Potentials and Trends in Biomimetics

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1st Edition. 2010. Buch. vii, 197 S. Hardcover
ISBN 978 3 642 05245 3
Format (B x L): 19,3 x 26 cm
Gewicht: 635 g

2 TRENDS IN BIOMIMETICS

»Who has not been used to this world from early childhood would go mad over it. The miracle of a simple tree would destroy him.«

CHRISTIAN MORGENSTERN, 1871–1914

2 TRENDS IN BIOMIMETICS

»Biomimetics« and »learning from nature«

A precise determination of the subject area of this study is anything but trivial. We are working within a narrow understanding of biomimetics and thus concentrating on the research, development, and actors that make direct reference to terms such as *biomimetics* and *bionics*. This viewpoint is then complemented by examinatining broader fields of biomimetics research and development in which these terms do not appear at all or only rarely, but in which a clear, recognizable focus on the role model of nature predominates, or in which an effort is made to find solutions to technical problems – in the broadest sense – by learning from nature. This report concentrates initially on this first area of *biomimetics in the narrower sense*. In the third chapter, with a view to potential technologies, the scope of the investigation is widend to include more general approaches to learning from nature *(biomimetics in a broader sense)*.

2.1 Definition

In the course of the already several-decades-long ongoing debate on the terms *biomimetics* and *bionics* (*Bionik* in German) and the underlying concept of "learning from nature" a number of definitions have been proposed. A selection can be found in Table 1. The listing is in chronological order beginning with the often-cited "first" definition by J. E. Steele from 1960.

History of the terms »biomimetics« and »bionics«

The definitions presented here convey an impression of the difficulties associated with an attempt to pin down the supposedly simple phrase "learning from nature." Problematic is the question of the form and quality this "learning from nature" model has or should have. The definitions suggested range from simple inspiration to the most exact copy possible. At the same time the specific purpose of the learning is a controversial issue which ranges from form-function relationships to systemic (organisational) relationships and from ontogenetic/phylogenetic development processes to the derivation of general guiding principles that can direct technological development.

Definitions are important in order to know what we are talking about. Definitions therefore have a double function: they serve to specify but also to delineate the division between biomimetics and non-biomimetics. Thus it is little surprising that in the biomimetics community controversial debates about such delineations are taking place. The result is that it is not

Table 1 — Definitions of biomimetics and bionics from the literature (authors' own compilation)

No.	Author / year	Definition	Source
1	J. E. Steele / 1958–60	"It [bionics] explores systems whose functions are modeled on natural systems, or whose properties resemble those of natural systems, or are analogous to them."	Gérardin (1972, 11)
2	J. E. Steele / 1958–60	"[the] science of systems that work like or in the same manner as or in a similar manner to living systems"	Forth/Schewitzer (1976, 62)
3	L. P. Kraismer / 1967 [initial publication 1962]	"Bionics is thus the science that investigates biological processes and methods with the goal of applying the results to the improvement of older and the creation of newer machines and systems. One could also say that it is the science of systems demonstrating features similar to those of living organisms."	Kraismer (1967, 12)
4	H. Heynert / 1976	"With respect to the present state of development, bionics can be viewed as one of the applied disciplines in the biological sciences with a tendency to integration induced by its objectives, which has as its content the systematic study of life forms for the solution of technical, technological, and architectonic problems; whereby structures and processes serve in their functional relationship in the systems of organisms as a stimulus and pattern, particularly as models for constructions and processes in the various branches of industry and engineering."	Heynert (1976, 37)

→ continuation next page

No.	Author / year	Definition	Source
5	E. Forth & E. Schewitzer / 1976	"Bionics: scientific field of integration, with a technically driven problem focus of heterogeneous scientific disciplines. Their scientific matter is characterized by findings that are acquired from *biological objects,* that embody principles superior to previous technology, and that can lead to a *technical utilisation;* thus / therefore it brings together various disciplines for the solution of specific technical tasks of a varying nature and changing priorities and taps into new types of technical problem-solving approaches." *	Forth / Schewitzer (1976, 58)
6	A. I. Berg / n.d. (possibly 1976 or earlier)	"The task of bionics is to investigate biological objects with the goal of modernizing present technical systems or creating new and more accomplished ones and using the results."	Greguss (1988, 5)
7	E. W. Zerbst / 1987	"In general, bionics can be described by three different groups of definition: (1) It is a science for the planning and constructing of systems whose functions emulate those of biological systems. (2) It is a science for the planning and constructing of systems exhibiting characteristic features of biological systems. (3) It is a science for the planning and constructing of organisational structures that emulate the interrelations of patterns of biological organisation."	Zerbst (1987, 27)
8	VDI-TZ / 1993 **	"Bionics as a scientific discipline looks systematically at the technical conversion and application of constructions, processes, and principles of development in biological systems."	VDI (1993, 10)

* Italics in original; boldface omitted

No.	Author / year	Definition	Source
9	W. Nachtigall / 2002	*The definition from VDI-TZ/1993 (see No. 8) with the following addition:* "Bionics also includes aspects of the interplay of animate and inanimate parts and systems as well as the scientific-technical employment of biological organisation criteria."	Nachtigall (2002, 3)
10	T. Rossmann & C. Tropea / 2005	"Bionics = learning from nature to improve technology"	Rossmann / Tropea (2005a, VII)
11	J. F. V. Vincent et al. / 2006	"Biomimetics (which we here mean to be synonymous with 'biomimesis,' 'biomimicry,' 'bionics,' 'biognosis,' 'biologically inspired design,' and similar words and phrases implying copying or adaptation or derivation from biology) is thus a relatively young study embracing the practical use of mechanisms and functions of biological science in engineering, design, chemistry, electronics, and so on."	J. F. V. Vincent et al. (2006, 471)
12	Y. Bar-Cohen / 2006	"*Bionics* as the term for the field of study involving copying, imitating, and learning from biology ... *Biomimetics* … [the] term itself is derived from *bios*, meaning life, and *mimesis*, meaning to imitate. This new science represents the study and imitation of nature's methods, designs, and processes. While some of its basic configurations and designs can be copied, many ideas from nature are best adapted when they serve as inspiration for human-made capabilities." [italics in original]	Bar-Cohen (2006, 2)

** The VDI Technology Center in Düsseldorf held a workshop on biomimetics in 1993, at which a dozen of known German experts in the biomimetics community of the time agreed upon a definition of biomimetics.

possible for biomimetics to be defined by any one individual; it will need to gradually crystallize along the course of further developments within the field in order to finally be accepted by a broad majority. Presently, biomimetics still (or perhaps once more) appears to be in a phase of development in which various definitions co-exist.

It is against this background that our own proposed definition must be viewed:

Definition of the term »biomimetics« within the scope of this study

> *Biomimetics is the attempt to learn from nature; it deals with the development of innovations on the basis of investigation of natural, evolutionarily optimized biological structures, functions, processes, and systems.*

Within the biomimetics community it became clear that even this definition is not quite adequate for the task of specification and delimitation. Elementary to every definition is, in our opinion, a composition of the three elements that are essential in characterizing biomimetics today: (1) new (technical) possibilities for (2) innovations solving societal problems and/or fulfilling demands and (3) "learning from living nature," or more precisely: learning, in the broadest sense, from "biological research."

Elements of the definition

Of great importance is therefore the linking of (new) (technological) options with society's problems and needs. Such matching up of possibilities and goals is constitutive for the definition of technology (as the link between means and goals) as well as for innovation (i.e., successful change that fulfills a need). It is a matter of technology and innovation. Biomimetics, specifically, is the source or well-spring at which new (technical) possibilities and solutions are being sought. This source lies less and less in the "direct" observation of nature; it is the biological sciences that deal with the phenomena of animate nature, i.e. the investigation of natural, evolutionarily optimized biological structures, functions, processes, and systems are increasingly serving as a source for innovation.

The definition against the background of present development dynamics

The problem with exact definitions of biomimetics is due in part to the currently rapid rate of dynamic change in the field, as well as the ongoing inclusion of fields in which comparable biomimetics approaches – though not labeled as such – are being pursued, as well as the increasing expansion of biomimetics into neighboring fields of technology and, above all, nanotechnology.

The definition proposed serves as a starting point for the further efforts to describe and circumscribe biomimetics that follows. Thus we shall attempt with the help of the subsequently outlined *three strands of biomimetics development and three levels of learning from nature,* to converge on a conclusive and, above all workable understanding of biomimetics. In connection with the remarks that follow on the relationship of biomimetics and sustainability (the biomimetic promise), our goal is to arrive at a comprehensive as well as reasonably consistent view of the field of biomimetics. In this context, work on a joint guiding principle or mission statement for biomimetic research will soon become much more important than efforts to find a sufficient definition.

2.2 The three main strands of development in biomimetics

Greatly simplified, biomimetics development to date can be represented as three successive strands of development in which each following strand has overcome substantial restrictions of its predecessors.

Three main strands of bionics development

Functional morphology – form and function

The first and oldest of these three strands of development focuses on the relationship between biological forms or structures and their functions. The origins are already to be found in pre-scientific observations of nature, which often served as stimuli for technical solutions. Among the most successful innovations in this strand to date are the parachute, the lift-generating aircraft wing, the streamline form and the hook-and-loop fastener (Velcro®).

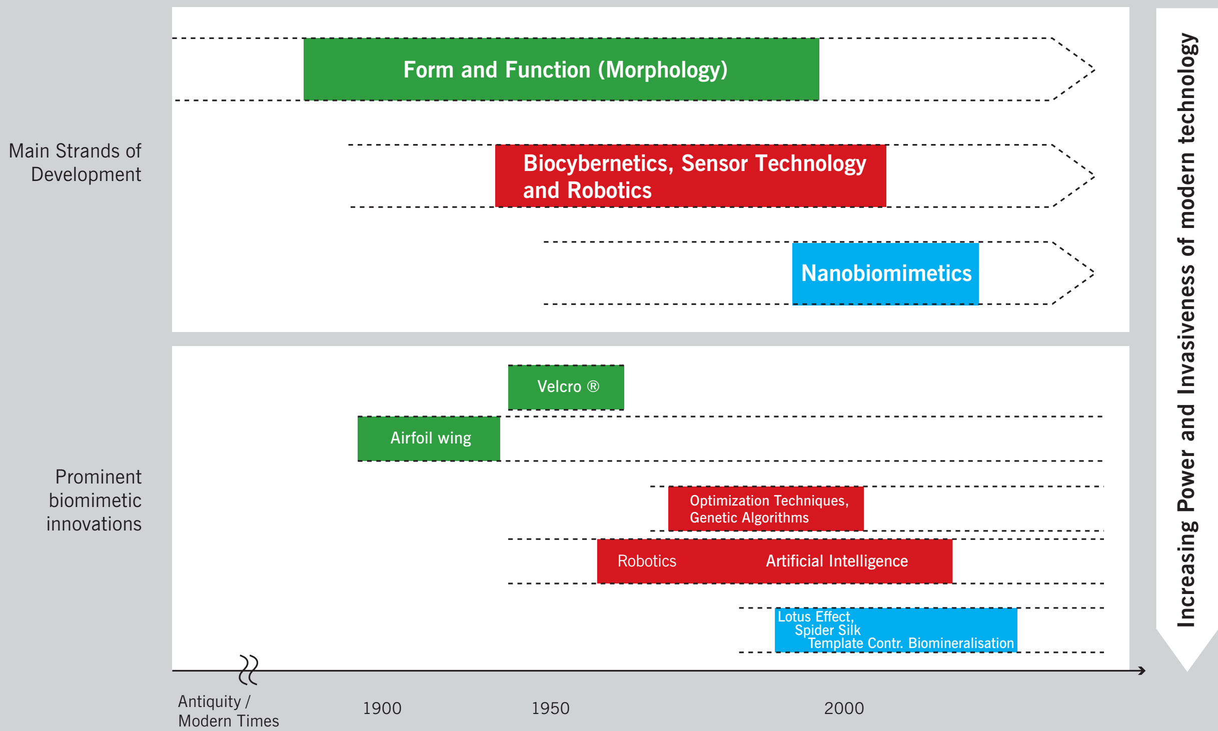
First and oldest strand of development: aircraft wings, parachute, hook-and-loop fastener

As long as scientific observations of nature remained in the macroscopic realm, technical implementations within this dimension were able to succeed using the techniques that were thus available; this worked especially well when the desired function was more closely related to its form and less so to the form-giving material. For the lift function of an aircraft wing it is its form, above all, that is decisive. Its technical realisation in a non-biological material does not change that. It is interesting that many of the examples of success in this form-function strand of development derive from the field of fluid dynamics, which leads to a second condition necessary for success. Part of the success of biomimetics in the area of fluid dynamics is due to the fact that the biomimetic approach was capable of compensating for the limitations of mathematical experimental physics. Neither the analytic nor the newer numerical models of fluid mechanics were capable of making calculations or predictions precisely enough to be able to work out optimisations on the board. In the end it was necessary to carry out an empirical experimental trial optimisation process in the fluid-dynamics test chamber (wind tunnel) – and in such trials biological evolution has an enormous lead. As research moves deeper into the relationship between structure and form – from the macroscopic to the microscopic and onto the nano-realm – the more difficult technical implementation problems or "manufacturing

Form-function dependencies

Production-related problems of implementation

Figure 0 — The three main strands of development in biomimetics



[Source: authors' own diagram]

issues" become. They are among the most significant restrictions today on far-reaching innovation within this field. Highly interesting discoveries for example, in the areas of structured surfaces and functionalized interfaces in biological systems (such as shark skin/riblet film, the lotus effect and anti-fouling) have not yet been technically implemented into production, so that the quality of its results achieved would be comparable to the corresponding natural sources of inspiration. In these examples, it is the quality of the technical realisation that is decisive for the desired functionality and thus for the success of the innovation.

Example lotus leaf

If we take, for example, products on the market today that try to technically implement the surface of the lotus leaf and examine them closely with a scanning electron microscope, it is clear that the technically realized surface is still far from that which could function in the manner of the lotus leaf. Decisive characteristics such as the hierarchical structuring of the papillae and their fine coating of wax crystals have not yet been achieved.

Transformation of the production paradigm

This is likewise true for the hierarchically structured biological materials such as bone, tooth, nacre, and spider silk that are increasingly a focus of biomimetic research. To manufacture such materials or products a fundamental change in our production paradigm is unavoidable. The two previously commanding paradigms of material processing consisted, first of all, of carving a form out of a given block of material (for example, stone or wood); in the second paradigm a material (such as metal or concrete) was first homogenized and then either poured into a mold or forged to form. However, hierarchically structured materials cannot be realized in this manner.

Self-organisation

The solution for manufacturing hierarchically structured materials may be self-organization processes, that means to learn not only from the biological form but also from the process of their formation, i.e. biological development or growth processes. Should this succeed, it would open the door to further desirable properties of such so-called smart materials, for example, the capability of self-healing and the ability to adapt to varying demands. Respective perspectives could open up with the bottom-up nanotechnologies.

Signal and information processing, biocybernetics, sensor technology and robotics

Second main strand of development: robotics and artificial intelligence

While the first and oldest strand of biomimetics development depends on the relationship between form and function, the cybernetic control loop is characteristic of this second strand. Part of this strand are the coining of the term bionics by Steele as well as sensor technology and robotics. This is the strand of development that is commonly referred to as "bionics". In contrast to the first functional-morphological strand, with its development from systematic biology (zoology and botany) to ecology and later on to technical biology and biomimetics, this second strand represents a different, but no less biomimetics-typical developmental logic from the beginning.

Biocybernetics

The fundamental approaches and models of biocybernetics, sensor-physiology and neurophysiology, as well as the ecosystem theory were initially developed in technical areas distant from biology, such as electrical engineering e.g. in resonant circuits, feedback effects, and control circuits, as well as sensors and actuators. Only with their help could important progress in bio-logy have been achieved – particularly in biocybernetics, sensor physiology, neurophysiology and even brain research. This progress in turn positively influenced (not only biomimetic) technical developments in sensor technology, information processing, and robotics. Ultimately in many areas of sensor technology, robotics and information processing up to artificial intelligence (AI), the human mind and body still is the unmatched model.

Artificial intelligence

In the years following the initial euphoria, the area of artificial intelligence has become noticeably quieter. It would seem that in this second strand of biomimetic development things are once again moving forward, if we include current approaches such as decentralized control, parallel computing, self-organizing software, and neuron networks among the biomimetic solutions based on natural models (as well as new actuators such as the pneumatic actuators based on muscles by the company Festo, for example). With the aid of these biomimetic approaches, some of the limitations that have accumulated in the areas of signal and information processing and robotics are being overcome. This second, rather biocybernetic strand of biomimetics seems to be taking on the legacy of artificial intelligence and picking up speed via the fusion of robotics, sensor technology and prosthetics.

Nanobiomimetics – molecular self-organisation and nanotechnology

Third and most recent main development strand: Nanobiomimetics, spider silk and biomineralisation

The third and most recent strand of development in biomimetics is found at the molecular and 'nano' level. This strand also can look back at a longer history (e. g., colloid chemistry, self assembling monolayers). Carried forward by driving forces in the general field of nanotechnology, biomimetic developments in this strand are about to reach a breakthrough (for example, spider silk, biomineralisation, functionalized surfaces, template-controlled crystallisation, neurobiomimetics, nanobiomimetics, etc).

High dynamics in research and development

The nanobiomimetics strand focuses on processes of molecular self-organisation as well as on the (ontogenetic) development of molecules, cells, and tissue, including their reconfiguration (reaction to load) and (self-) healing. With this third and presently extremely dynamic strand, some very promising approaches to solutions are coming up, among these, solutions for the previously mentioned limitations due to "manufacturing hierarchically structured materials" in the first strand of development are rising. Principles of molecular self-organisation, for example template-controlled crystallisation and other bottom-up nanotechnologies, will make possible technical (production) approaches to manufacturing surface textures such as those based on the lotus leaf or shark skin models in the long-term. They also may lead to methods for manufacturing hierarchically structured anisotropic materials based on the model of bones, teeth and plant stems. In a further perspective on development, we can expect "smart materials" capable of reacting to differing loads and, if necessary, even repairing themselves. Presently – and in a foreseeable future – strong dynamics among the three strands are likely to be found in this rather development biology' oriented strand of biomimetics (learning from ontogenetic development processes). Both with respect to the dynamics of the research itself as well as to the possibilities for implementation.

Bottom-up nanotechnologies

Promising perspectives

2

For now though, the great innovative successes in this nanobiomimetics strand is yet waiting to happen as most is still at the stage of basic research. But the perspectives are quite interesting and very promising, particularly with the development of hierarchically structured materials – preferably also responsive to load, adaptive and self-healing – as well as functionalized surfaces. Such surface functionalisations can range in effect from reducing resistance or friction to increasing friction, from bonding and adhesive properties (chemical and physical) to self-cleaning, and from biocompatibility to antifouling and biocide effects.

»Biomimetics«

Particularly widespread in this third strand is a phenomenon that could already be seen in the second biocybernetic strand of development. Research and development on molecular self-organisation principles (for example, self-assembling monolayers or SAMs, micelles, artificial biological membranes, functionalized surfaces, template-controlled biomineralisation, etc.) is clearly based on a nature model. It can thus be included in biomimetics, even when researchers themselves do not do so. In the second strand, for example in robotics, labels such as "bio-inspired" are used frequently and relatively carelessly, but in this third strand comparable vocabulary is used rarely – if at all, researchers might fall back on the term "biomimetic." This is particularly true in the English scientific literature, in which this third strand is more often referred to as "biomimetics" (as compared to the use of the term "bionics" in the second strand).

Convergence of the development strands

»Letting things grow«

It would appear as if a trend towards convergence among the three most important strands of biomimetic development exists. In particular, the form and function and nanobiomimetics development strands appear to be merging. In many cases, it is only now with the technical possibilities offered by the third strand, that an extensive realisation and technical implementation of the results derived from the micro- and nanodimension of the functional morphology strand becomes possible. The following brief example of the lotus effect will make this clear. In order to produce a nanostructured surface based on the lotus leaf, it is not only necessary to solve the problems of technical production of the hierarchically structured surface, but also to deal with the significant problems that exist or would exist with the maintenance of this structure over the lifetime of a product. Only when scientists are able to come closer to the biological model and its capabilities of growth and self-repair will they be able to suitably solve these problems. Thus it would appear that in the biomimetics community the feature of autonomous growth of complex (hierarchical) structures will further develop into a guiding principle or model for the development of a biomimetics of the future. This applies above all but possibly not only to the functional morphology and nanobiomimetics strands of biomimetics.

»Converging technologies«

And finally, biomimetics too, may not be able to avoid the present clear trend towards an ongoing fusion of the once separate lines of scientific and technological development. This is currently a prominent topic of discussion under the subject heading "converging technologies" (Roco/Bainbridge 2002, Nordmann 2004). It is quite likely that biomimetics – like nanotechnology – will play an essential role in the course of this consolidation process. The most important candidates that have been put forward for convergence along with nanotechnology, are the information and communication technologies (ICT), the cognitive sciences, robotics, bioengineering and genetic engineering. In all these areas, the concepts of self-organisation, adaptability, self-healing, and self-optimisation (all concepts found in biomimetics) play an important role.

2.3 The three levels of learning from nature

Difficulties of classification

Similarly to the definitions of biomimetics, numerous attempts to internally differentiate and classify the biomimetic field and areas of operations have been publicized. The largest differences in these efforts occur when an attempt is made to classify biomimetics by field of application (e.g. biomimetic civil engineering, biomimetic climatisation, etc.), but then at the same time by technical function (e.g. locomotive biomimetics and sensor biomimetics; see Nachtigall 1998, 19 et sqq.). The problem is that biomimetics approaches are, in principle, possible in almost all areas of science and engineering research and development and even in economics, such that a classification of any kind must be able to accommodate an extremely wide range of science and areas of applications.

Three levels of »learning from nature«

In addition to the subdivision of biomimetics development into its three primary strands of development (functional morphology, signal and information processing and nanobiomimetics), it is also useful to distinguish between three different levels of learning from nature. These three levels consist of: "learning from the results of evolution" (hook-and-loop fasteners, the aircraft wing, etc.), "learning from the process of evolution" (optimisation techniques, evolutionary optimisation strategy (e.g., Evolutions-technik, see Rechenberg/Schwefel), genetic algorithms, etc.), and finally, "learning from the success principles of evolution" (closed loop economy, adaptability, etc.) which is the third and most abstract level. Naturally such an attempt at classifying or structuring must contend with reality, which is substantially more complex; so these strands and levels do not exist in a pure form and working scientists have of course long made use of objects, models, methods, and knowledge acquired from other such strands and levels whenever they seemed useful or promising for their respective research programs.

Learning from the results of evolution

Learning from the results of evolution: shark skin, winglets

The first level, learning from the results of evolution has to date been the most intensively pursued biomimetics. The further technical development of image-making processes, in their spatial as well as temporal resolution (such as the electron or atomic force microscope, slow-motion camera) opened the gates wide on this level, particularly for recording form-function relationships (e.g. the lotus effect and gecko feet using van der Waals' forces, etc.). The ongoing success in modeling the interaction of dynamic bodies (especially their surfaces) and their surrounding media (aero- and hydrodynamics as well as particle dynamics, e.g. the sand skink) may well lead us to expect a strong spurt forward into understanding cause and effect, application, and usage of a targeted generation of microturbulences. This branch of fluid dynamic biomimetics – with recourse to the results of evolutionary optimisation processes lasting millions of years – has thus profited from previous inadequacies of the analytic, mathematic experimental (mechanistic) and also numerical approaches in this field. If, in the future a deeper more functional understanding of this surface-medium interaction can be achieved by numerical methods, a stronger theory-supported and therefore systematically more successful dynamic could develop at this level of learning from nature, which in many areas still largely consists of greatly simplified replication (wings, bulbous bow, shark skin, winglets, etc.).

Evolutionary tested

Regarding these main results of the first level of learning, we may justifiably refer to a certain "validation of technological solutions through evolution". Naturally, for the transfer of this validation into biomimetic innovations, a great deal still depends on the 'process of learning' or the specific knowledge-transfer process, which is based on the fundamental findings. For aero- and hydrodynamic approaches, the recourse to a certain holism is thus also justified, as one more or less takes on the full complexity of the interactions between body and medium; with this, at least the degree of not only theoretical but also practical experimental abstraction remains small. The latter is therefore of importance, because the so-called "noise factors," which can be eliminated relatively successfully within scientific experiments often turn out to be a source of unexpected side effects of technologies (in real life) that later build on these scientific findings (von Gleich 1989 and von Gleich 1998). The experimental and technical power over the object is quite limited in exactly those biomimetic approaches that first and foremost are based on learning from the results of evolution. It is more a matter of fitting in and adapting to the natural circumstances than trying to control them.

Learning from the evolutionary process

Learning from evolution: »soft kill option«, ants' algorithm, evolutionary strategy

Those biomimetic approaches at the second level, where learning from or simulation of the process of evolution (but also the respective ontogenetic adaptation strategies) takes place, have also acquired a comparatively large significance. This would include bioanalogue optimisation methods, for example, evolutionary optimisation strategy (Rechenberg/Schwefel) and evolutionary algorithms, but also swarm intelligence, ant algorithms and the programs developed by Mattheck for component part optimisation (computer-aided optimisation (CAO) and the soft-kill option (SKO)).

Importance of optimisation processes

In attempting to assess the current significance of these processes, their dynamics, and future potential, the results are not so easy to pin down. That may particularly have to do with the fact that the processes themselves as well as the respective application situations (or the respective optimisation problems to be solved) are so heterogeneous that a comparison of the bioanalogue processes to each other as well as a comparison to non-bioanalogue competing optimisation approaches simply does not seem possible.

The best-known bioanalogue methods are apparently in wide application, even though they are in part not always well documented. Currently an exceptionally strong scientific dynamic and particular element of success cannot be seen in any of the bioanalogue or competing methods. Due to the continually increasing complexity in economics and, above all, in the area of logistics, one would have expected more in this connection. Those actors in the field of logistics explain the situation by pointing to a current lack of pressure to solve such problems (or a too-low awareness of the need for such problem-solving). Companies are apparently able to solve their present (optimisation) problems using simpler means and are displaying a certain restraint with respect to the necessary training/adjustment period that more complex methods would require.

Learning from the (success) principles of evolution

Learning from the (success) principles of evolution: solar economy

The third level of learning from nature is based on an abstraction of the – admittedly only somewhat – generalizable principles of evolutionary success. These principles thereby serve a double purpose. They serve as an argument for the validity and scope of the “biomimetic promise” with respect to ecologically more suitable and lower risk technological solutions using biomimetics (see next section). And they can be put into service as guiding principles or models in engineering design, when the goal is to develop ecologically more beneficial, intelligent, adaptive, flexible, robust, and intrinsically safer technical solutions.

Among these principles of success are:

- solar energy and raw material opportunism (use of that which is proximate available)
- modularity, hierarchical structuring, and multi-functionality
- resource efficiency (with a view to limiting factors) and recycling
- resilience (adaptability, diversity, redundancy)
- self-organisation and self-healing
- multi-dimensional optimisation.

2.4 The exceptional scientific and technological nature of biomimetics

Biomimetics as a specific form of R&D

Biomimetics, in many respects, should be considered as an exceptional form of research and development. A strong focus on applications links biomimetics to the engineering sciences and their focus on technical solutions, although in contrast to the engineering sciences, which are primarily based on physics and chemistry, biomimetics' foundations derive primarily from biology. Viewed this way, biomimetics is applied "technical biology" (focusing on form-function relations) – but not exclusively. It is also applied neurobiology, applied molecular biology, applied ecology and ecological system theory, applied evolutionary research, and much more.

No traditional engineering science?

On the other hand, one can scarcely call biomimetics an engineering science in the classic sense, since biomimetics in its scientific and technological form, at least, has more in common with biotechnology and computer science. The impulses for biomimetics research and development from the field of biology (new technological possibilities or technology push) are much stronger than those coming from engineering demands (demand pull). Typical of biotechnology, computer engineering, and biomimetics, too, is the equiprimordiality *(Gleichursprünglichkeit)* and particularly close interdependence of technical and scientific development; this form of science has repeatedly been referred to as "techno-science" (see Nordmann 2004).

»techno-science«

However, biomimetics differs in some respects from these "techno-sciences," particularly in its emotional and normative content. The emotional aspect of biomimetics derives its attractiveness from our fascination with (animate) nature. The normative aspect of biomimetics, in its promise of better, more ecological and appropriate solutions, derives from the tested and proven (over millions of years) optimisation of biological models through evolution. The so-called biomimetic promise thus deals with biomimetics' relationship to the topics of risk, ecology, and sustainability.

The "biomimetic promise" – biomimetics and sustainability

Fascinating biomimetics

Initially it can be stated that biomimetics *fascinates* – in a way that is quite different and much stronger than in other areas of research and development. The many (popular) science publications alone make this clear with their numerous wonderful pictures (for example, Blüchel/Malik 2006; Cerman et al. 2005; Kesel 2005; Nachtigall/Blüchel 2003; Benyus 2002, WWF 1991) as well as a whole series of television and radio programs on biomimetics. And not least, biomimetics fascinates young people, for whom engineering might otherwise not be so accessible.[1] Biomimetic topics and solutions enjoy an enormous and enormously positive resonance with the public. Little is known about the reasons behind this fascination and therefore there is much speculation. With great likelihood, the widely held fascination with (animate) nature plays a large role, and also the associated aesthetic and elegance of its many manifestations and modes of action, in which "everything is so perfectly interconnected." As if in confirmation of this hypothesis, almost all (popular science) publications dealing with biomimetics offer up an abundance of especially beautiful and aesthetically pleasing images of nature.

Special quality of biomimetic solutions

Biomimetics also has a significant normative content – and this forms, so to speak, the core of the "biomimetic promise". Biomimetics promises, more or less explicitly, to provide solutions of exceptional quality. This exceptional quality is often justified by reference to the "tested and proven" nature of evolutionary development and an "evolutionary process of optimisation lasting millions of years" (Riechey 2008). The exceptional quality of biomimetic solutions (in addition to the previously mentioned emotional, i.e. particularly aesthetic aspects) is expected to manifest itself in three aspects: (1) in a low degree of risk, (2) in a greater possibility of ecological appropriateness and thus a contribution to sustainability, and (3) in a previously unattainable ingenuity with the respective solution, which mostly (but not only) is justified with reference to a fundamentally multi-dimensional optimisation process. It is presumed – and, it seems not entirely without reason – that solutions which have proven themselves in the competitive process of evolution must possess the respective qualities for success. Even so, the factual justification and respective scope of the validity of this promise needs to be critically questioned.

Reasons for the »biomimetic promise«

But first, let's look at the reasons behind a possible legitimacy of the biomimetic promise. These are closely related to the general evolutionary principles of success, which we already addressed with the third level of

1 In the light of the rapidly growing demand for personnel with scientific and engineering qualifications in the industrial nations in the course of globalisation, and at the same time, a rather sinking – or in any case, certainly not as rapidly growing – interest on behalf of young men and women for an education in the natural sciences and engineering, such corresponding motivation and enthusiasm must be viewed as a valuable (and scarce!) resource, not least from an innovation policy point of view.

learning from nature. The following principles can be formulated as factors for success in biological evolution and as guidelines to a more sustainable technology:

- *Solar energy opportunism*
  Natural processes are essentially based on the usage of solar energy (in the form in which it is available)
- *Raw material opportunism* (usage of what is at hand)
  Biological evolution of organisms is based on comparatively few elements (structure is provided primarily by C, O, H, N, P, Ca, P, S and Si). Organisms primarily use those substances and energy sources that are directly available to them. This does one the one hand radically restrict their possibilities, but it allows them on the other hand to tap into nature's massive energy and bio-geochemical flows and material circles (the latter being a central aspect of sustainability).
- *Resource efficiency and life cycle engineering*
  In those areas where natural resources are among the limiting factors in an ecosystem, efficient utilisation of such scarce resources is an evolutionary advantage. Naturally, a fully closed loop is the theoretical ideal (a closed-loop economy); in nature there are no perfect closed loops either, but when new substances are developed from organisms, as a rule, corresponding catabolic pathways arise in a co-evolutionary process. Organic "waste" is re-used in a cascade-like manner by other organisms, until only humus or mineral components remain.
- *Diversity, redundancy, modularity & multifunctionality*
  The diversity of resources and solutions plays an important productive and stabilizing role in evolution, even when widespread beliefs of a direct relationship between diversity and ecological stability generally represents a crude simplification. Modules such as organs, cells, organelles, and molecules make diversity possible over the basis of a limited set of structures.
- *Multicriteria (multi-dimensional) optimisation in dynamic environments*
  Multicriteria optimisation is perhaps one of the most interesting achievements of the evolutionary processes. Our own technical artifacts are all too often optimized focusing only on a few target functions and are furthermore dependent on well-defined constraints. Organisms in contrast are capable of functioning in turbulent environments. Even in a muddy soup, for example, snails are able to produce their pearlescent nacre. The (biomimetic) optimisation processes, based on the evolutionary processes, offers an approach to multicriteria optimisations.

- *Adaptability, resilience & self-healing*
  Disorders, assaults, etc. are normal in nature. Natural systems cannot limit themselves to only defense or flight. They must learn to manage disorders and assaults without being thrown completely off balance (falling into dramatic system states). Operative terms here are the construction and reinforcement of defense or immune systems; as well as mechanisms for self-healing, resilience, and robustness; and formative goals such as intrinsic safety, etc.
- *Self-organisation*
  The capability of building complex structures (far from thermodynamic equilibrium) is likewise among the most interesting capabilities of organisms and populations and entire evolutionary processes. Opportunities for a biomimetic technological implementation of this principle may already be beginning in the inorganic area with SAMs (self-assembled monolayers) and template-controlled crystallisation. On a long-term perspective, this becomes a question of "letting things grow", of the controlled growth of complex structures and hierarchically structured materials – of which template-controlled crystallization already represents a good example. Such forms of not direct, but only "context-control" make very efficient use of energy, practical monitoring, and control performance.

Validity of the »biomimetic promise« depending on implementation contexts

In reality, biomimetic solutions cannot and do not necessarily need to fulfill all of these aspects at once, but the more that they are met, the greater the legitimacy of the biomimetic promise. Validity, however, can then only be achieved when the respective principles are implemented in the corresponding technology, i.e. in proffered solutions. Thereafter, the respective conditions of use and the application contexts could then also lead to a very different judgment.

Limits of the »biomimetic promise«

A critical examination of the reasons and conditions for the validity of the biomimetic promise thus also shows its clear limits. Here, the following aspects play a key role:

- *A guiding principle is not a label*
  One can treat biomimetics as a guiding principle, whereby the biomimetic promise represents important aspects. But it must be recognized from the beginning, that the pursuit of an overall mission statement or guiding principle for development will not necessarily bring about the corresponding success. "Well meant" – as elsewhere – does not necessarily correlate with "well done."
  "Biomimetic" should therefore certainly not be misunderstood as being some sort of seal of approval. Such a seal of approval can

only be assigned following a methodically flawless established process of approval; however, such a quality-assurance process does not (yet) exist, and it is doubtful whether such a procedure is even possible.

- *Every technology/innovation must be separately tested and evaluated*
  The following must be considered as elements of a possible hazard or risk: first, the potential hazard that arises out of (new) technical capabilities (in toxicology, for example, this would be the toxicity of a substance), and second, the potential danger that arises in the respective application context (in toxicology this would be the exposure).
- *Ambivalence of opportunism (as an enormous form of self-restraint)*
  The use of solar energy as an energy source and the use of the materials immediately at hand (tapping into nature's massive energy and bio-geochemical flows and material circles) certainly increase the probability of a sustainable solution, but at the same time, they drastically limit the possibilities of human creativity and the art of engineering.
- *The more radically new the structure, the more tenuous its claim on the validation by evolution.*
  The stronger the constructive (synthetic) element of a biomimetic approach or innovation is, the more the argument of being proven by evolution becomes invalid. The more profound the depth of intervention and the more powerful the technology is, the more likely it is that there will be relevant side effects and consequential effects (the greater the reach through time and space of the resulting cause-and-effect chains).

2.5 Tentative conclusion about trends in biomimetics

Heterogeneity and dynamics of biomimetics

Even if one only concentrates on biomimetics in the narrow sense, it is not easy to precisely describe this field; this is due to its heterogeneity, but also the dynamics of biomimetics research and developments. Looking at the trends in biomimetics i.e., the dynamics of the field, a differentiation between the three main developmental biomimetics strands can be made. The first, "functional morphological", strand is the oldest and dedicated above all to the form/structure-function relationships. The second strand focuses more on the biological forms of signal and information processing and introduced successful technical implementations; particularly in the areas of biocybernetics, sensorics, and robotics. The third and youngest strand of development in biomimetics is a result of progress in the area of nanotech-

Three strands of development in biomimetics nology and draws on, among other areas, molecular self-organisation processes. In our opinion, taking a mid to long-term perspective, the greatest potential for biomimetics may well lie in this area. A significant reason for this is that this third strand is capable of overcoming significant restrictions of the first two strands.

Additionally, latest observations suggest that the convergence of these three strands is becoming ever greater, to some extent they may have already merged. This convergence has its counterpart in other areas of science and technology and is frequently referred to as "converging technologies."

»converging technologies«

In addition to the three strands in the development dynamic, the core of the biomimetic basic idea can also be broken down further. We distinguish between three levels of "learning from nature," where the question arises as to the conceptual source of the respective biomimetic knowledge-transfer processes. In the case of "learning from nature's findings," it is the structures and mechanisms of living systems that are found in nature and described in biology that are used as models for technical products and processes. At the second level, it is neither the findings nor the results of evolution but rather the evolutionary process itself that is the object and starting point of the knowledge transfer processes in biomimetics (evolutionary optimisation, genetic algorithms). There is also an effort underway in biomimetics to distill out the general principles of the evolutionary success and the structure and functionality of natural systems (for example, resource efficiency, opportunism and adaptability); this can be considered the third level of learning from nature.

Three levels of »learning from nature«

Finally, biomimetics clearly stands out from other areas of science and technology with two more characteristics: a) the fascination it exerts on many, inside as well as outside the sciences, and b) the normative content which it more or less implicitly transports. The fascination may well be attributed to the fact that biomimetics, regardless of the form in which it is pursued always takes living nature with its positive attributes as its starting point and, in a way, as its goal. The intent is to emulate nature, in its fascinating and endless variety, not to manipulate it or fight against it. The normative content shows itself, particularly in the popular reference to the evolutionary seal of approval, i.e., that the systems (organisms, etc.) of living nature have undergone an evolutionary process lasting millions of years during the course of which they have in many respects become "optimized." This optimisation took place not only in the respective individual systems, but also and foremost in the interactions between the system and its environment and the resulting effects. The latter can be associated with a certain degree of ecological "suitability" or appropriateness which, against the backdrop of the ongoing debates on sustainable technology (and development) lets biomimetics appear as a very promising alternative.

The »biomimetic promise«