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Biornametics: Architecture Defined by Natural Patterns

Ille C. Gebeshuber[a]*, Petra Gruber[b] and Barbara Imhof[c]
[a]Institute of Applied Physics, Vienna University of Technology, Wien, Austria
[b]Transarch – Biomimetics and Transdisciplinary Architecture, Vienna, Austria
[c]LIQUIFER Systems Group, Wien, Austria

Synonyms

Arts-based research; Biomimetics; Lateral thinking; Transdisciplinary approaches

Definition

Biornametics – Architecture Defined by Natural Patterns – is an emerging contemporary design practice that explores a new methodology to interconnect scientific evidence with creative design in the field of architecture. The word biornametics is generated from "ornament," referring to the famous Austrian architect Adolf Loos, and "biomimetics," the abstraction of good design from living nature (see "► Biomimetics").

Overview

In biornametics research, role models from nature, static and dynamic patterns (e.g., nanostructured surfaces or materials with functional hierarchy from the nano- to the macroscale), are investigated, and the findings are applied to design strategies. The emergence of patterns in nature at all scales of existence of organisms as one of the most important signs of life – order – is not arbitrary but highly interconnected with boundary conditions, functional requirements, systems requirements, material, and structure. The three main areas of investigation for role models in biornametics are, firstly, **surface patterns, nanotextured surfaces, and nanostructured materials**; secondly, **shape, growth, and deployable structures;** and, thirdly, **adaptation and reorganization**. Biological building strategies rely basically on repetition, variation, and self-similarity. Often simple building blocks are arranged with molecular precision and thus achieve diverse and highly specialized material properties.

Biornametics research aims at understanding the functionality of these natural patterns by extracting the principles found in current nanotechnology research and transferring these principles to an architectural interpretation. Colors are just one very important example. In contrast to pigment colors, structural colors that are found on some butterfly wings and beetles and even on plants [1–3] are primarily determined by the geometry of the underlying material. Interesting is also the generation of these surfaces and materials, as well as multifunctional properties such as durability, degradation, or self-repair. Further examples include plant-environment interactions such as the pitcher plant that lures animals onto a super-sliding surface or the lotus leaf's self-cleaning properties and nanostructured composite materials with high toughness such as the abalone shell. The patterns in these role models from living nature fulfill their purpose and are surprisingly elegant and appeal to the aesthetic dimension of the human perception (Fig. 1).

*Email: gebeshuber@iap.tuwien.ac.at
*Email: ille.gebeshuber@mac.com

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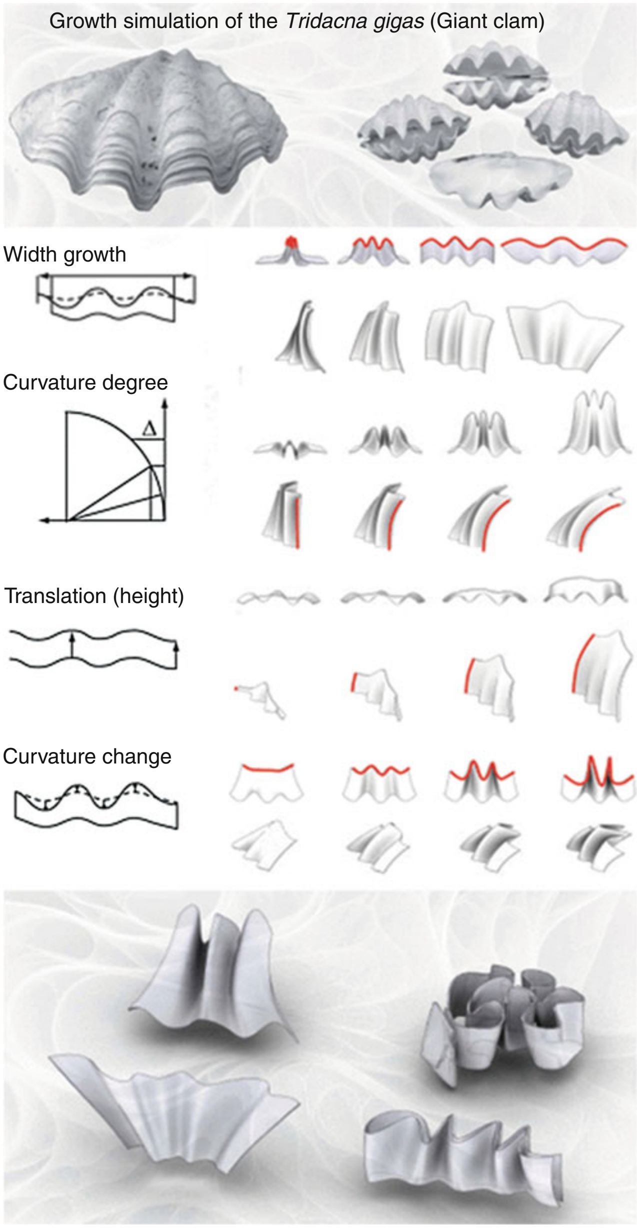

Fig. 1 Ornaments for architecture inspired by a growth simulation of the giant clam, starting from the initial nanocrystalline composite, followed by the formation of a two-dimensional disk protrusion and the formation of crystalline curls

The transfer of surface patterning to architectural elements may deliver added or integrated functionality or reinterpret specific functions on another scale.

Summary

Biornametics – Architecture Defined by Natural Patterns – is a transdisciplinary arts-based design practice that explores different approaches to a new design methodology to interconnect scientific evidence from the life sciences with creative design in the field of architecture. The starting point of *biornametics* takes on the history of one of the composed parts of the word "ornament" referring to Adolf Loos [4] and extends into another "biomimetics [bionik in German]" [5–7].

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Biornametics especially refers to the more recent terminology where the “New Ornament” as an emerging contemporary design practice is based on digital techniques. It is less concerned with serial rationality but with algorithmic, digital operations and connecting the processes of planning and production. The second part of the artificial word biornametics stems from biomimetics and means the strategic search for nature’s solutions. The hypothesis underlying this strategy is that living nature has evolved in a process of continuing adaptation to become a complex changing environment and that the exploitation of highly optimized solutions is likely to deliver innovations that provide more intelligence and higher efficiency than our standard methods.

Biornametics research and the simulation of role models from nature, static and dynamic patterns (e.g., growth principles, movement patterns, adaptation and differentiation as key for emergence of patterns, etc.), provide the basics for subsequent applications in art. The emergence of patterns in nature at all scales of existence of organisms as one of the most important signs of life – order – is not arbitrary but highly interconnected with boundary conditions, functional and systems requirements, materials, and structure. The findings from role models and their simulation are applied to design strategies and translated into prototypical architectural concepts.

As a result of the first ever biornametics research cycle, performed between 2010 and 2013, a physical installation was set up temporarily in the Silver Gallery of the University of Applied Arts in Vienna, Austria, demonstrated one of the unlimited possibilities of interpretation of a single principle, and was thus closely related to the perception of the executing team. The goal was to build a lightweight and cost-efficient spatial structure with an inherent potential to move, or to be moved, by stimuli from the external environment.

A paramount step in biornametics research is panel discussions with panelists from different backgrounds (such as architecture, mathematics, engineering, physics, and biomimetics) to produce more aspects of methodology and scientific input with feedback from the interested general public. The aim of such explorative debates is to present different approaches to science-based design and to reason about the value of incorporating findings from the life sciences into architectural design methodologies. Springer Scientific Publishing published results from the first biornametics research cycles in a book that takes this approach further and creates the context of the current discussion of arts-based research [8].

Future continuous research can be deducted from the potential that was discovered and lies in the theme of growth and how one can make use of the functions the growing element offers during different phases and the topic of nanotechnology in building and creating in a yet rather unknown scale.

Background

The first biornametics research cycle started in 2010. The Austrian Science Fund installed in the year 2009 a funding program for arts-based research, called PEEK. In this program any person engaged in arts-based research who has the necessary qualifications can apply for funding for up to 36 months. PEEK goals are to support high-quality and innovative arts-based research in which artistic practice is integral to the inquiry. In this way, research capacity, quality, and international standing of arts-based researchers in Austria shall be increased. Further benefits are an increase of both public awareness and awareness within the academic and the arts communities of arts-based research and its potential applications.

The team around architect and artist Barbara Imhof was one of the first to secure PEEK funding: for the first ever cycle of biornametics research, architecture defined by natural patterns. Biornametics research combines scientists, architects, and artists in a highly creative, innovative team.

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Host research institution of this first cycle of biornametics research was the University of Applied Arts, Vienna, Austria; key people were Barbara Imhof and Petra Gruber. Collaborating institutions were located in Austria, Germany, Italy, the United Kingdom, and Malaysia. The duration of this first cycle of biornametics research was from May 2010 until March 2013.

Aims of Biornametics Research

The intellectual aim of biornametics arts-based research is the exploration of an aesthetic and functional interpretation together with utilization of new manufacturing technologies and elaboration of biomimetic design methods and the New Ornament.

1:1 implementation is used to communicate the approach and its theme as test bed experimenting the physical translation process and experience the implications arising from unexpected solutions or developments.

Aims of biornametics arts-based research:

- Research, analysis, and simulation of dynamic patterns from nature.
- Patterns from nature are investigated and deep principles behind morphogenesis defined. Analogies in architectural design are identified to clarify application possibilities.
- Successful transfer of found principles to architectural application shall deliver intelligent, efficient, and ecological designs which also will create new forms and new aesthetics.
- Deliver visualization and prototypes of the architectural interpretation.
- Application to an architectural scenario is crucial for the success of transfer. The development of a real project manifests the validity of the approach.
- Further development and refinement of the biornametics methodology to transfer nature's patterns to architectural application.
- The development of a methodology for the transfer of information into the architectural discipline is important as a pathway for follow-up studies. The biomimetic method goes beyond superficial interpretations of findings from nature.
- Serve as a role model for interdisciplinary architectural design work.

Integration of findings from other disciplines such as the life sciences is not an easy task. The new design approach needs a formal framework that allows dynamic exchange of information. Preconditions for this exchange are the willingness to cross the borders between disciplines and to deal with other "languages" (terminologies) and cultures [9]. By involving different researchers and consultants with various backgrounds such as nanotechnology, biomimetics, informatics, mathematics, structural engineering, architecture, and design, a multidisciplinary team is created that investigates and develops novel design strategies for architecture with an exemplary application structure.

Limitations

The integration of new production technologies to the research approach can only be achieved in follow-up attempts (e.g., subsequent projects together with industry). The main reason for this is to keep the simulations and computational results as broad and systemic as possible, to allow for potential application developments in a wide variety of fields. Collaboration with industry will supply the necessary production workspaces and machines.

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Effects of the Design Practice Outside the Core Field of Research

Biornametics research is cross-disciplinary work based on a scientific approach to architectural design; it is a new teaching method with high potential to strengthen innovation in architecture. A continuously growing database of potential role models and principles provides the basis for further more specific follow-up arts-based research approaches that explore the applicability in the field of architecture. One more general aspect that shows great potential to be developed further is the integration of new production technologies into the process.

Research Areas

The research areas for biornametics research refer to a main issue in biomimetics: the relation between structure and function. Three initial main areas of investigation for role models from nature were defined in the first research cycle:

1. Surface patterns, nanotextured surfaces, and nanostructured materials
2. Shape, growth, and deployable structures
3. Adaptation and reorganization

These three areas reflect the specific scientific expertise in the scientific team of the first biornametics research cycle: expert consultant George Jeronimidis is versatile in biomimetics and fiber structures, and therefore the role models focus rather on plants than on animals, and Ille C. Gebeshuber is an expert in nanotextured surfaces and structural colors.

In biornametics research the sample role models from nature to be investigated need to be chosen with regard to:

- Availability of reliable information
- Tangibility of scales and processes
- Exclusion of biochemistry and metabolic processes
- Expected innovative potential for spatial and architectural applications

The methodology starts with a selection of role models from nature ("scientific input"). At the same time a primary investigation in successful transfers, architectural applications, and outcome scenarios delivers exemplary knowledge and guarantees novelty of the selected approach.

The base of biornametics research, patterns and their scientific exploration, partly finds a feedback in the architectural theory of the ornament. After the first phase of data collection starts the computation of models, followed by concept development and design.

The first transfer generally takes place when the selected role model patterns are analyzed regarding their potential application and their abstracted principles. Digital simulations are used to investigate the principles. In the second transfer analogy is established by exploring applications where the abstracted principles could be applied.

The final step is the proto-architectural implementation of showcase applications to be exhibited and communicated to the scientific and architectural community by means of publications and scientific papers in journals and conference proceedings.

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Surface Patterns, Nanotextured Surfaces, and Nanostructured Materials

Biological systems exhibit a wealth of functional units highly optimized for a range of parameters, also on the nanoscale, by only combining a handful of starting materials. Biological building strategies rely basically on repetition, variation, and self-similarity. Often simple building blocks are arranged with molecular precision and thus achieve diverse and highly specialized material properties.

Colors are just one very important example. In contrast to pigment colors, physical colors that are found on some butterfly wings and beetles are primarily determined by the geometry of the underlying material. The process of generation of these surfaces and materials is also interesting, as well as their properties such as durability, degradation, or self-repair.

Further examples include plant-environment interaction, for example, the pitcher plant that lures animals onto a super-sliding surface or the well-known self-cleaning principle that was discovered in the lotus leaf. Patterning on the nanoscale also produces materials that have unequaled properties, for example, the abalone shell ([10]; Fig. 2).

The patterns found do not only fulfill their purpose but are surprisingly elegant and appeal to the aesthetic dimension of the human perception. The transfer of surface patterning to architectural elements may deliver added or integrated functionality or reinterpret specific functions on another scale.

Biornametics research role models with relevance to surface patterns, nanotextured surfaces, and nanostructured materials are photonic crystals in the jewel beetle (Fig. 3); super-sliding nanostructure-based slippery surfaces of the yellow pitcher plant (Fig. 4); multifunctional nanostructures on the *Morpho* butterfly (Fig. 5), providing coloration, tuned wettability, unidirectional water runoff, and further nanoscale-based properties; superhydrophobic surfaces of the giant Amazon water lily (Fig. 6); complex nanocomposite of the abalone shell (Fig. 7), with high fracture resistance and iridescent colorations (abalone parts are used in jewelry, for their color play and durability); opal-like photonic crystals of the peacock feather (with exquisite control of the color-generating nanostructures for the various colors, Fig. 8); the octopus (Fig. 9), who can quickly and reversibly change color; the *Strelitzia* plant (Fig. 10) with impressive superhydrophobic properties; and, last but not least, insect wings (Fig. 11) and more generally surfaces of insects with various functionalities based on nanoscale organization of the material.

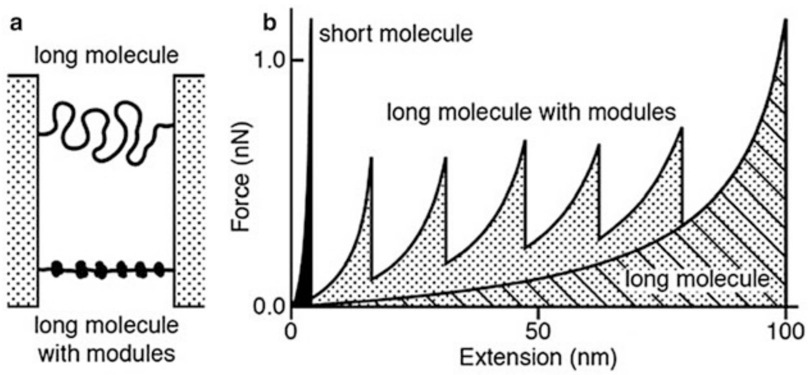

Fig. 2 Concept for an adhesive [10]. (**a**) Two ways to attach two particles: with a long molecule or with a long molecule with nodules. (**b**) When stretched, a short molecule can only be extended a little and would then break. A long molecule would be stretched much more and finally break. However, a long molecule with nodules, with sacrificial bonds that break before the backbone of the molecule breaks, increases the toughness of the adhesive. Such a strategy is applied in the abalone shell and also in diatom adhesives (Reprinted by permission from Macmillan Publishers Ltd: Nature, Smith et al. [10], copyright (1999)

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Fig. 3 Jewel beetles are living jewels. Their cuticle is organized similar to precious opal, a highly prized iridescent gemstone. The brilliant coloration originates from photonic crystals, composed of spheres of a couple of hundreds of nanometers in diameter, arranged in hexagonal densest packing, acting as a Bragg reflector for visible light

Fig. 4 Nanoscale structures are the physical basis for the super-slippery inner surfaces of pitcher plants

Fig. 5 Multifunctional nanostructures on the *Morpho* butterfly and on various other butterflies provide brilliant coloration, temperature regulation, water runoff paths (unidirectional), and much more

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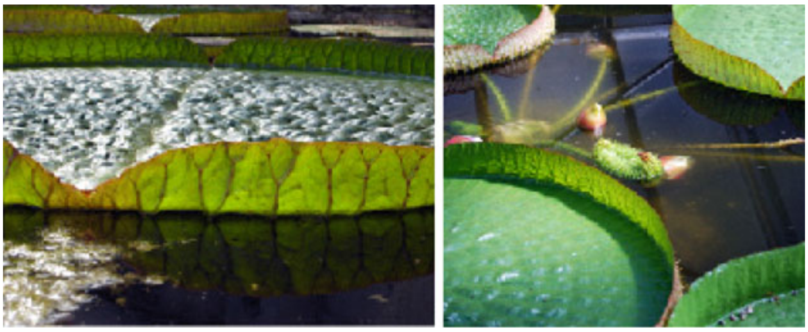

Fig. 6 The giant Amazon water lily grows up to 2.5 m in diameter. Hierarchical micro- and nanostructures provide exquisite self-cleaning properties

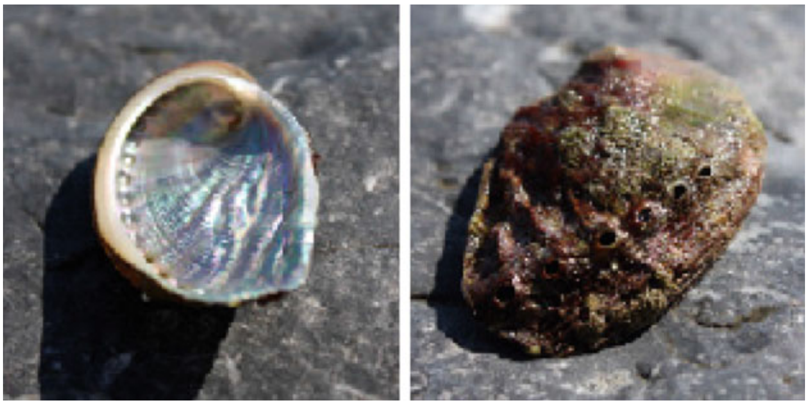

Fig. 7 The abalone shell is a fascinating natural nanocomposite made from calcite and some % of adhesive protein matrix. The fracture toughness of the composite is 1000 times larger than the one of a single calcite crystal

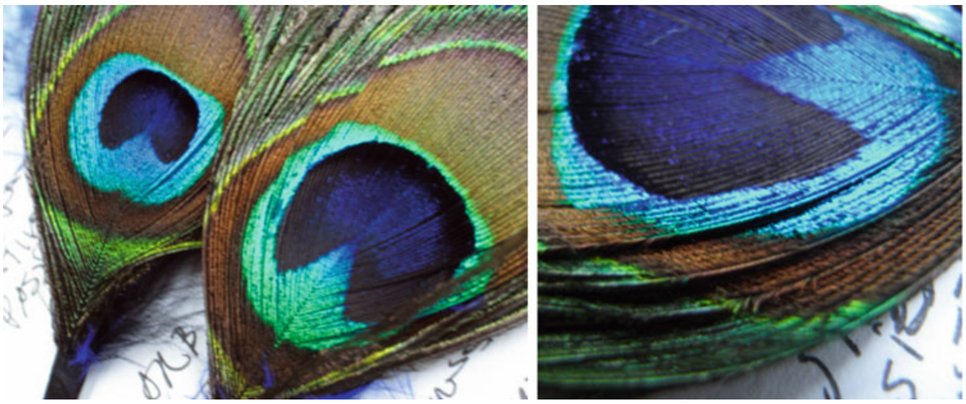

Fig. 8 The brilliant colors of the peacock originate from nanostructures, not from pigments. In the *blue*, *green*, and *light blue* regions, the size of the color-generating nanostructures only differs by some nanometers – an exquisite example of control on the nanoscale by animals

Shape, Growth, and Deployable Structures

The topic of morphogenesis in nature is about the development of shapes in general. In the context of biornametics research, the interest lies in the dynamics of shapes and shape change. The topic focuses on the ontogenetic development of three-dimensional complex shapes (in contrast to an evolutionary perspective) and on other phenomena related to shape change in organisms.

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Fig. 9 The color change abilities of the octopus are legendary. Just recently researchers found the nanoscale reason behind the fast and reversible color change: photonic crystals with tunable size

Fig. 10 The beautiful shape of *Strelitzia* flowers has inspired the shape of quite a few houses. And also on the nanoscale, *Strelitzia* is inspiring: unidirectional water runoff properties on the plant, as if painted by the brush of an artist

Fig. 11 Insects can deploy their wings without anybody from the outside pulling. This makes them interesting for space applications. And on the nanoscale, insect eyes and wings exhibit various structures responsible for functionalities such as antireflectivity, increased reflectivity, and self-cleaning

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The development of organisms is based on cell division, the basis for the generation of tissues and organs. The principles of cell growth as investigated in microbiology can be included, but the focus of the topic lies on the research findings in developmental biology.

Interesting issues are the principles of growth in organisms and the differentiation of tissues and materials [11]. The time-based rules of growth and the spatial geometric definition of growth principles (growth patterns) are of specific importance. Specific topics, for example, branching, should be included.

Especially in the plant realm, the relation between growth and deployment is of interest. On a shorter timescale, fast deployment promises to yield significant biornametics research results or, more general, fast shape change in organisms, which aims at, for example, defense or attraction purposes.

The research of mechanisms leading to shapes and shape change in nature shall go beyond the generation and control of complex geometries by establishing a strong link to efficiencies and functionality. This is also a focus in current architectural research and development.

Biornametics research role models with relevance to shape, growth, and deployable structures are the *Morpho* butterfly (Fig. 5) with interesting nanoscale-based biomechanics; the giant Amazon water lily (Fig. 6) which can grow up to 2.5 m in diameter, supported by functionalities based on nanostructures, nanomechanics, and nanochemistry; the abalone shell (Fig. 7), in which the self-assembly of its toughness-providing complex nanocomposite of protein matrix and calcite bricks can inspire in situ growth of building materials, using, for example, CO_2 from the air and water, similar to various further biomineralizing organisms [12]; and spider silk (Fig. 12), forming strong, tough, large, mechanically stable lightweight constructions.

Adaptation and Reorganization

The topic Adaptation and Reorganization treats the stabilization capacity in dynamic and living systems. The adaptive capacities include structural change that might affect physical properties such as strength, stiffness, or mass/surface ratio. Also deformation relates to the topic Adaptation and Reorganization; it is about form change due to disturbances. Adaptation can also refer to organizational aspects, for example, the implementation of failure-tolerant systems or mass management tools in case of circulation.

Adaptation and reorganization in biological systems are triggered by a change in environment that the organism or system is either subjected to or actively looking for. Therefore methods of adaptation comprise active, explorative strategies and passive, responsive methods to environmental changes. Examples for both explorative strategies and response can be found in climbing plants, lianas, and vines that actively look for a suitable environment and react to change in structural support with reorganization of tissue. Hierarchical vine-tree-like carbon nanotube architecture inspired by the natural role model shows interesting properties of self-assembly into scaffolds with extraordinary material properties that can yield completely new building materials, for architecture and artistic applications, as well as devices that have to withstand specific conditions (parameters in tunable materials are responsive to environmental conditions).

In these cases, adaptation is often achieved by local decision-making and local differentiation. The topic focuses on long-term processes that aim at creating or reestablishing equilibrium in a dynamic system that can deliver valuable strategies for the creation of built environment.

Biornametics research role models with relevance to adaptation and reorganization are spider silk, which can mechanically adapt to changing mechanical conditions by unfolding extra units (such as the need when an insect is trapped, preventing rupture of the net, Fig. 12); the octopus (Fig. 9), with amazing adaptation and reorganization properties on all length scales, of high importance for adaptive buildings and reorganizing structures depending on external needs (e.g., deployable guest rooms); the *Strelitzia*

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Fig. 12 Spider silk is a strong and lightweight material. Its functionality is based on properties emerging from smart arrangement of perfect nanocrystals within a soft matrix and further levels of hierarchy at various length scales

flower (the physics of unfolding flowers is complex and has only recently been treated in detail, Fig. 10); and insect wings (Fig. 11), with their amazing transparent, tough, and strong lightweight deployable structures that serve for a lifetime.

Role Model Research

Role model research is an integral part of the biornametics approach. Being together in a botanic park (or, even better, in a virgin rainforest) with high species diversity, with scientists, architects, biologists, artists, and people from further fields, inspires interdisciplinary and lateral thinking, transdisciplinary discussions, and cross-fertilization of ideas. The first round of biornametics research established 37 role models, 10 of them with functionalities based on nanoscale properties (see Figs. 3, 4, 5, 6, 7, 8, 9, 10, 11, and 12). This collection shall be extended with each cycle, resulting in a "treasure chest" for biornametics researchers and further interesting audience aiming at inspiration from living nature.

Research in the areas of surface patterns, nanotextured surfaces, and nanostructured materials; shape, growth, and deployable structures; as well as adaptation and reorganization yields:

- Relevant new and established literature that is new to the team
- Finding of new interesting phenomena fitting to the three topics
- Good photographs/videos of phenomena (for use in websites, publications, talks, outreach work, etc.)
- Establishing and outfitting of the website with first information

Role Model Search

Starting with the three main research areas, the team applies a solution-based methodology to extract information from living nature and investigates the three areas and the role models through scientific papers. In this bottom-up process, biology delivers the input, with basic topics and specific examples. From these inputs, deep principles are extracted, in an abstraction step, which are subsequently realized in an artificial material, and implemented to architecture, taking into consideration respective boundary conditions and target aims.

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Role Model Data Sheets

The role models need to be investigated further regarding their value for the specific arts-based research approach. A datasheet needs to be developed for each role model. These serve as working draft of the observed role model phenomena and present the underlying scientific information for the arts-based research approach.

The datasheets are organized in two sheets per role model containing an image, the Latin name, the area of defined research, an abstract with a selection of the most interesting features, references, first application ideas, and a functional diagram of the feature to be explored in the further process.

There are ten role models from the first cycle of biornametics research that are based on nanoscale effects; they are introduced in more detail below.

Role Model 01: Jewel Beetle, Coleoptera

Jewel beetles (Fig. 3) are tropical beetles. Their brilliant, iridescent, metallic-looking coloration is highly durable – million-year-old fossil jewel beetles still show magnificent coloration. The color is generated by periodic nanostructures that interact with light. For the coloration, the size of the structures is important, and far less important is the material of the structures (at this size, all is transparent) – which makes this role model very interesting for transfer to technological applications. In some cases, these nanostructures are reactive, i.e., they swell or shrink with certain stimuli, simultaneously changing color. The principle of structural coloration is an example of the deep principle *structure rather than material* and is often applied in living systems.

Role Model 02: *Sarracenia flava*, Pitcher Plant

The yellow pitcher plant (Fig. 4) is a carnivorous plant. Its insides are covered with nanostructures that result in a highly slippery surface for prey insects, yet some symbionts such as pitcher plant spiders can perfectly manage the slippery surfaces and walk on it. Tunable surfaces, which are slippery for certain materials and sticky for others, promise high application potential in architecture.

Role Model 03: *Morpho peleides*, Blue *Morpho* Butterfly

The *Morpho* butterfly (Fig. 5) has such strong, brilliant colors that it can be seen from kilometers away – flashes of blue light in the Costa Rica rainforest. The scales of certain butterflies are covered with multifunctional periodic nanostructures that control wettability, cause coloration, tune water runoff directions, control temperature, etc. Transfer potential to architecture is high, especially for walls and skins of buildings.

Role Model 04: *Victoria amazonica*, Giant Water Lily

The giant Amazon water lily (Fig. 6) can have up to 2.5 m in diameter. Similar to the lotus leaf, its leaves show self-cleaning abilities that are not based on ultrasmooth surfaces but on hierarchical structures, bridging from the nano- via the micro- and meso- to the macroscale. Self-cleaning surfaces are of high interest in human applications (buildings, cars, dishes, clothes, etc.), and also this effect is based on *structure rather than material* and can easily be transferred to art and architecture applications, by using different materials. The size of the structures is crucial though, in combination with the surface tension of the fluids that will come in contact with the surface.

Role Model 05: *Haliotis*, Red Abalone Shell

The abalone shell (Figs. 2 and 7) mainly consists of calcium carbonate, a rather brittle material. Nevertheless its fracture toughness is 1000 times higher than a crystal of the pure material. The secret is in the few % of protein in the material and in the structure of the arrangement. Little bricks of calcium

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carbonate, a couple of hundreds of nanometers in size, are glued together with proteins as mortar. The protein is soft, and an attempt to break the abalone shell results in some little brick breaking, but most of the energy being dissipated in the soft protein matrix. Furthermore, the glue between the calcium carbonate bricks shows highly interesting nanomechanical properties (Fig. 2) that majorly contributes to the fracture toughness of the material: it is a self-healing adhesive. The transfer of properties of the complex nanocomposite of the abalone shell can yield the development of fracture-resistant building materials, which is interesting for earthquake-prone regions, and strong, tough, self-repairing adhesives that are needed in various architecture applications.

Role Model 06: *Pavo cristatus*, Peacock

The peacock (Fig. 8) is a beautiful bird. Its feathers have already been mentioned by Sir Isaac Newton in his classic book *Opticks* as an example for structural colors. When watched with high-resolution microscopes, the physical basis of the brilliant colors of the peacock becomes obvious: feather material is arranged as photonic crystals, with little spheres of similar size in hexagonal densest packing. Regions with different colors on the peacock feather refer to different sizes of the spheres in the natural opal. These size differences are on the order of just some tens of nanometers. The order of this arrangement is amazing.

Role Model 23: Spider Silk

Spider silk (Fig. 11) is one of the toughest materials in living nature. Cloth woven from spider silk is stronger than similar materials woven from Kevlar fibers. On the nanoscale, spider silk is a complex nanocomposite, with beta sheet nanocrystals embedded in semi-amorphous protein phase.

Role Model 34: *Octopus vulgaris*, Common Octopus

In octopus (Fig. 9), part of the impressive and rapid color change is based on nanostructures and their interaction with light. The size of the photonic crystal changes, by smart rearrangement of the matrix between the single optically relevant particles, and this causes the color change – this effect is physically similar to the color change in soap bubbles when they become thinner with time.

Role Model 36: *Strelitzia reginae*, Crane Flower or Bird of Paradise

There are various houses with shapes inspired by the extraordinary form of *Strelitzia* flowers (Fig. 10). *Strelitzia* leaves exhibit unidirectional water runoff characteristics and superhydrophobic properties that are based on minuscule surface structures. Transfer of these properties to surfaces of buildings can result in unique, beautiful patterns for water runoff, in the case of rain, for example, and even the appearance of messages and other text on windows, invisible on sunny days. They can also inspire bird-protective coatings, if their reflective properties are in the UV range, a wavelength portion of light that cannot be seen by people but can very well be detected by birds, who can see in the UV range. In this way, the huge number of birds that die every year from collisions with buildings (this number is in the billions!) can be drastically reduced, without compromising the visual appearance of the building to the human eye. A further property worthwhile of being transferred to architecture and art, and technology in general, is self-cleaning abilities based not on toxic chemical coatings but on structural coatings, which can in principle be obtained by structuring the most outer material of the building, without adding another layer (biomimetic principle: *integration instead of additive construction*).

Role Model 37: Insect Wings

Insect wings (Fig. 11), such as the self-deployable wings of ladybirds, have been inspiring self-deployable structures for space applications and further uses in territories that are unfriendly to people for various decades. With the arrival of the age of nanotechnology, further amazing inspiring properties of insect

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wings and more generally surfaces of insects have been identified. The nanostructures in these organisms are multifunctional and serve various purposes depending on the environment, current situation, and further parameters. Self-cleaning, beautiful non-bleaching coloration, temperature regulation, control of wetting behavior, self-repair, and various optical properties (e.g., reflective, antireflective) have been identified and are starting to be used in applications such as antireflective surfaces of optical lenses and glasses (inspired by the moth eye).

Role Model Categories Diagram

In the following step of the biornametics research methodology, the role models are categorized into the three main established groups. Due to the multifunctionality of biological materials, there will be many overlaps, so some role models fit into several groups, and the aspects that are interesting to investigate are ambiguous.

For example, spider silk (Fig. 11) fits into the category *shape, growth, and deployable structures* and into the category *reorganization and adaptation*.

> Some spiders use glues while others deploy strands of fine filaments for fixing flies. Recent work has provided new insights into the mechanical properties of these nanoscale ropes.
>
> A spider's web, typically in combination with a powerful poison, is its principal tool in the struggle for survival. It is a highly tuned, lightweight net-structure that relies heavily on skillful engineering and the fitting deployment of a most versatile material: the spider's famous silk. A typical web spider makes up to seven different types of silk, some of which can be tuned to suit environmental circumstances by adjustment of the spider's spinning physiology. Individual silk threads, each around a micrometer in diameter, are actively drawn from microscopic spinning spigots perched on motile spinneret mounds, resembling miniature batteries of battle-ship gun-turrets. . . . The resulting filamentous tangle clings to, and often totally covers, a pair of much thicker support fibers issuing from spigots on the main spinnerets. This multiple-fiber rope can be further reinforced by crimped, spring-like fibers from yet another set of spigots, which pull up tight the by now rather complex, composite fiber. ([13], text slightly adapted)

Thus the spider silk follows interesting growth principles during its "spiderfacturing." In this way it also adapts to the neighboring environment so well that it can provide the framework of catching food for its producer.

Art Installation

A physical installation shall be the result of the translation of specific principles encountered, analyzed, and discussed during the research work of the biornametics research approach. The installation shall demonstrate one of the unlimited possibilities of interpretation of a single principle and thus be closely related to the perception of the executing team. The goal in the first round of biornametics research was to build a lightweight and cost-efficient spatial structure with an inherent potential to move, or to be moved, by stimuli from the external environment (Fig. 13).

The primary structural system of the installation reflects a specific organization of fibers arranged in concentric layers twisted clockwise and counterclockwise around a virtual axis. This organization of fibers can be found as a structural principle in several role models investigated during the research, displaying a high capacity to resist and adapt at the same time. This capacity depends on the geometry of the arrangement and the material properties of the fibers. Possible deformations can only happen within certain limits relative to the stiffness of the material and structure. The adaptive capacities of the structure exceeded by far those of conventional structural building elements.

Glass fiber tent poles were chosen for the fibers because of their structural properties, the modularity of the system, and the easy availability at appropriate costs. A few reversible and numerous irreversible

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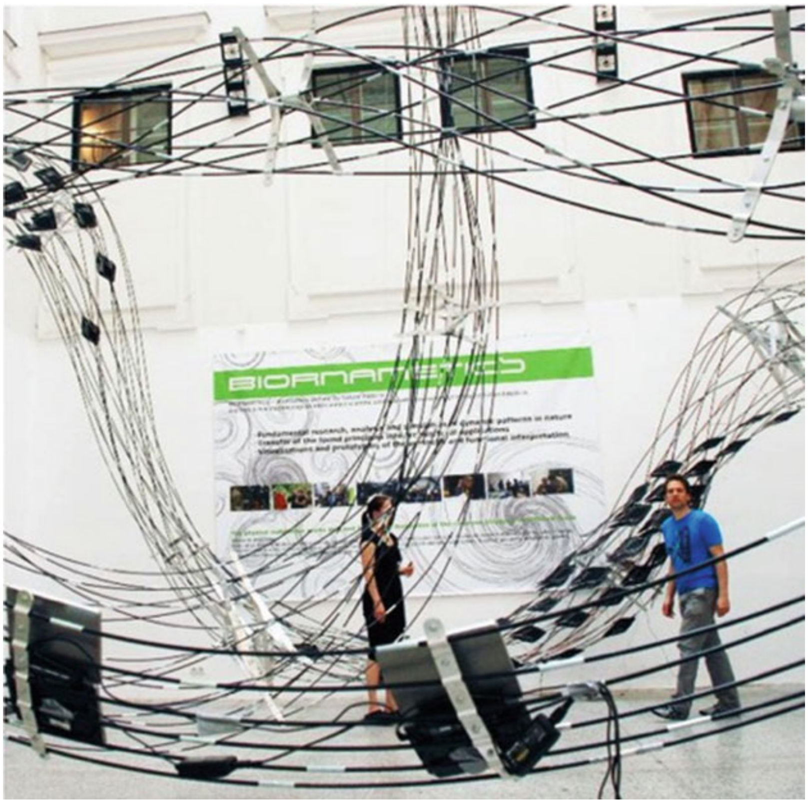

Fig. 13 Art installation in the Silver Gallery at the Vienna University of Applied Arts, Austria. The single parts of the installation were developed in the biornametics research approach

joints had to be defined. The so-called spacers kept the elements at specified distances and positions in order to maintain the spatial arrangement of the overall system.

The joints between the spacers and the fibers were designed to produce as little friction as possible and so allow easy movement by gliding along the fiber’s axis. On the other hand, fixing of the connection points was necessary to ensure that the system would lock temporarily in a chosen position.

The use of a test setup with sensors and movement control would have exceeded the given budget and time restrictions, so the installation was fixed in space, but change in shape was enabled by a controlled and synchronized setup process, specifically by altering unlocked joints in specified places. The whole construction was suspended from the ceiling, and its performance demonstrated a resistance sufficient to maintain its shape.

Adaptable stiffness of the structure (not necessarily of the material involved) could be a point of departure for future development of more flexible and even reversible building systems (e.g., structures exerting increasing resistance under increasing external forces). On a second level of hierarchy, the installation demonstrated another adaptive process often found in nature: speeds of transformation varying in reaction to specific environmental changes. The system consisted of reactive leaflike structures that were partially fixed to the primary fiber structure together with sensory, control, and actuation equipment. The elements were added in a cantilevering mode and therefore reached a higher level of flexibility and of visible change.

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Future Directions of the Field

In the fourth round of the PEEK funding scheme, *GrAB*, *Growing as Building*, the sequel arts-based research approach to biornametics, was funded by the Austrian Science Fund FWF in the frame of PEEK 2011. *GrAB – Growing As Building* – runs from 2013 until the end of 2015. GrAB takes growth patterns and dynamics from nature and applies them to architecture with the goal of creating a new living architecture. The aim of GrAB is to develop architectural concepts for growing structures. Three main directions are investigated: transfer of abstracted growth principles from nature to architecture, integration of biology into material systems, and intervention of biological organisms and concepts with existing architecture. Key issues of investigation are mechanisms of genetically controlled and environmentally informed, self-organized growth in organisms and the differentiation of tissues and materials.

Research parameters include, for example, size, height, speed, and properties such as the stiffness or flexibility of structures, which are equally important in living systems and in architecture [14].

The methodology of biomimetic information transfer used is based on refined methods from biornametics research. Computer simulations remodeling relevant principles and physical models are used to understand selected natural phenomena and inform the translation process. Artistic and architectural tools and methods are jointly used with practices from the natural sciences. A Biolab provides hands-on experience with growth of organisms.

The architectural interest lies in the development of structures in a specific environment following an interaction of elements derived from natural pattern formation. To support the transfer of dynamic, growing structures, recent advancements in processing technologies such as additive manufacturing systems are investigated and possibly integrated into design concepts and both analogue and digital models. Scales tackled can include materials (also nanoscale), built elements and structures, as well as urban systems.

Along with architects and artists, scientists from the field of biology, biomimetics, and engineering including students collaborate to develop this arts-based research approach in a holistic way and to supply all the necessary expertise.

The work on GrAB commenced in June 2013 and will run for 2.5 years until the end of November 2015. The host research institution is the University of Applied Arts, Vienna; key people are Barbara Imhof and Petra Gruber. Collaborating institutions are located in Austria, the United Kingdom, Germany, the Netherlands, and Ethiopia.

Nanoscience and nanotechnologies are important for various aspects of GrAB, with the language of life being spoken and programmed on the nanoscale, with evident effects on the micro- and mesoscale, and finally on the macroscale of the built environment and urban systems.

Cross-References

► Biomimetics
► Nanostructures for Coloration (Organisms Other Than Animals)
► Structural Color in Animals

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