Arnim von Gleich, Christian Pade, Ulrich Petschow, Eugen Pissarskoi

# Potentials and Trends in Biomimetics

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Submitted by:

Universität Bremen
Technological Design and Development

University of Bremen
Department 4 – Production Engineering
Badgasteiner Str. 1, 28359 Bremen
Prof. Dr. Arnim v. Gleich
Tel: +49 (0) 421 218 2844
E-Mail: mtimmerm@uni-bremen.de

Cooperation partner:

iöw INSTITUTE FOR ECOLOGICAL ECONOMY RESEARCH

The Institute for Ecological Economy Research (IÖW),
Potsdamer Str. 105
10785 Berlin
Christian Pade
Ulrich Petschow
Eugen Pissarskoi

With the assistance of:
Silke Affinas, Sascha Fechner, Ole Glöckner, Arno Häusler, Laura Spengler,
Sandra Stricker, Sönke Stührmann, Thorsten Wuest

Design:
Andreas Wolter & Ricarda Löser, Weimar

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Arnim von Gleich, Christian Pade, Ulrich Petschow, Eugen Pissarskoi

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Prof. Dr. Arnim von Gleich
Universität Bremen
FB 4 Produktionstechnik
FG 10 Technik Gestaltung und
Technologie Entwicklung
28359 Bremen
Germany
mtimmerm@uni-bremen.de

Christian Pade
Institut für Ökologische
Wirtschaftsforschung (IÖW)
Potsdamer Str. 105
10785 Berlin
Germany

Dipl.Vw. Ulrich Petschow
Institut für Ökologische
Wirtschaftsforschung (IÖW)
Potsdamer Str. 105
10785 Berlin
Germany
ulrich.petschow@ioew.de

Eugen Pissarskoi
Institut für Ökologische
Wirtschaftsforschung (IÖW)
Potsdamer Str. 105
10785 Berlin
Germany

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## Foreword

There is a wide consensus about the necessity of sustainable development. There is also a consensus that wide areas of our economy, industry, and technology and the life styles in industrialized countries are not sustainable. Science and technology are widely regarded as (main) causes for this situation. Issues in this context comprise the generally low resource efficiency, an increased and mostly undebated technological power, an increased invasiveness of modern technologies, increasing amounts and diversity of pollutants, and high technological risks.

On the other hand science and technology are also regarded as (main) solution providers towards more sustainability. Thus the question is which type of science and technology is rather a part of the problem, and which type is rather a part of the solution?

'Learning from nature' may give some orientation in this context. Biomimetics and bionics are widely regarded as being a part of the solution. Organisms and ecosystems have learned to solve (technological) problems since the beginning of evolution. In many technological fields they outperform manmade solutions by far. Ecological systems have learned to sustain themselves in dynamic environments. Their achievements are results of an evolutionary optimisation process lasting over millions of years. This is the main reason why biomimetic solutions are widely regarded as not only being ingenious, but also as being ecologically sound, resilient (stable in dynamic environments), and low-risk. These expectations are shared not only by the public and the media, but also by most of the actors in the field itself (Richey 2008). We refer to these sentiments as the 'biomimetic promise' (or the 'biomimetic expectation').

The aim of this study is, to evaluate the potentials and trends in biomimetics and to compare the performance of actors in this field in leading countries. On a more general level, however, this study inspects the evidence for and against the statement that biomimetic solutions can live up to their promise. A promise which, if kept, implies that biomimetics is rather part of the solution than of the problem of unsustainability.

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# 1 INTRODUCTION

*»Nature does not strive to be meaningful, it already is.«*

ROBERT WALSER, 1878–1956

# 1 INTRODUCTION

Biomimetics and bionics are artificial concepts. The term biomimetics is a synthesis of bios (life) and mimesis (to imitate, to mimic). Bionics is a made-up word derived from biology and technics.

The scientific and technological concepts of biomimetics and bionics can be characterized as the attempt of developing technological solutions by learning from nature. Based on a long process of evolutionary optimisation organisms, populations, and eco-systems surpass the achievements in many fields of the previously available technical solutions. Biomimetics turns to "nature's patent bureau" and takes as its role model such organism-based achievements. The public as well as the media hold a relatively positive opinion of biomimetic solutions, which are often a subject of fascination. Biomimetic solutions are generally viewed as ingenious, ecologically appropriate, and low-risk.

The terms biomimetics and bionics are used interchangeable in this publication. We are aware that even further terms could be used (as for example biomimicry or bio-inspired) and that the different terms are often connected with some special meanings in different countries and different disciplines. For example the term bio-inspired is often used in robotics and bionics is in the American scientific literature often used in the sense of augmenting or replacing operations and functions of human extremities through machinery controlled by neural systems (Johnson/Schreuders 2003).

The purpose of this study is to take an in-depth look at the most important trends and potentials of biomimetics as a basis of science and engineering development and innovation and to assess the standing of biomimetics research and development in different countries with the focus on Germany. Based on case studies, literature, patent and research networks analysis, interviews and workshops, statements about the status of biomimetics as a research and development area were worked out. Furthermore a closer look on the validity of the "biomimetic promise" of ecological adaptation and low risk biomimetic solutions, the current trends in biomimetics, as well as the general setting, driving forces and obstacles in the realisation of its potential for innovation were taken.

As with every study, it was necessary to carefully define the subject area and make preliminary decisions with respect to the methodological approach. Among the decisions made regarding the basic approach, the one with the most far-reaching implications for the possible results from this study was, without doubt, the demarcation of the area of investigation.

We chose to look not only at research and development areas and stakeholders who explicitly use terms such as biomimetics or bionics: our goal was also to collect information on those areas that follow a more general biomimetics approach in the sense of "learning from nature" but without making a direct reference to terms such as biomimetics or bionics. Thus the field in an initial step was extended to include large aspects of robotics and prosthetics from the field of medical technology; both modeling, foremost on the example of the human body or human nature. In a further step we also included those areas modeling the fundamental capabilities not only of individual organisms, but also biological systems or more fundamentally, "life forms." The capabilities that characterize life forms is not only self-organization (which we already find in simple forms in chemistry and physics), but rather the ability of self-preservation and self-reproduction in a steady state condition within dynamic environments (homeostasis, adaptability, self-regulation, self-healing). By focusing on such capabilities (many of which bear the prefix "self-") we find ourselves directly on the leading edge of an entire series of highly topical scientific and technological developments, from the material sciences to the hardware and software used in information and communication technologies.

# 2 TRENDS IN BIOMIMETICS


2.1 Definition
2.2 The three main strands of development in biomimetics
2.3 The three levels of learning from nature
2.4 The exceptional scientific and technological nature of biomimetics
2.5 Tentative conclusion about 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®).

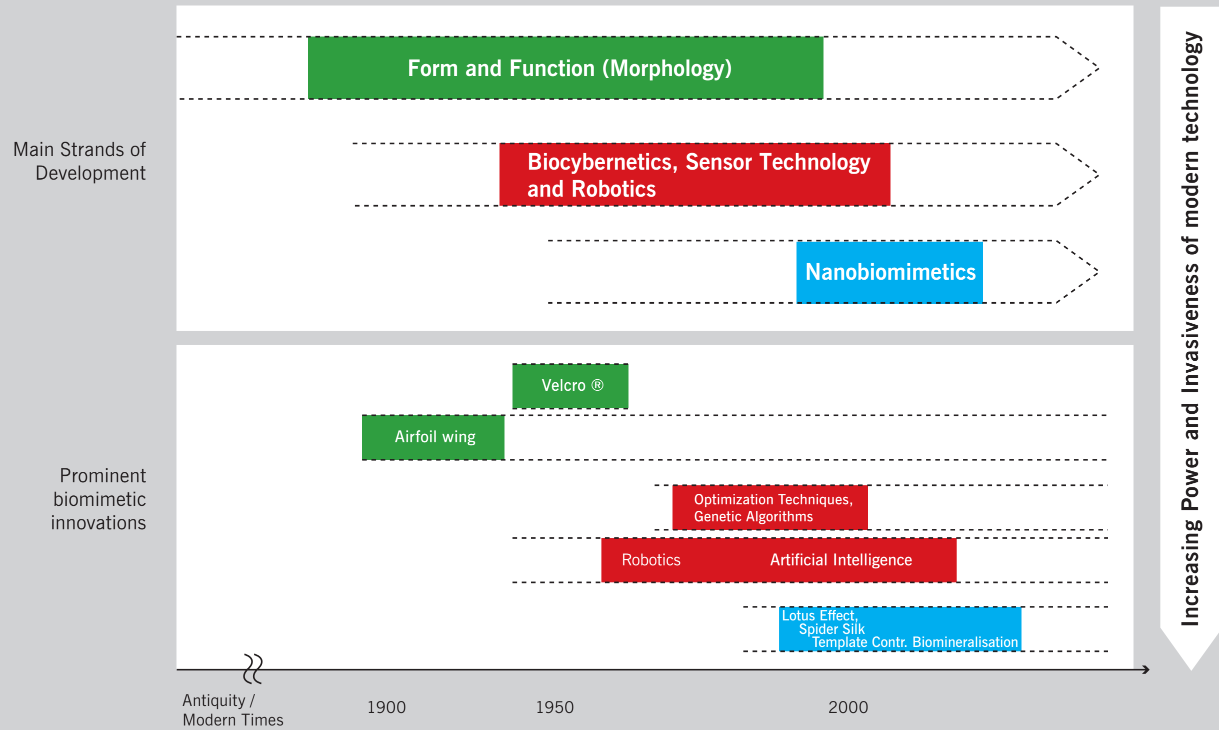
First and oldest strand of development: aircraft wings, parachute, hook-and-loop fastener

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, sensorphysiology 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