens of famous scientists and genetic engineers. The goal was more than a potentially juicy patent. It can be also understood as a collective attempt to determine the minimal conditions for life.[15] The intermingling of cognitive aims and engineering aspects thus characterizes this new branch of biology.

4.2 Engineering practice

Venter's claims express the credo of early molecular biology that living organisms are working like computers. Once you handle the program that controls the cell, when you gather the building blocks then you get the house built. More precisely Leduc's obscure notion of a *dunamis* inherent in matter has been replaced by the more fashionable notion of a program. The central dogma being that each structural unit carries an amount of information and that the information is processed in a single way, from DNA to RNAs and proteins. The second tacit assumption suggested by the computer metaphor is that the hardware and the software can – at least in principle – be separated so that the program can be transferred through cut and paste of DNA sequences.[16]

Since the basic structural elements are few, it is possible to make in vitro cell-free syntheses of DNA, RNAs, and proteins. Thus synthetic biology would expand the scope of bioengineering with the ultimate goal of collecting all the building blocks in a library of independent and interchangeable parts ("Registry of Standard Biological Parts").[17] Then by changing parts in an organism it is possible to reprogram its functions and to perform a specific function everywhere. For instance, Chris Voigt, from the pharmaceutical department of the University of California at San Francisco, reprogrammed an infectious bacterium to secrete spider silk instead of its own proteins. Moreover by taking advantage of the various possible combinations between the standard parts it is also possible to rewrite the program of living organisms in order to correct errors in gene expression and to improve on nature. Clearly the rewriters are not mimicking chemistry but computers.[18]

Synthetic biology is not the mirror image of traditional synthetic chemistry, which relied on the inner dynamics and spontaneous reactions of a large number of molecules. Rather it draws inspiration from another practice of chemistry, *i.e.* chemical engineering. As it was taught at MIT in the early twentieth century, chemical engineering was a science in itself based on the concept of unit operation. Complex industrial chemical processes were redefined as a sequence and coordination of a finite number of unit operations – such as grinding, extracting, evaporating, distilling, and so on. This emphasis on the unit operations allowed the exposition of the general laws controlling them and a quantitative treatment of specific industrial processes (Furter 1980).

4.3 From simple to complex

However a question remains open: what kind of system can be generated by the attempts at synthesizing forms of life? As long as synthetic biology is shaped by Crick's and Watson's central dogma, the living entities synthesized may well resemble integrated circuits.

Michel Morange's contribution in this issue as well as a recent article by De Lorenzo and Danchin (2008) suggest that most current synthetic biology programs rely on the questionable assumption that it is possible to identify and isolate a finite number of modules performing specific tasks and to rearrange them without taking into account their interactions and the metabolism of the cell. De Lorenzo and Danchin question the mechanical model of the machine underlying the MIT Program of Registry of Standard Parts. They do not question the engineering project in itself.

To be sure there are various research trends under the umbrella of synthetic biology ranging from single molecule manipulation in the cell to *in vitro* synthesis of minimal cells.[19] They differ in their aims as well as in their views of living systems. *In vitro* synthetic biology is of particular interest for the purpose of this paper because certain of its aspects are reminiscent of Leduc's synthetic program. George M. Church from Harvard clearly states that the purpose is to obtain autocatalytic replication and evolution from small molecules with the ultimate goal of understanding life in its origin and developing new biological tools for new therapeutics (Foster & Church 2007). The assumption is that the performances displayed by living organisms such as inheritance, adaptation, growth, and repair are requirements at the level of the population not at the level of individual components. We could thus expect a dynamical view of the cell as a hierarchical system of structural complexity. On the contrary, Church plans the synthesis of a minimal cell from bottom up. The cell is divided into biochemical subsystems for the unit operations (replication, transcription, and translation) and the aim is to define the sufficient components for each subsystem, then to integrate the subsystems. Although the authors acknowledge that the project would need the integration of decades of work in the reconstruction of DNA, RNA, and proteins from pure ingredients, it is a logical stepwise procedure from the simple to complex. Following a Cartesian model, in vitro synthetic biologists correctly divided the problem in as many elements as possible, and its resolution follows Condillac's precept – enthusiastically championed by Lavoisier – that to avoid error one needs always to proceed from the simple to the complex.

What is exactly the purpose of such an enterprise? The goal is to identify the necessary and sufficient conditions for living entities. The machine analogy is used to justify that life cannot be understood simply by looking at it and making a list of its parts. It has to be assembled from its parts. In this perspective Venter's and Church's projects belong to the same genre as Leduc's synthetic biology. They share the conviction that we understand only what we build, what is made from scratch by human art. As Church and Forster (2007, p. 5) put it:

> Until we can assemble a form of life *in vitro* from defined, functionally understood macromolecules and small molecules substrates, how can we say that we understand the secret of life?

Just as a mechanical machine should have no mystery for its designer, the machine of living cells will be understood when all its parts will be man-made and assembled. The ultimate aim of in vitro synthetic biology is to obtain replication without the cell. And the mystery of life will be eradicated only when all the parts of the machine will have been re-engineered, by alteration of the genome. Knowing is making and making is an analytical process from the simple to the complex.

In this respect the minimal cell project can be seen as a remake of Marcellin Berthelot's program exposed in *La chimie organique fondée sur la synthèse* in 1860. For Berthelot to synthesize living matter, it was sufficient to proceed methodically, starting from the building blocks – carbon, hydrogen, nitrogen, and oxygen – and proceeding step by step to binary compounds, then tertiary compounds such as alcohols, then to combine these compounds to make more complex compounds, and so on. With this grandiose plan in mind, Berthelot felt justified in claiming that synthesis "has eliminated the barrier between mineral and organic chemistry", and that "the chemical effects of life are exclusively due to chemical forces" (Berthelot 1876, p. 272).

Is it an old-fashioned and out-dated fight? In June 2007, one could read an editorial of the journal *Nature* entitled: "Synthetic biology provides a welcome antidote to chronic vitalism" (Anonymous 2007). The paper under this title argued that synthetic biology brought "a cultural benefit" as it demonstrated that "life is a molecular process lacking moral threshold at the level of the cell". It thus challenges a religious dogma about life and the "popular belief" that "life is something that appears when a clear threshold is crossed".

5. Conclusions

Three final remarks conclude this comparison of research programs at the borderline between chemistry and biology.

First, looking at nanotechnology and synthetic biology from a historical perspective shows a remarkable continuity despite the paradigm shifts that occurred in twentieth-century biology. It suggests that chemists and biologists are playing the same game with different balls between similar camps. The threshold between life and inanimate matter remains a matter of debate, which suggests that the cultural context is remarkably stable. Despite the post-modernist tendencies to blur all kinds of boundaries – between nature and technology, between men and machines – drawing a demarcation line apparently remains a hot issue worth of a page in *Nature*. Boundaries are robust even though the issues at stake are changing. Remarkably the notion of a threshold seems to revive the old battle between science and religion rather than a science war.[20] Defending disciplinary boundaries and identities seems less strategic than defending the empire of science against popular beliefs.

Second, the mirror image of two sub-disciplines walking across the firing line is not just superficial. Biomimetic chemists are trying to make life-like machines while synthetic biologists are making machine-like life. And it is clear that the symmetry effect rests on a common ground and a convergence of goals. Both communities share the conviction that knowing is making, that knowledge is acquired through synthesis. Moreover they converge in their common interest in self-assembly which they consider as the major issue in science for the next decades. On both sides the cognitive aims of understanding how living organisms work supersedes the practical purposes of making useful things. On both sides the ambition is to explain the origin of life. This paper thus suggests that the word 'technology' in the converging technologies program should not be understood as science for technological purposes. Rather it seems to be technology in the service of science and a science driven by great metaphysical ambitions.

Third, however, the convergence of metaphysical agendas should be distinguished from the metaphysical assumptions underlying scientific practices. Both biomimetic practices and synthetic biology lead to the clear recognition that the structures self-assembled in test-tubes will never be identical to natural living entities as they actually developed. However the distance does not have the same meaning. Even for biomimetic chemists with the ambition to shed light on the origin of life, mimicking life simply means self-organization of matter according to the laws that were responsible for the origin of life. But the origin of life remains a contingent event depending on unknown historical conditions. They assume that nature is not entirely rational and can neither be fully understood by science nor faithfully simulated by technology. By contrast the major assumption behind synthetic biology is that it is possible to decipher and rewrite the program of living cells, step by step in a laboratory. The distance between nature and artifact is only provisional, transitory in synthetic biology whereas it is becoming essential in biomimetic chemistry.

Notes

[1] For a more detailed view of chemistry as transgression of cultural frontiers see Bensaude-Vincent & Simon 2008, chap. 3.

[2] See Canguilhem 1947 and Monod 1971; on the history of synthetic biology, see Fox Keller 2002.

[3] Leduc 1910 and 1912. I am grateful to Pr. Jacques Livage who lent me his copies of Leduc's two volumes. The keen interest that a famous chemist, known as the founder of 'soft chemistry', developed in Leduc's writings provides a clue for link

here established between Leduc's exotic experiments and contemporary biomimetic chemistry.

[4] Leduc analyzed nutrition as a sequence of absorption of nutrients from the surrounding medium, chemical transformation of the nutrients, and fixation in every part of the organism (which he called intussusception), and ejection of the waste products in the environment.

[5] It is a two-dimension continuity. First in time, there was a gradual and insensible transition from inanimate matter to living organisms. The same forces applied to the same chemical elements generated rocks and mountains in geological times and later on, in living organisms. "The step between a stalagmite and a polyp is less than the step between a polyp and a man." (Leduc 1910, p. xiiv) Second, the continuity in space is due to the dependence of organisms upon their environment. "The living being and the medium in which it exists are mutually interdependent. The medium is in its turn dependent on its entourage and so on from medium to medium throughout the regions of infinite space". (*Ibid*., p. 6)

[6] For instance Geoffrey Ozin synthesized porous materials with all sorts of shapes. Not surprisingly he considers D'Arcy Thompson as the founder of the paradigm of biomimetics; see Ozin & Arsenault 2005, p. 10.

[7] In the latter case Emil Fischer is celebrated as the pioneer because he characterized the lock-and-key principle.

[8] Whitesides & Grzybowski 2002; Ozin & Arsenault 2005, p. 5.

[9] Cf. Jean-Pierre Sauvage's interview by Xavier Guchet and Sacha Loeve, May 17, 2006.

[10] He founded Celera Genomics for running a parallel version of the Human Genome Project for commercial purposes. He has been fired from this company when it turned out that the human genome could not be patented. Now his expectation is to commercialize artificial bacteria to reduce the dependence on fossil fuels. On the various aspects and future applications of synthetic biology and their societal impacts, see Balmer & Martin 2008.

[11] In 2007 Craig Venter was listed among the most influential hundred people by *Times Magazine*.

[12] *The Guardian*, October 6, 2007; accessed October 30, 2007.

[13] See, for instance, De Lorenzo & Danchin 2008.

[14] *Nature*, vol. 438, 24 November 2005, pp. 417-18; Foster & Church 2007.

[15] It is clear that the hype and rhetorical claims at making artificial life should not be taken literally. All scientists will understand that only the DNA is synthetic, since the artificial genome will have to be implanted into a living bacterial cell. It can generate a new life form only with the help of the complex interactions performed within the cell into which it has been implanted.

[16] See for instance Danchin 2009.

[17] The design of the site of the Registry for Standard Biological Parts full of Lego and cogwheels eloquently reveals the mechanical model of life underlying the project [http://parts.mit.edu/registry/index.php/Main_Page, accessed 30 October 2007].

[18] For instance Drew Endy from MIT Biological Engineering department, co-founder of the Biobricks Foundation, assumes that biological engineers can al-

ready, to some extent, program living organisms in the same way a computer scientist can program a computer [http://openwetware.org/wiki/User:Endy].

[19] O'Malley *et al*. 2007 distinguish three broad approaches: DNA-based device construction, genome-driven cell engineering; and protocell creation.

[20] A comparison of the current debates raised by synthetic biology with similar debates that took place in the 1970s over self-organization around Prigogine would be extremely interesting as it would reveal what was at stake, what is at stake now, and what becomes 'a hot issue'.

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