What is mimicked by biomimicry?

Synthetic cells as exemplifications of the three-fold biomimicry paradox

Abstract

This paper addresses three paradoxes of biomimicry. First of all: how can biomimicry be as old as technology as such and at the same time decidedly innovative and new? Secondly: how can biomimicry both entail a "naturalisation" of technology and a "technification" of nature? And finally: how can biomimicry be perceived as nature-friendly but at the same time (potentially at least) as a pervasive biotechnological assault on nature? Contemporary (techno-scientific) biomimicry, I will argue, aims to mimic nature on the level of bio-molecular processes and structures: contemporary biomimicry as micro-biomimicry. Moreover, building on Aristotle, Delbrück and Schrödinger, I will emphasise that what is mimicked by contemporary (techno-scientific) biomimicry, in contrast to *traditional* (artisanal) instances of biomimicry, is not the morphological *form* (εἶδος), but rather the program or *formula* (λόγος) of living systems. Contemporary biomimicry is "in accordance with nature", but not in the tradition sense. Rather, building on decades of biomolecular research, it strives to reconcile nature and technology against the backdrop of advanced technicity. But biomimetics will only achieve its goals if it is not pursued purely as a technological endeavour, but complemented by an ethos of sustainability and respect for nature. These claims will be elucidated with the help of two case studies: a research project (namely the BaSyC project, launched in 2017 and aimed at producing a synthetic cell) and a science novel (namely *Solar*, revolving around the epistemic and moral challenges involved in artificial photosynthesis).

Keywords: Biomimicry; Philosophy of biomimicry; Synthetic cell; Sustainable technologies; Aristotle; Erwin Schrödinger; Continental philosophy of science

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Introduction: biomimicry, three paradoxes

Biomimicry, also known as biomimetics (Schmidt, 1969), bio-inspiration (Forbes, 2005; Bonser, 2006) or homeotechnology (Sloterdijk, 2001), has been defined in various ways: as the design and production of materials, structures, and systems that are modelled on biological entities and processes,[1] as an approach to innovation that seeks sustainable solutions by emulating nature's time-tested patterns and strategies,[2] and as the imitation of the models, systems and elements of nature for the purpose of solving complex human challenges (Vincent et al 2006). While the label "biomimicry" became associated with Janine Benyus's *Biomimicry: Innovation inspired by Nature* (Benyus, 1997; Harman, 2013, Van Hout, 2014; Dicks, 2016; Blok & Gremmen, 2016), Otto Schmidt, a biomedical engineer who developed a device to mimic the electrical action of neurons, has been credited for coining the neologism "biomimetics" (Schmidt, 1969, Vincent et al, 2006).[3] While acknowledging the importance of Janine Benyus's elaboration of the biomimicry concept, which provides an important conceptual bench-mark, "biomimicry" will be regarded here as a broader (converging and evolving) term, with a long history and representing a whole discourse, a collective, deliberative endeavour, rather than as a concept that can be exclusively attributed to one author.

Whilst biomimicry is often presented as something innovative and new, there is a clear awareness in current biomimicry discourse that human technology has been inspired by nature for millennia (Benyus, 1997; Vincent et al, 2006, Dicks, 2017). Indeed, it may even be argued that biomimicry is as old as human technology itself. And this immediately points to a first paradox of the biomimicry concept. For how can biomimicry be a relatively recent phenomenon and at the same time boast such a respectable history? Contemporary biomimicry's newness, I will argue, is primarily a matter of precision and scale (cf. Sloterdijk, 2001). The moment of discontinuity resides in the fact that current biotechnologies aim to mimic nature on the level of bio-molecular

[1] https://en.oxforddictionaries.com/definition/biomimicry
[2] https://biomimicry.org/what-is-biomimicry/
[3] As indicated, the term homeotechnology, as an alternative version of the same concept, was coined by Peter Sloterdijk: "Eine nicht-herrische Form von Operativität [ist] im Entstehen, für die wir den Namen Homöotechnik vorschlagen... Materie hört auf zu sein was traditionell als Rohstoff bezeichnet zu werden pflegte" (Sloterdijk, 2001: 227).

processes and structures. Thus, although the idea of nature as a model or teacher for developing human artefacts (*artis natura magistra*) builds on a long history, the current wave of biomimetic technologies aims to learn from and comply with nature first and foremost on the biomolecular scale.

This implies however that, rather than emulating natural phenomena as they are encountered in the lifeworld of everyday existence (where artists and artisans for centuries have worked hard to mimic the visual or morphological *gestalt* of natural entities), current biomimicry rather aims to capture what Gaston Bachelard (1931, 1951) refers to as the *noumenal* (i.e. the biochemical or biomolecular) dimension of natural processes and entities.

This inevitably points to a second paradox, however, because in order to adequately mimic nature's miniscule, fine-grained, molecular circuits and structures, they first have to be revealed, disclosed and brought to the fore, – with the help of highly advanced precision technologies. In other words, what is mimicked by biomimicry is apparently not nature as such, but rather a profoundly technological enframing of natural processes and entities, building on a decidedly technological view of nature, a biotechnological laboratory view, under the sway of human-made technologies. In other words, in order to be able to mimic nature on the bio-molecular scale, nature must first be disclosed as something which is already profoundly technological (Heidegger 1953/1954; cf. Zwart, 2010, Blok & Gremmen, 2016; Zwier, 2018). Thus, biomimicry builds on a particular view of nature (*Naturbild*), perceiving nature as an immense, outdoors laboratory that can subsequently be emulated by tools and technologies developed in human-made laboratories. In order for nature to be copied and emulated by technology, it must first be enframed as or transformed into something decidedly technological: nature as envisioned by molecular engineers. This line of thinking will be more fully elaborated and verified below, notably in the context of the case studies. It raises the question whether and to what extent nature as such (nature as ***φύσις***) coincides with this profoundly technological view of nature, emerging under the sway of scientific technicity.

So far, we have explored the historical and ontological ambiguities of the biomimicry concept, but we may also approach it from an ethical perspective, focussing on the goals which biomimicry or biomimetics aims to achieve, the ideals by which the endeavour is inspired: nature as "mentor" (Benyus, 1997; Dicks, 2016). Seen from this perspective, biomimicry or biomimetics is a form of technoscience focussed on developing tools and materials that are more biocompatible and nature-like than previous technologies, thereby enabling us to interact with nature and natural systems in more intimate, sensitive, considerate and sustainable ways. Rather than seeing nature as a huge (but nonetheless finite) resource for raw materials (to by transformed into sophisticated products and devices by human technology), biomimetics aims to mimic and imitate the technologies nature herself has already produced in the course of evolution (Mann, 1997; Ball, 2001; Bensaude-Vincent, 2002, 2011; Bensaude-Vincent & Newman, 2007; Sanchez et al, 2005; Zwart, 2010). In other words: nature as a "mentor" who provides us with a "model" (Benyus, 1997; Baumeister, 2014; Dicks, 2016). The objective is to embed artificial (human-made) systems in natural systems in more considerate ways, by taking into account the fact that natural systems already display high levels of sophistication. In the course of evolution, nature has developed a plethora of techniques that can now be explored and imitated by contemporary technoscience: Ali-Baba's cave of solutions to functional problems of living systems, as Sanchez et al. (2005) phrase it. The ultimate goal is to reintegrate the technosphere into the biosphere. Whereas in the past the focus was on *mastering* nature, and on using technology to *overcome* natural restrictions, nature's "pool of ideas" now becomes a source of innovation and improvement for molecular technology itself (Ball, 2001). Notably, wasteful and disruptive systems of production may be mitigated or replaced by the more cyclical and sustainable dynamics of natural systems. Nature's inventions (proteins, enzymes, DNA, membranes, sensory mechanisms, etc.) can be used for energy production or information storage. The idea is that in the near future it will become increasingly possible to imitate characteristics of living materials such as self-repair, self-assembly and recyclability. And the ultimate challenge will be the creation of a synthetic cell: a bio-machine or bio-object that not only mimics the functioning of living cells, but is even able to reproduce itself (the proverbial Grail of synthetic biology).

This ambition, to produce more sustainable, nature-friendly and bio-compatible technologies, entails a third paradox, however. For biomimicry may at the same time raise the suspicion that a technological will to power, an obfuscated *will to control* nature is decidedly still at work here, albeit now focussing on the molecular level. Such a will to control seems evidently at work in the effort by Craig Venter and colleagues to implement (in a top-down fashion) a synthetic genome in a living cell, with the aim of demonstrating that the latter will subsequently be "controlled only by the synthetic chromosome" (Gibson et al, 2010; Hutchison et al, 2016). This would suggest that biomimetics actually may amount to a technification and exploitation of nature in an even more radical and pervasive sense (Calvert, 2010; Zwart, 2010).

This leaves us with three paradoxes or basic questions. First of all: how can biomimicry be as old as technology as such and at the same time decidedly innovative and new? Secondly: how can biomimicry both entail a "naturalisation" of technology and a "technification" of nature? And finally: how can biomimicry be perceived as nature-friendly, but at the same time as a pervasive biotechnological assault on nature (cf. Van Hout & Drenthen, 2017)? As Mathews (2011) argued, biomimicry is a promising concept, but "philosophically underdeveloped", so that "critical ambiguities lurk in it" (p. 364). Until these are brought to light and resolved, or at least addressed, biomimicry remains vulnerable, notably to co-optation by the very anthropocentric attitude that has ravaged the biosphere since the dawn of the Anthropocene. A "deeper *philosophy* of biomimicry" is needed (Mathews, 2011: 364).

In the following sections, this summons will be taken up by systematically addressing the three paradoxes listed above. Methodologically speaking, I will opt for a mixed methods approach, a combination of: (a) a philosophical *discourse analysis* of contemporary biomimicry discourse; (b) a *genealogical rereading* of the views of Aristotle and Schrödinger on technology and life; (c) a *case study analysis* concerning a recent exemplification of biomimicry in synthetic biology (namely the BaSyC project, devoted to building a synthetic cell); and (d) *literary case analysis* (a close philosophical reading of a science novel entitled *Solar*). First of all, I will elucidate the newness or discontinuity of current biomimicry with the help of a concise dialectical reconstruction of its history. Secondly, building on Aristotle and Erwin Schrödinger, I will emphasise that what is mimicked by *contemporary* (i.e. techno-scientific) biomimicry, in contrast to *traditional* (artisanal) biomimicry, is not the *form* (**εἶδος**) but rather the *formula* (**λόγος**) of living systems. Finally, I will argue that the power dimension of biomimicry (i.e. the attempt to control nature in a radically pervasive manner) can only be contained if the technological dimension of biomimicry is complemented by a concurrent transition on the ethical dimension as well, so that biomimicry as a technological form of responsiveness is complemented by an eco-oriented ethos (cf. Mathews, 2011; Blok, 2017).

A concise dialectical genealogy of biomimicry

From a dialectical perspective, three decisive moments can be discerned in the history of biomimicry. Initially, it seemed evident that, although humans (as *Mängelwesen*) depend on technology for their survival (with technology complementing our natural deficiencies or lack), technology, in order to function adequately, must at the same time be attuned to nature. For instance, as Aristotle argues in *Physics II*, instead of sleeping in the open air, human artisans produce artefacts such as bedsteads to allow furless humans to sleep safely and comfortably. But although a bedstead is natural insofar as it is made from natural materials (i.e. wood), the form (**εἶδος**) of the bed is artificial and the product of human intervention (Aristotle, 1980: 193a). At the same time, Aristotle acknowledges that artisans are only able to produce a proper bedstead insofar as they are sensitive and responsive to the natural materials they work with. Art imitates nature (1980: 194a) and human labour and craftsmanship is not only guided by knowledge of the proper form (the optimal shape and design of a bed), but by familiarity with the material as well (1980: 194b). Likewise, physicians will only be able to cure ailing human bodies insofar as they are sensitive and responsive to the inherent tendency of the human body itself to maintain and restore its own health. Indeed, the physician must be a servant of nature, a *minister naturae* (cf. Heidegger, 1967). Therefore, the art of medicine (i.e. artisanal medicine) is *natural* (i.e. in accordance with nature: ***κατα φυσιν***) rather than unnatural: it is a collaborative dialogue with nature. Nature is "observed" by human artisans (carpenters, physicians, sculptors, etc.) in the original sense of the Latin verb *observare*, which means: to *heed*, to *serve* and to *respect* nature (Zwart, 2017). This is the first moment (M_1) in the dialectical unfolding of technology. Although human artisans transform nature (transforming a tree into a bed for instance, or a piece of marble into a statue, or a forest into a cultivated field, or an ailing body into a healthy one), they must remain sensitive to nature as ***φύσις***: nature as that which emerges, comes forward on its own accord, that which has its own inherent principles of movement and change (Aristotle 1980: 192b).

Subsequently, however, systematic observation of nature inevitably results in a more thorough knowledge of natural systems (trees, human bodies, soils, etc.). Moreover, while actually working with natural entities, thereby deepening human knowledge concerning nature, an important *experience* emerges, namely that the inherent tendencies of natural systems may often diverge rather than coincide with the interests and desires of human beings. Therefore, increasingly, technology assumes a position of *negativity* vis-à-vis nature, so that human technologies increasingly *negate* rather than endorse the inherent tendencies of nature. And this gives rise to a situation of opposition rather than convergence between technology (***τέχνη***) and nature (***φύσις***). Technology becomes increasingly Faustian, i.e. bent on controlling and manipulating nature (as an adversary) rather than on merely modifying nature. Nature and technology collide rather than coincide, and human technology seems driven by a will to power over nature. Thus, technology becomes disruptive, bent on realising human domination over nature. Nature is distorted rather than supported by technology. Technology and nature become antithetical: the second moment (M_2) in the dialectical unfolding of technology. Sloterdijk (2001) refers to this anti-natural stance of modern technology as "allotechnology". Eventually, rather than respecting and acknowledging the inherent tendencies of nature, nature is reduced to a mere resource and regarded as raw materials or input for human technology and sophistication.

To the extent that human technology becomes increasingly successful in realising its desire to dominate and manipulate nature, however, it becomes increasingly disruptive and destructive as well. And this once again gives rise to an important *experience*, namely the experience of estrangement of humans from nature, of human forgetfulness of nature, as exemplified by various symptoms of crisis and disruption (ecological disasters, climate change, mass extinction and so forth), eventually resulting in a new challenge: how to contain the disruptiveness of our own technological interventions? How can nature and technology be reconciled again (on a higher level of sophistication)? How to negate or sublate the negativity of human technologies? This third moment (M_3, the *negation of the negation*, dialectically speaking), is currently unfolding and aims to interact with living nature (with trees, soils, human bodies and other living systems) in a more considerate and sophisticated manner ("homeotechnology", as Sloterdijk phrases it). Biomimetics or biomimicry seems a prefect exemplification of this drive towards sublation and reconciliation.

This analysis helps us to address the first question listed above, the one concerning the paradoxical newness of biomimetics. Biomimetics strives for what in psychoanalysis is known as *reparation*, i.e. the effort to restore a damaged world (Zwart, 2018). Contemporary biomimicry is radically different from ancient artisanal forms of sensitivity to living nature as articulated by Aristotle in *Physics II* (M_1, dialectically speaking) because it builds on the tools and insights that were developed during the second moment, the era of experimental scientific research and industrial production, resulting in disruption and estrangement (M_2). Thus, biomimicry's core objective entails a sublation ("Aufhebung") or reconciliation of the nature-technology-divide (M_3). But this preliminary answer still lacks sufficient specificity and precision. In the next section I will argue that, to answer the question concerning the newness of contemporary biomimicry (M_3), as compared to artisanal biomimicry (M_1), we should more explicitly focus on *what* exactly is mimicked by biomimicry. And in order to address this question, attention to *living beings* must be complemented with a focus on our way of *knowing* about them. Therefore, I will now shift attention from ontology to epistemology; and from *Physics II* to *De Anima*.

From ancient to contemporary biomimicry: from *form* to *formula*

According to Aristotle (1986), all entities are composites of form and matter. In the case of artefacts, humans actively *form* or *reform* natural matter, but in a way that remains sensitive to matter, as we have seen. From this perspective, biomimicry or biomimetics (both terms are combinations of ***βίος*** and ***μίμησις***) reflect the desire to *mimic* the *form* of *living* entities. And in the case of living entities, Aristotle argues, the soul (***ψυχή***) is the principle (***ἀρχή***) of life; it is the *form* (***εἶδος***) or *formula* (***λόγος***) of living beings (Aristotle 1986: 402a, 415b). All living beings are realisations or actualisations (***ἐντελέχεια***, 412a) of their formula or plan (***λόγος***: Aristotle 1986: 412b, 415b).[4] While plants grow and reproduce (thus realising their *vegetable* soul), animals also perceive and move (thereby realising the sensitive part of their soul), but it is only in humans that Aristotle discerns the presence of a thinking soul (***νοῦς***). And it is due to this thinking soul that humans are able to discern that living entities are indeed fusions of matter (***ὕλη***) and form (***εἶδος***), and realisations of their basic formula or plan (***λόγος***).

Although hylemorphism is well-known, it is important to point out that a basic ambiguity already seems at work here. For how exactly do we, thinking humans, consider living entities? On the one hand, Aristotle regards thinking as a continuation of visual perception in the sense that, whereas via eyesight we perceive the things as such (as compounds of matter and form), the human mind only assesses their form (***εἶδος***) stripped of matter, so that thinking is a more abstract version of sense perception. In other words, whereas perception focusses on external things (***πράγματα***), the soul reflects on their inner images (***φαντάσματα***). But Aristotle also suggests that the thinking soul focusses, not on the visual shape or *form* (***εἶδος***) of living beings, but rather on their plan or *formula* (***λόγος***). Seen from this perspective, Aristotle argues, thinking is more similar to considering letters (***γραμματείον***) before they are actually written down on tablets (430a). Remember that "logos" not only pertains to human beings (as rational animals), but is also the organising principle of nature as such: it is present at both sides of the equation as it were. This explains why we (as rational beings) are able to *read* the programs of nature: because nature is inherently logical. In other words, thinking (in the sense of mentally considering formula: a rational consideration of the inherent logic of nature) is comparable to reading or writing a text. The tension between these two versions of thinking, namely thinking as considering mental *images* (***φαντάσματα***) versus thinking as considering mental *characters* (***γράμματα***), corresponds with a similar ambiguity concerning the concept of form as such, because "form" may either be interpreted in a *visual*, morphological sense (***εἶδος***) or in the sense of the *formula* (***λόγος***): the plan that is realised in the actual living entity. In technical terms: what

[4] "The soul is the first principle (ἀ□□□), the realisation (ἐ□□□□□□□□□) of that which exists potentially: its essential formula (□□□□□)" (1986: 415b).

we attempt to mimic in our artefacts may either be the visual form (**εἶδος**) or the inherent logical plan (**λόγος**) which realises itself in this form.

This tension or difference, although not clearly spelled out by Aristotle, is important to emphasise, first of all because it corresponds with a basic distinction in contemporary philosophy between the *imaginary* (focussed on images or **φαντάσματα**) and the *symbolic* (focussed on symbols or **γράμματα**). Aristotle notices the difference of course, for instance when he explains that, when we see a beacon, we initially recognise it as fire (an entity with a particular, recognisable, visual form), until it begins to move, for then we realise that it actually is a signal which signifies something (for instance: the approach of the enemy). Thus, the distinction between fire as a natural gestalt (or *image*) and fire as a (conventional) human signal (a *symbol*, i.e. an element in an alphabet of signals, bearing a human signature) is recognised, but not further pursued by Aristotle.

Moreover, a second reason for drawing attention to this ambiguity is that it corresponds with an import shift which has taken place in the history of bioscience as such, in terms of the basic *focus* of research, namely a shift from the visual (**εἶδος**, morphology) to the symbolic (the plan, the program, the code, the **λόγος** of life). Whereas in the eighteenth and nineteenth century, biology was first and foremost morphology (oriented towards exploring the visual structure, the *gestalt* of living entities), as exemplified by the work of Goethe (1817/1824) for instance, contemporary biosciences focus rather on the codes, programs and circuits of living systems, on the symbolic or **λόγος** dimension.[5]

It is precisely for this reason that physicist Max Delbrück, the founding father of molecular biology, argued that, in retrospect, Aristotle should be credited for anticipating contemporary life sciences research, or, more precisely, for discovering "the principle implied in DNA" (Delbrück, 1973: 55; Mauron, 2011). According to Delbrück, molecular biology echoes Aristotelian conceptions, as is suggested by the title of his paper (*Aristotle-totle-totle*). Aristotle, Delbrück argues, anticipated DNA because he discerned that living beings are indeed composite creatures, composed of matter and form. Yet, for Delbrück, the term "form" clearly does not refer to the morphological gestalt of an organism (**εἶδος**), but rather to the basic programme or plan (**λόγος**) of the organism: the genotype (i.e. DNA) which gives rise to the phenotype (i.e. the

[5] Cf. "Whereas the comparative anatomy or morphology of animals and plants, based on collection, observation, comparison, and description, was the definitive technique for the classification of life forms during the classical period of natural history, it is molecular biology that today provides the primary analytic perspective on the essence of life and its defining mechanisms… What is considered to be "the stuff of life" in modern scientific terms [i.e. DNA, composed of nucleotide chains that guide the manufacture of essential proteins, that all living beings are now known to have in common] is today more similar to biochemistry than to zoology" (Franklin, 1995/2014: 1811).

visual form), the noumenal molecular program which gives rise to the living being as a visible, thriving phenomenon.

This understanding of living beings, namely as *realisations* of a molecular *program*, was already elaborated by physicist Erwin Schrödinger in his science classic *What is Life?* (1944/1976) – one of the grounding documents of contemporary bioscience. Life, Schrödinger argues, seems to be something highly exceptional, representing a diversion, an aberration compared to abiotic nature. For Schrödinger as a physicist, nature is under the sway of the entropy principle (unknown to Aristotle): the process of inevitable and relentless decay. Anything that is well-ordered and complex is transient and bound to return to dust, to dissipate into the inorganic mayhem of molecular debris. Against the backdrop of an entropic world, the question emerges how something as complex, sophisticated and intricate as a living organism (or even a living cell) is able to maintain itself (with inconceivable persistence) and even to reproduce itself. Life, for Schrödinger, is negative entropy. It is the ability to withstand the pervasive, disruptive natural tendency towards entropy. How is this possible?

For Schrödinger, the answer is that life (negative entropy) is possible because of the program (Aristotle's **λόγος**), more precisely: the "genom" (spelled without an *e* at the end by Schrödinger), an "aperiodic crystal" which carries a molecular Morse code (program) that allows living cells to keep themselves "in shape" and to maintain their astonishing complexity and homeostasis, and even to replicate themselves. This code consists of a strand of letter-like elements or characters (Aristotle's **γράμματα**) which *realises* itself in living organisms. Inspired by Schrödinger's vision (Zwart, 2013), Watson and Crick were indeed able to uncover the basic molecular structure of this code (the nucleotide alphabet: the **γράμματα** A, C, G and T). As realisations of their program, living cells function, maintain their homeostasis and replicate themselves. And it is because of this logical program that human beings, as *logical* animals (**ζῷον λόγον ἔχον**) are able to discern and read this intelligible **λόγος** pervading living nature, with the help of high-tech sequencing equipment.

Precisely this shift of focus from the morphological *gestalt* of an organism to its noumenal molecular *essence*, from the visual phenotype to the "logical" genotype, allows us to specify the newness or discontinuity of contemporary biomimicry, compared to more ancient or artisanal mimetic technologies (**κατα φυσιν**, in accordance with nature in the traditional sense: M_1). Contemporary biomimicry has *worked through* the whole dialectical endeavour. It builds on the second moment (M_2), on decades of bio-molecular and techno-scientific efforts to reduce living entities to their noumenal, symbolic, letter-like codes or programs, it builds on the *negativity* of technoscience: obliterating life, replacing living entities by bio-molecular barcodes (**γράμματα**), not only in order to understand life (making life transparent), but also to control and manipulate life. But now, as a third moment, this negativity of technoscience is itself negated or sublated by biomimicry as an effort to restore and retrieve the living whole (M_3): a dialectical turn away from twentieth century reductionism to post-millennial holism (albeit on a higher level of complexity and sophistication). The bio-molecular insights that were gained during the second moment (negativity, reductionism) are now used precisely in order to *reconcile* technology and nature once again, in order to *replace* manipulative and disruptive technologies by bio-compatible and nature-friendly ones.

A similar dialectics can be discerned on the level of scale. Traditional biomimicry (M_1) focusses on mimicking the whole, so that a cathedral, for instance, conveys the form, the idea (the ***εἶδος***) of a sacred grove, capturing it in stone. But contemporary biomimicry first of all tries to capture and mimic the basic molecular circuits of living systems, the noumenal programs, the basic logic (***λόγος***) of life (Zwart, 2012, 2016). Current biomimicry reflects the shift from the molar to the molecular (M_2), so that contemporary biomimicry becomes micro-biomimicry. It is a form of biomimicry made possible by the bio-molecular disclosure of the barcodes of life. But again, to become truly biomimetic, we somehow must recover the whole, carefully putting the fragments together again, so that technoscience may move way from and overcome reductionism (M_2) by mimicking the organic whole, but now on a higher level of complexity and sophistication. What is mimicked is not only the external form (on the organismal macro-scale), but also the elementary molecular components (on the molecular microscale): so that biomimicry evolves into a systemic synthesis of bio-molecular holism (M_3). Building on technoscientific experiences on the molecular level, biomimicry eventually aims to mimic complete ecosystems: cities functioning in ways that are modelled on how forests work, for instance, or corn fields which not only look like, but also function like prairies, or submarines designed in such a way that they glide through the oceans more or less like whales). After reductionism (i.e. the analysis of eco-systems in terms of bio-molecular processes and particles: M_2), molecular reductions and ecological holism become reconciled again (M_3): the culmination of a dialectical history of obliteration and informatisation, but at the same time a cusp or turn: towards a more holistic and sensitive interaction with nature. Ideally, precisely because we now understand nature not only on the phenomenal, but also on the noumenal (bio-molecular) level, this (in principle at least) could enable sensitivity to the bio-molecular specifics of multi-layered natural systems. I will now further elucidate this philosophical (dialectical) account by making it more concrete, with the help of two case studies.

Building a synthetic cell

My first case study is the BaSyC ("Building a Synthetic Cell") project, an 18.8 million Euro research project funded by the *Netherlands Organisation for Scientific Research* (NWO) and launched on September 1, 2017: a scientific effort to produce an autonomous, fully functional and self-reproducing cell.[6] The aim of the consortium (representing five Dutch universities and a NWO research laboratory) is to elucidate how a living cell (an astonishing feat of sustainable self-organisation by myriads of molecules) is possible.[7] The interdisciplinary consortium draws from various fields of expertise, including philosophy. Indeed, as the press release phrases it, the consortium does not "shy away from" addressing the philosophical quandaries entailed.[8] As the Consortium argues in its project proposal, building a synthetic cell is one of *the* grand scientific and intellectual challenges of the 21st century. While we have acquired extensive knowledge about the molecular building blocks of life, we do not understand how these building blocks collectively operate. Cellular life results from a plethora of highly controlled, dynamical processes of self-assembly and spatiotemporal self-organization, giving rise to autonomous or semi-autonomous entities that can interact, transfer information, reproduce and evolve. The idea is that we can only really understand life's complexity by actively reproducing it. The decisive question will be, however, to what extent a synthetic cell will really mimic a biological cell, both on the bio-molecular and on the cellular level. Or will the result rather be that technoscience is about to replace the living original by something artificial (and therefore more easily manageable and modifiable)? In the latter case, nature continues to represent "otherness", something that should be by-passed, rather than endorsed. How to tell the difference? In other words: what should be regarded as the decisive biological signature of living cells that should be captured by the technoscientific replica? Would a combination of metabolism and self-replication suffice?

That the synthetic cell (as exemplification of this dialectical unfolding) constitutes a relevant item for philosophical reflection on biomimicry, seems obvious. As indicated above, molecular biotechnology allows us to discern the noumenal, bio-molecular essence of living entities, thereby making living systems accessible for manipulation. But the only convincing proof that we, as logical animals, are really able to grasp and come to terms with life, is by mimicking and reassembling it again, in the form of a synthetic cell, representing a dialectical turn from

[6] www.basyc.nl
[7] https://www.nwo.nl/en/research-and-results/research-projects/i/45/29045.html
[8] http://www.ru.nl/english/news-agenda/news/vm/imm/organic-chemistry/2017/gravitation-grants-2017-artificial-cell/

analysis to synthesis, and from reductionism to regained holism (Zwart, 2018). We only know that we understand how a living cell functions if we can *realise* its program, but now *in vitro*. This line of reasoning is captured by Richard Feynman's famous idea that what we cannot create, we do not understand, although as Van den Belt (2009) convincingly argued, this adage echoes statements already made by eighteenth-centuries authors such as Giambattisto Vico ("verum et factum convertuntur"). If we can build a structure which mimics a natural cell, functioning like a cell and even replicating itself, life becomes technologically reproducible. If this is achieved, would technoscience be entitled to claim that it understands what life is?

While the scientists within the consortium primarily focus on the *adequacy* of the project (on optimising the *correspondence* between synthetic biological artefacts and living cells), the author of this paper (as an "embedded" philosopher) approaches the project from a slightly different angle, raising a different set of questions, such as: what is the mode of disclosure, the *Naturbild* on which this project relies? And although the synthetic cell has not been realised yet, it seems nonetheless possible to venture a prediction, building on the three paradoxes outlined above. In exploring these paradoxes we have argued that the newness of contemporary biomimetics (compared to previous forms) resides in the fact that it reflects a biomolecular view of nature, enabled by the technicity of contemporary technoscience. Is this technification of nature (as a condition of possibility for a thorough naturalisation of technology) discernible in the BaSyC project?

As a practicing, embedded philosopher, working in a Faculty of Science (surrounded by scientists and laboratories) and actively involved in the BaSyC project, it often strikes me that nature is not only *studied in* laboratories (in vitro), but also *represented as* a laboratory (Zwart, 2016; Zwart et al, 2015). In synthetic biology, nature *as such* emerges as an outdoors laboratory of immense complexity and proportions, where a plethora of interminable experiments are being conducted in vivo ("evolution"), while in man-made laboratories these natural experiments are continuously replicated and modified (in vitro). Rather than being a mere *metaphor* for nature, an ontological claim seems to be at stake here: nature really *is* a laboratory, from the viewpoint of contemporary technoscience. Or, as materials chemist Julian Vincent phrases it: nature constitutes "4 billion years' worth of R&D" (Vincent, 2001: p. 321; Blok & Gremmen, 2016: 205).

After deciphering the molecular codes and circuits of life, the human will to know (our *cupido sciendi*) still seems dissatisfied. The question of whether life has really become intelligible can only be addressed by means of a decisive experiment: the building of a synthetic cell. Not by reducing a bacterial genome or transferring a nucleus from one bacterium to another (Galperin, 2008; Hutchison et al, 2016), nor by merely inserting a synthetic genome into a living cell (*in vivo*), thereby turning cells into containers into which additional genetic modules can be inserted (Moya at al, 2009: 232), but rather in a bottom-up fashion, starting from the biomolecular building blocks (*in vitro*). More concretely, unlike Craig Venter's top-down approach (implementing a chemically synthesized genome into a living cell: Gibson et al, 2010), the BaSyC consortium aims to assemble life *de novo* in a test-tube environment. This, I would argue, would be biomimicry par excellence, reflecting the dialectical turn from biomolecular reductionism (M_2) to regained holism (M_3), from manipulation and control to imitation and emulation. For whereas top-down strategies aim to create a minimal genome by removing all nonessential parts, bottom-up strategies rather aim to create synthetic cells or protocells out of non-living matter, as systems with function in ways that are comparable to living cells. The idea is that, after having systematically dismantled living entities (M_2), we should now be able to put them together again, by synthesising a minimal cell, component by component (Deamer, 2005; Forster & Church, 2006; Pereto & Catala 2007). In this endeavour, the analytical and reductionist approaches of previous decades give way to (or rather: are "taken up" in) a holistic, synthetic turn (Moya et al, 2009: 225),[9] so that natural (Darwinian) evolution (a process of tinkering and improvisation) can give way to a more rational, engineering approach: self-directed evolution, thereby speeding up evolution to the extremely rapid rates of industrial innovation ("genetic engineering on steroids").[10] Moreover, in the synthetic cell discourse, the philosophical importance of such an endeavour is explicitly emphasised. Synthetic biologists such as George Church (Church & Regis, 2012) and Craig Venter (Venter, 2013), for instance, expect that the synthetic cell will put an end once and for all to "vitalism", i.e. the tendency to fill the parallax or gap between *synthetic* nature and *natural* nature, between in vitro and in vivo nature, between reproducible and real nature, and will allow us to eliminate all "pre-scientific" ruminations about vital sparks.

Dialectically speaking, the first moment of the dialectical process was the desire to understand the natural, visible, living organism as a whole; that which appears to us as a recognisable gestalt, something we can meaningfully relate to (M_1). In order to understand this living entity, however, we increasingly focussed on the noumenal, "symbolic" structures (representable with the help of chemical, genetic or other alphabetic symbols: the "literation" of life) so that, in molecular life sciences research, the living entity eventually became increasingly obliterated (Zwart, 2016). Scientists became interested in molecules rather than in organisms, resulting in an estrangement (M_2) from nature as we experience it in the everyday lifeworld. How

[9] "One of the main goals of synthetic biology is the synthesis of a living cell" (Moya et al, 2009: 230). The use here of the term "living cell" is controversial of course.

[10] http://www.sciencemag.org/careers/2012/01/genetic-engineering-steroids

to sublate the obliterating *negativity* of technoscience into something more holistic? From a dialectical perspective, the synthetic cell would be a negation of the negation: the return of the whole, but now in a fully intelligible and transparent way, *in vitro*, and on a higher level of precision and sophistication (M_3). The building of a synthetic cell would indicate that we finally *know* what life is, that nature and technoscience finally converge, and that our molecular knowledge finally corresponds with the living thing as such (*adaequatio rei et intellectus*). Or have we *missed* something? A synthetic cell will probably never *completely* mimic a living cell, will rather amount to a simplified version, but how big will be the gap be, between the *in vitro* artefact and the living thing? Only the production of a convincing replica of a living cell can give the answer.

But again: in order to achieve this adequacy, that is, in order to produce an adequate and convincing replica of a living cell, life has to be revealed, has to appear before us *in a certain manner*. In Heideggerian terms, *adaequatio* presupposes that we disclose nature in a certain way, through a revelatory moment of disclosure: **ἀλήθεια**. And Heidegger (1953/1954) became increasingly aware of the disclosing power of technology, forcing nature to reveal itself in a particular manner. The production of a convincing synthetic cell presupposes that the natural world is brought to the fore in a technical manner, namely as a laboratory of immense proportions, as we have seen. Biomimicry (exemplified by the objective to build a synthetic cell which convincingly mimics a biological cell) presupposes a particular *view* of nature, a particular *Naturbild*, namely nature-as-a-laboratory. What is mimicked by the synthetic cell is not the natural cell as a gestalt, for visual similarity is irrelevant here. The synthetic cell will not necessarily *look like* a natural cell, but should effectively *function* like a cell. What is mimicked (i.e. realised in vitro) is not the visible *form* (**εἶδος**), but the program or *formula* (**λόγος**) of a cell. This raises the question whether we will really find our way back from bio-molecular reductionism (M_2) to the whole thing, the target of our will to know: the living cell as a synthesis of program, form and matter (M_3)? Or will the BaSyC project rather become trapped midway, in the form of a partial reconstruction? Such an outcome would reflect that the project was technologically biased and constricted form the very outset. The technological preconception would be explicated by the product. By highlighting certain aspects of living cells and obfuscating others, a partial reconstruction will partly reveal, but at the same time obscure what living cells really are.

What about the third question or paradox, namely that the profile of biomimicry can be depicted in terms of nature-friendliness and biocompatibility, but also in terms of pervasiveness and manipulation? In the synthetic cell discourse, the societal dimension is explicitly emphasised. A synthetic cell would be a decisive step, it is argued, to develop more sustainable, bio-compatible products and systems of production. A plethora of bio-chemicals and pharmaceuticals will become quickly and easily available, for instance. Synthesised cells may clean up pollution, break down toxins, generate self-cleaning materials and provide clean energy, but they may also be used as biosensors or as artificial anticancer microbes (Russ, 2008). A synthetic cell would be a minimal streamlined organism that can be easily reprogrammed and redesigned, an easily modifiable laboratory tool, producible in assembly-line fashion and easily put to use for the assembly-line production of anything we like: plastic polymers, biofuels, pharmaceuticals or food ingredients (Church & Regis, 2012). Via synthetic cells, industrial production can be transported into biological cells so that, eventually, bio-products can be 3D-printed on demand, turning synthetic biology into a sub-branch of industrial engineering (Delgado & Porcar, 2013).

Now the question is, what is driving this process: the desire (emerging in the face of the current global environmental crisis) to make human existence more sustainable; or rather a will to power and control? Are we making technology more natural; or nature more artificial (Simons, 2016)? In the latter case, biomimicry becomes eclipsed by "techno-mimicry" (Bensaude-Vincent, 2001), so that, rather than making technology more natural, living beings are re-engineered into streamlined, reprogrammable pseudo-organisms, behaving more like technological than like natural systems: industrial tools, semi-alive, without an identity of their own, but easily controllable, re-fashionable and technically reproducible (Church & Regis, 2012). Or should we rather accept that the logical term "or" is out of place here, because the most credible answer to this this type of question is "both"? From an ethical point of view, the profile of the BaSyC project is ambivalent. It oscillates between the desire to learn from nature and the desire to technologically control nature. In order to convincingly steer the project in a genuinely biomimetic direction of eco-compatible sustainability and responsiveness, the techno-scientific dimension should be complemented by a turn towards an eco-oriented ethos. In other words, besides developing the necessary biomolecular technologies, the BaSyC project should also foster a basic attitude of responsiveness to nature. Before addressing this more fully, however, I will discuss my second case history.

Case history 2: *Solar*

The science novel *Solar* (McEwan, 2010/2011) tells the story of a fictitious Nobel laureate named Michael Beard, a science celebrity who, as a young theoretical quantum physicist, building on the photovoltaic work of Albert Einstein and others, made his name with the so-called Beard-Einstein Conflation: a quantum explanation for the emission of electrons, suggesting new ways of harvesting energy from sunlight. But all that is long ago and Beard has now entered the emerging field of "Big" applied solar energy research, attracting large amounts of funding as CEO of the newly established *National Centre for Renewable Energy*. The idea is to use quantum photovoltaics for optimising solar energy, as a key contribution to mitigating global climate change. But from the very beginning it is clear that Beard no longer is the devoted young researcher he once was. Rather, he has evolved into a spoiled, egocentric and obese opportunist who spends his time on public lectures and invitational travels to privileged places, ranging from Italian lakes to Spitsbergen.

After the accidental death of a promising and multi-talented post-doc named Tom Aldous, however, he comes into possession of the latter's notes, explaining (in abstruse mathematical equations) how nano-scientists may understand and effectively mimic the ways of plant leafs ("natural solar panels", McEwan, 2010/2011: 234), using sunlight to produce biomaterials and oxygen. Beard decides to decipher Aldous's legacy and to present the latter's ideas as his own, translating his notes into useful applications on an industrial scale. He mobilises ample funding for building a prototype solar energy plant (the LAPP: the *Lordsburg Artificial Photosynthesis Plant*) near Silver City, New Mexico, while filing a series of promising patents for personal gain. When he is about to proudly present his project to the world, as a "world-historical event" (McEwan, 2010/2011: 361), however, a lawyer pays him a visit, claiming to represent a client who, apparently in position of a copy of Aldous's original files, accuses him of theft of intellectual property.

Quite convincingly, I would argue, *Solar* depicts artificial photosynthesis as an area of converging research in the intermediate zone between nano-technology, photovoltaics and climate politics, and as a sub-field of biomimicry (Zwart, 2017). The epistemological backdrop of the narrative is a transformation that is actually taking place in laboratories world-wide, where biotechnology is evolving into copy-pasting nature on the molecular scale (Church & Regis, 2012; cf. Zwart et al, 2015). As Beard phrases it, artificial photosynthesis is about "copying the ways of plants, perfected by evolution during three billion years" (McEwan, 2010/2011: 142). In principle, the biomimetic turn entails a positive ambition, as we have seen. The aim is to develop technologies which, while highly advanced, are much more sustainable and nature-friendly than the technologies which humankind has managed to produce so far. Indeed, artificial photosynthesis basically aims to see plant leafs as biological factories from which human technology still has a lot to learn in terms of efficiency, sustainability and circularity. Nature is the paradigm, the teacher (*natura artis magistra*) for molecular life scientists and bioengineers, notably on the quantum or nano-scale.

This transformation, presented in *Solar* as an emerging scientific-industrial "revolution" (McEwan, 2010/2011: 36, 211, 336); as a "new chapter in the history of industrial civilisation" (McEwan, 2010/2011: 293) is quite credibly reflected in the novel, and it is clear that Ian McEwan has conducted a considerable amount of preparatory research.[11] Although Beard is said to hold "an irrational prejudice against physicists who defected to biology, Schrödinger, Crick and the like" (McEwan, 2010/2011: 121), he basically follows in their footsteps, moving from "pure" quantum physics[12] to "applied" molecular life sciences research.

At the same time, there is a lot of investment, prestige and politics involved in Big Science endeavours so that artificial photosynthesis (as a subfield of biomimetics) runs the risk of becoming tainted by privatisation, commercialisation and politicisation. And indeed, the most dramatic discontinuity in Beard's career is not the shift from basic physics (studying photons and electrons) to biomimetics, but from original research to big science management. As a result of this shift, Beard increasingly neglects and loses contact with genuine research, now performing on a completely different podium, basically working for the "plutocrats" (McEwan, 2010/2011: 211): for funding agencies, investors, venture capitalists, managers, international policy makers, the international media and the like, by giving lectures to non-physicists and joining artistic elite expeditions. Superficially, there still seems to be some continuity in his life, insofar as his work relates to electron physics, the science of his youth, but "that was when he was a scientist, and now he was a bureaucrat and never thought about electrons", at least not any longer in a scientific sense (McEwan, 2010/2011: 57). He travels as a VIP, occupying expensive airplane seats payed for by others, addresses conferences attended by institutional investors and pension-fund managers for "unnaturally large" fees (McEwan, 2010/2011: 154), and is even paid for "contractual mingling" with the audience, while owning a dozen or so serious patents. All this fuels his megalomania and narcissism, but it also increasingly estranges him from his original scientific inspiration, from his scientific past. He deteriorates physically, as an "overweight", "dysmorphic", "pink mess" of "human blubber" (McEwan, 2010/2011: 7), but also morally, falling victim to a chronic state of "restless boredom" (McEwan, 2010/2011: 67), becoming increasingly cynical and "anhedonic" (McEwan, 2010/2011: 3), with plagiarism as merely one symptom of overall moral decay.

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[11] In an appendix, the expert advice and input from Graeme Mitchison of the *Centre for Quantum Computation*, Cambridge, is explicitly acknowledged, notably for his guidance concerning the physics and mathematics discussed in the novel (McEwan 2010/2011: 389).

[12] Claims made by Beard such as "Let the philosophers of science delude themselves to the contrary, physics was free of human taint (McEwan, 2010/2011: 11)" refer to this *pure* version of physics: the type of research conducted by researchers such as Paul Dirac, "a man entirely claimed by science, bereft of small talk and other human skills" (p. 34); an irrevocably lost world, perhaps. Still, although Beard himself becomes morally tainted during the process, the basic idea is that the world as a whole, polluted by fossil fuels, will be "cleansed" by his photovoltaics (p. 159).

How to analyse this story in terms of the three paradoxes outlined above? As to the first paradox: the newness of artificial photosynthesis resides in the fact that it builds on technicity, on quantum physics and photovoltaics. Thus, contrary to more artisanal and traditional forms of sustainability and circularity, the technicity of contemporary technoscience allows us to learn from nature and mimic nature on the molecular or even quantum level. Although Beard at a certain point joins an elite expedition to Spitsbergen to discuss climate change, he does not seem interested in nature (as a landscape, as a vulnerable unique ecosystem, etc.) at all. His liaison with nature revolves around his obsession with electrons. And he approaches nature from a decidedly technological perspective. Thus, his "naturalisation" of technology decidedly builds on a "technification" of nature (the second paradox outlined above).

The novel also addresses the third paradox, however, the normative one, namely by contrasting Beard's rhetoric of sustainability and mitigating climate change with moral depravity and self-estrangement on the personal level. The project eventually falters, not because of technical shortcomings, but because of a basic moral deficit, of which plagiarism (copy-pasting a post-doc's file) is merely a symptom (Zwart, 2017).

Thus, the morale of McEwan's story is that, to realise biomimicry and sustainability, technicity alone will not suffice. Besides biomolecular technologies, biomimicry also requires a complementary ethos. This morale, I would argue, concurs with the view of Blok (2017) and others that biomimicry will not work if it is merely regarded as a bio-technological fix, as happens in *Solar*. A biomimetic *ethos* must inform the socio-technological system in which sustainable technologies have to be embedded (Mathews, this issue; Blok & Gremmen, 2016). This lesson, taken from the second case (*Solar*), has broader implications for biomimicry as such, including my first case study, the BaSyC project. So far, my analysis initially focussed on the thing (i.e. the synthetic cell) as such, but cells (even synthetic ones) require an ecosystem, an environment: not only in the biological and chemical sense of the term, but also in the societal and cultural sense. In a Faustian environment, bent on controlling and exploiting nature, synthetic cells will easily evolve into instruments of radical manipulation, regardless of the intentions of the scientists who created it. In order for biomimicry to work, the development of the techno-scientific *thing* (of the artefact, the synthetic cell as such) will not suffice. In isolation, it will prove a fragile entity. Attention should also be given to ethos, to the socio-cultural environment in which it will become embedded. A purely technological attitude might turn biomimicry into an even more pervasive form of nature exploitation than previous (Faustian) assaults on the natural environment and would therefore aggravate the problem instead of helping us to address the anthropocenic challenge.

Conclusion

This paper addresses three paradoxes or basic questions concerning biomimicry. How can biomimicry exist since time immemorial *and* at the same time be decidedly innovative and new? How can biomimicry be a greening (a "naturalisation") of technology *and* at the same time entail a massive "technification" of nature? And finally, how can biomimicry be both nature-friendly and biocompatible *and* manipulative and pervasive?

The first question was addressed by arguing that biomimetics is not focussed on mimicking the visible, morphological *form* (**εἶδος**) of the biological object, but on the program or formula (***λόγος***). Should the project to build a synthetic cell be successful, for instance, its envisioned product may not look like a biological cell at all. Regardless of whether a synthetic cell actually acquires the form of a sphere, a dodecahedron or a cube, it is the molecular formula that counts. Likewise, in the case of artificial photosynthesis, a biomimetic solar panel may not look like a biological plant leaf at all. Quite likely, its shape and appearance will be rectangular, blue-coloured, etc. What is mimicked by an artificial plant leaf is the program or formula, the basic molecular logic. Biomimetics, in the contemporary, techno-scientific sense of the term, is symbolic rather than eidetic. Therefore, biomimetic bio-objects may perhaps mimic natural entities in a functional sense, but this does not mean that they can replace nature as a phenomenal ambiance, for instance in terms of esthetical experiences. Nature cannot be reduced to the technological view of nature at work in contemporary technoscience, not even if technoscience becomes biomimetic. The very idea of a molecular programme already entails the idea of life as something which, in principle, is technologically reproducible, but what is mimicked in biomimicry is not the esthetical, but rather the functional dimension of cells, organisms and ecosystems. Therefore, a parallax or gap is bound to reappear between artificially reproduced, biomimetic nature (synthetic cells, artificial plant leafs, etc.) and real nature out there, which continues to emerge in the folds and margins of biomimetic nature as a recalcitrant "something" which somehow has been overlooked.

In other words, real nature will never completely coincide with the laboratory view of nature of contemporary technoscience, and the "otherness" of nature will never be completely overcome or captured. Rather, biomimicry constitutes an interminable endeavour. Even successful efforts to mimic nature will experience that there is something else to explore which so far has been outside our scope, but which would not have come into view without the biomimetic experience. Therefore, biomimicry is learning by doing, "poetic" research in the etymological sense of the term, for it is by trying to mimic nature, even on the bio-molecular level, that new avenues for experience will be opened-up. The building of a synthetic cell is not mere application of knowledge (engineering), but rather an experiment dedicated to exploring our blind spots: the aspects of living systems which were missed (or only experienced in a negative way, as recalcitrance) by the reductionist and disruptive approaches of the past.

Last but not least, biomimetics will not work if pursued as a purely technological endeavour, a biotechnological fix (Van Hout & Drenthen, 2017; Blok, this issue). Rather it should be complemented by an ethos of sustainability and respect for nature. Beard embodies and personifies an ethos of consumption, exploitation and mastery (regardless of whether the target of exploitation is nature or a team of post-docs). As Mathews (2011) has already argued, if this moral ambiguity is not addressed on the level of mind-set, biomimicry might simply come to mean that solar cities (equipped with artificial photosynthesis plants) take the place of forests, while industrial plants (equipped with devices to purify and reticulate water) take the place of wetlands (Mathews, 2011: 382). In that case, rather than realising a basic reconciliation between technology and nature, the latter would be eclipsed and absorbed by the former. A biomimetic emulation of nature's time-tested patterns in the purely technological sense will not be sustainable by definition, as Mead and Jeanrenaud (2017) convincingly argue, but must be supported by an ethics and politics of sustainability as well: by a sustainable, nature-friendly and eco-centric socio-cultural eco-system. Without a supportive ecosystem, the synthetic cell remains a fragile thing, vulnerable to exploitation. This also applies to artificial leafs and synthetic cells: besides developing high-tech *biophysical* scientific knowledge, the *metaphysical* and *ethical* dimensions must be explicitly addressed.

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