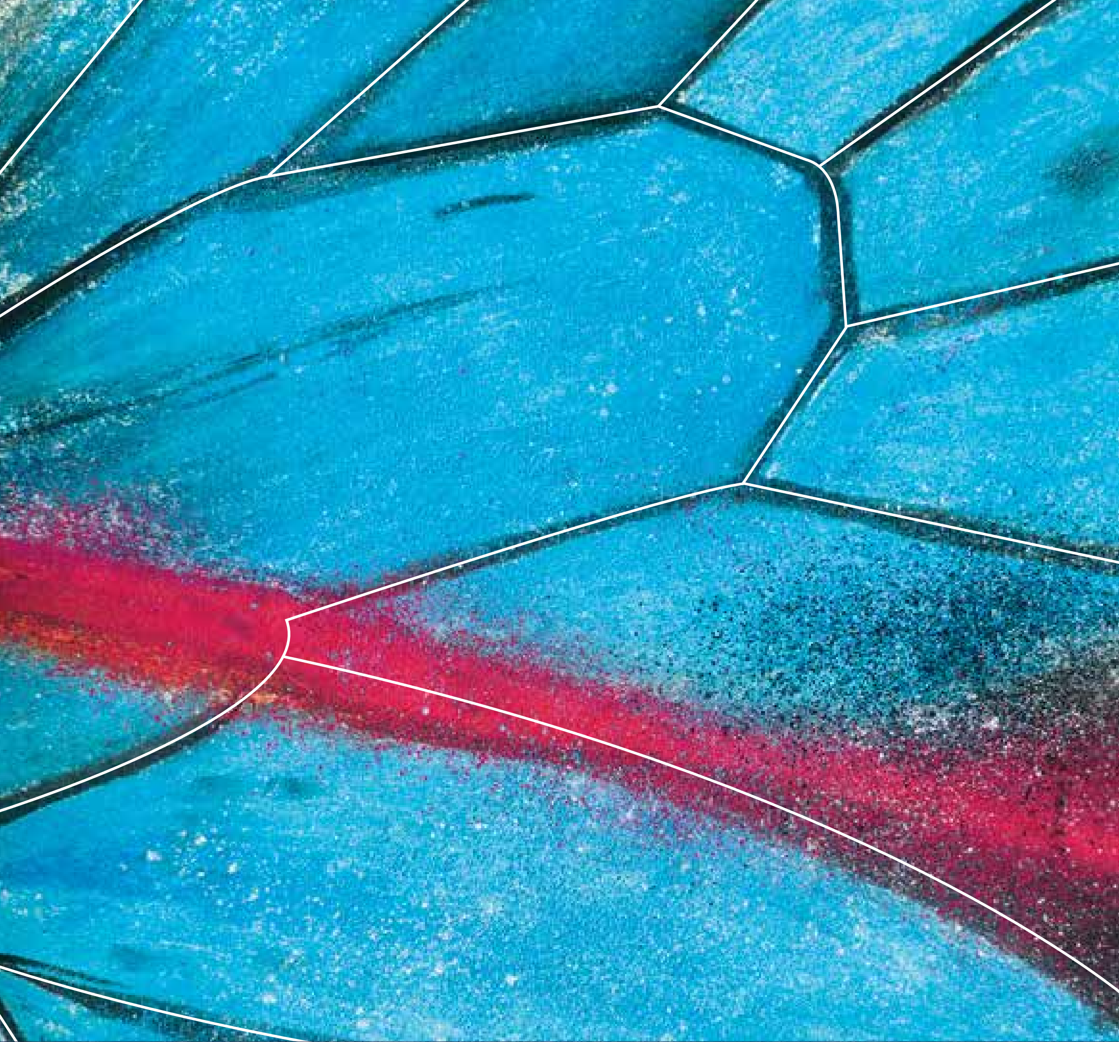

Biomimicry: “Learning from nature for sustainable solutions”

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Colophon

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Content

Preface

Since 2017 Aeres University of Applied Sciences Wageningen, InHolland University of Applied Sciences and Van Hall Larenstein University of Applied Sciences have been collaborating in the Biomimicry lectorate set up by the Ministry of Economic Affairs.

Biomimicry is a discipline that, in order to resolve a 'human' problem, first investigates how nature has resolved it. The core idea behind biomimicry is that innumerable organisms have already 'discovered' what works, what is suitable and what lasts, and then look and learn from this to create new products, processes and conceivable ways of living and working together over the long term.

Biomimicry is primarily linked to technological developments. There are many examples of products and innovations based on biology. Engineers, architects and designers make use of new knowledge that we have gained and continue to gain through studying nature using modern resources. Mauro Gallo provides examples of this and is conducting further research in this area.

There is more to be learned from nature as a whole. In practice 'nature' is often used in teaching, training, consultancy and organisational development as a metaphor, as a source of inspiration or as an example for all kinds of processes, including leadership, cooperation, relationships and the development of organisations and society. Mainly ecological, and much less frequently biological, processes are generally involved here. The question has gradually arisen whether we can learn more from nature in the social environment than what we 'see' on the surface - which is often translated in metaphors. Seen more holistically, this is about the systemic side, the complexity, the context and the coherence. For example, can we demonstrate that applying fundamental ecological principles, such as cycles (learning, self-organising, self-regulating and self-sufficient capacity), succession, diversity and resilience, social and cooperative behaviour, interconnectedness and interdependency within an organisation leads to a sustainable organisation?

In his lectorate, Mauro Gallo is conducting research into the significance of technical innovation in and for the agricultural and food sector, and into the question whether biomimicry can in fact be backed up in such a way that it contributes to the social sciences domain. At the same time there is a clear teaching issue: Is it logical from the perspective of our green DNA to include biomimicry thinking in our teaching? Is it possible to learn to apply biomimicry, and can biomimicry be applied in teaching/learning? (How) can we apply biomimicry in green VMBO and MBO, pass it on to the teachers of the future in teacher training courses and include it in making current lecturers more professional? Is it conceivable that it could become an integral component of the curricula in green HBO?

As outlined above, these are sufficient practical questions for a lectorate.
However, the focus here is not only on application, but emphatically on the scientific justification of bio-inspired solutions and on teaching. Mauro Gallo is attached to a research group at each of the three universities of applied sciences, conducting separate research at each of them. Bringing together the people and the experiences, and developing expertise together and sharing it, also form part of the scope of the lectorate.

Madelon de Beus
Director Aeres University of Applied Sciences Wageningen

What is biomimicry?

Biomimicry and biomimetics are synonyms and derive from ancient Greek: 'bio' (life/nature) and 'mimesis' (imitating). Therefore, biomimicry and biomimetics literally mean 'imitating nature'. It is worth noting that the term bionics can also be considered as a synonym of biomimicry even though its origin is different. Bionics derives from the contraction of the words 'bio' (life/nature) and 'like'. Jack E. Steel, a medical doctor and US Air Force Colonel, used the term bionics in the 50s-60s to indicate systems that copy some function and/or characteristic of a biological system. However, as a result of the television series 'Bionic Woman' in the 70s, the term bionics also has the connotation of 'biological + electronics'. The literal definition of biomimicry, biomimetics and bionics does not provide us with a full understanding of this new emerging discipline because it does not answer the questions: 'Why', 'How' and 'What' do we need to imitate from nature? Before introducing a more detailed definition of biomimicry capable of answering these questions, it is important to clarify the concept of nature and the relationship of humans with it.

1.1 Nature and humans

Nature comprises those classes of living things and systems that come into existence independently of human intention. Environmentalism, conceived to protect these living things and systems, has its roots in the movements of nature conservation and nature preservation. Conservationists aim to conserve natural resources such as timber, minerals, soils and water so that they continue to be available for future generations. As the conservationist approach consists mainly of maintaining a status of the ecosystems that is productive for human purposes, it can also be considered as an anthropocentric approach. Nature preservationists seek to maintain ecosystems undisturbed in their original status or to restore the original conditions in ecosystems modified by human intervention (Mathews F. 2011). The preservationist approach can also be considered a biocentric approach because it considers the life system as morally relevant as humans. In other words, the preservationists or biocentrists are on the side of nature. The opposing anthropocentric and biocentric approaches result from the dualism inherent in the definition of nature considered as an entity in contrast with humanity. It is worth noting that the anthropocentric and biocentric approaches are both unsatisfactory. The anthropocentric approach sees nature as a resource, thus denying the fact that living things and systems share moral qualities with us. Being on the side of nature, as biocentrists are, is strategically incorrect since this stance neglects the fact that humanity has a prominent role in the struggle for the earth. To prevent this conflict it is necessary to introduce a new conception of nature that is able to accommodate both the human and nonhuman components without erasing the distinction between them. This new conception of nature is based on an environmental ethic where humans and their activities and artifacts are on the same moral level as nature. The inclusion of humans in nature does not imply living in small communities almost fully dependent on nature and with minimal technological development. On the contrary, the absorption of humanity into nature means that human activities and artifacts are a potential expression of nature. This means that just as nature is expressed in the handiwork of spiders and bees, in the same way nature has to find its expression in human artifacts too. The reintegration of humanity into nature introduces a change in our design philosophy. Nature and the related governing laws should be integrated in the design process. Therefore, humanity needs to understand the laws and functions governing living things and systems and incorporate them into the design of new artifacts. This means that humans need to look at nature as a mentor, i.e. as an entity from which they can learn.

1.2 Definition of biomimicry

A more comprehensive definition of biomimicry is given by the biologist and scientific writer Janine Benyus who has also developed it further with the connotation of sustainability (Benyus 1997):

> *"Biomimicry is learning from and then emulating natural forms, processes and ecosystems to create more sustainable designs."*

The analysis of Benyus' definition enables us to answer the questions: 'Why', 'How' and 'What' do we need to imitate from nature? The definition beginning *"Biomimicry is learning from..."* describes the terms of our interaction with nature and therefore provides the answer to the question: "How should we imitate nature?". Indeed, as illustrated in section 1.1, we have to imitate and be inspired by nature by regarding it as a mentor and not as a bank of resources to be exploited for the realisation of human artifacts and activities.
The definition also answers the question: "What do we need to imitate in nature?". Indeed, as stated in the definition, nature can be emulated in all its expressions: *"natural forms, processes and ecosystems"*. To better support bio-inspired design, it is important to express in more detail the biological levels that can be emulated. Vakili and Shu listed (Table 1) the levels of biological organisation that can be used to identify biological analogies (Vakili and Shu 2001). They range from the molecular level, e.g. DNA, to the biosphere/ecosystem level. Moreover, table 1 shows the possible fields of applications for each biological level of emulation.
The reason (why) of this kind of emulation/inspiration is to *"create more sustainable design"*. The diagrams of Fig. 1 show quantitatively the capability of nature-inspired design to generate more sustainable solutions of human/technical problems (Vincent, et al. 2006). Fig. 1a and b show the resources (energy, information, material, etc.), arranged according to size, employed by humans (Fig. 1a) and by nature (Fig. 1b) to solve problems.

At size levels of up to 1 m, where most technology is sited, the most important variable for the solution of a problem is manipulation of energy usage, closely followed by significant use of material and space (Fig. 1a). Thus, faced with an engineering problem, our tendency is to achieve a solution by changing the amount or type of the material or changing (usually increasing) the energy requirement. However, in biology the most important variables for the solution of problems on these scales are information and space (Fig. 1b).

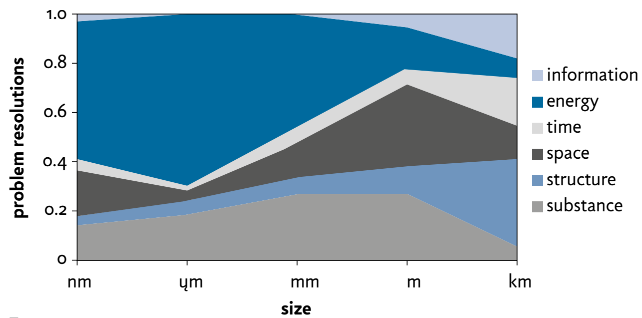


Fig. 1a

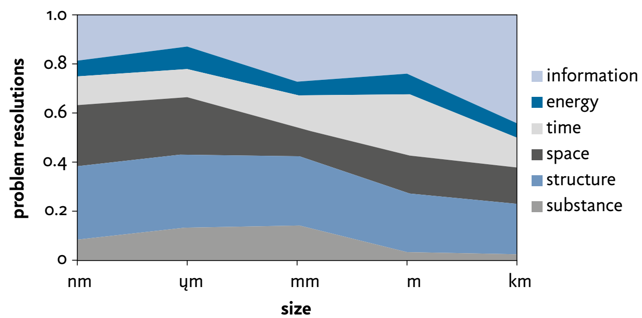


Fig. 1b

Fig. 1 – Problem solutions arranged according to size hierarchy (Vincent et al., 2006): a) engineering solutions; b) biological solutions

Levels	Intermediate levels	Possible applications
Molecule		Chemical, processes, catalysis, nanosystems
Organelle One of several formed bodies with specialised functions suspended in the cytoplasm found in eukaryotic cells.	Protein	Components, single function systems, microsystems
Cell The lowest level of organisation where all the properties of life appear.	Virus	Microsystems
Tissue An integrated group of cells with a common structure and function.		Materials, composites, smart materials
Organ A specialised centre of body function composed of several different types of tissues.		Single function systems, sub-systems
Organ system An organised group of organs that carries out one or more body functions.		Multi-function systems, information systems
Organism A complete living being composed of one or more cells.		Autonomous systems, multi-function systems
Population A group of individuals of one species that live in a particular geographic area.	Family unit	Self-organising systems
Community All the organisms that inhabit a particular area; an assemblage of populations of different species living close enough together for potential interaction.	Host–parasite symbiosis	Competing systems, co-operative systems
Ecosystem A level of ecological study that includes all the organisms in a given area along with the abiotic factors with which they interact; a community and its physical environment.	Biome	Complex systems, macrosystems
Biosphere The entire area of the earth that is inhabited by life. The sum of all the planet's ecosystems.		Macrosystems, isolated systems

Table 1 – Levels of biological organisation and possible applications (Vakili and Shu 2001)

1.3 Terminology

As many disciplines intersect the biological and life science domain, it is useful to define related, commonly used terms. This will define the position of biomimicry and biologically inspired design in this intersection. Moreover, several terms are reciprocally used for biologically inspired design.

Bioengineering, biological engineering, biotechnical engineering: application of engineering principles and tools, e.g. physics, mathematics, analysis and synthesis, to solve problems in life sciences, and may involve the integration of biological and engineering systems.

Biomechanics: application of mechanical principles, e.g. mechanics, to study and model the structure and function of biological systems.

Biomedical engineering: application of engineering principles and techniques to the medical field, e.g. the design and manufacture of medical devices, artificial organs, limbs, etc.

Biophysics: term used by Otto Schmitt (Schmitt 1969) to mean both applying physical sciences to solve problems in biological sciences, and the biologists' approach to problems in physical sciences/engineering.

Biomimetics: the study of formation, structure, or function of biologically produced substances and materials (such as enzymes or silk) and biological mechanisms and processes (such as protein synthesis or photosynthesis) specifically for the purpose of synthesising similar products by artificial mechanisms which mimic natural ones (Schmitt 1969).

Biomimesis, Biomimicry, Biognosis, Bioinspiration, Biomimetic design, Bioanalogous design, Biologically inspired design: synonymous with biomimetics to mean emulating natural models, systems, and processes to solve human problems.

It is interesting to note that, with the exception of the bidirectional term biophysics, there are two main directions in the above intersection between biology and engineering. The first aims to apply engineering principles to solve problems in life sciences, and includes terms such as bioengineering, biomedical engineering and biomechanics. The second aims to apply principles of biological systems to solve engineering problems (Shu, et al. 2011).

Usually biomimicry is erroneously associated with biotechnology, which is the use of living systems and microorganisms to develop, make or modify products or processes. The following example effectively highlights the difference between these two disciplines (Fig. 2): a piece of land is contaminated by pollutants produced by industrial activities. Researchers know that a certain family of bacteria, spread all over the field, can ingest these pollutants, making them inert and no longer harmful for the environment. These bacteria colonies can therefore be used to restore the original environmental conditions altered by the products of industrial activities.
This remediation strategy cannot be classified as a biomimicry application because in this context humans have used living systems or microorganisms from nature to solve a problem and therefore nature emulation, which is the main feature of biomimicry, is absent.

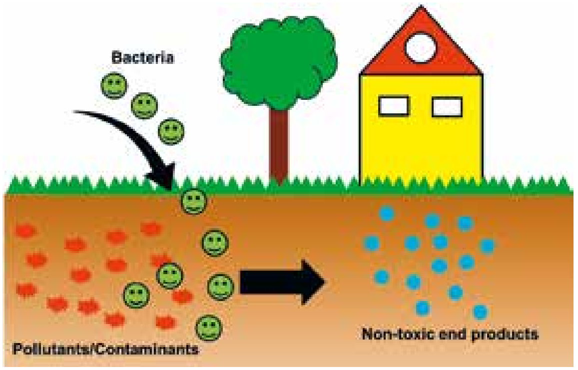


Fig. 2 – Example of biotechnology application

Velcro

The name Velcro, a common hook-and-loop fastener, comes from the French words for velvet, "velour," and hook "crochet". In the early 1940s, Swiss engineer George de Mastral noticed the tendency of the fruit of the burr *(Xanthium strumarium)* to stick to a dog's hair and used a microscope to observe the hooks on the fruit which attach to animal hair (Fig. 3a). He discovered that an elliptical fruit with a length of 1 cm had densely packed hook-like projections. These latched onto peoples' clothing or animals' hair, allowing seeds to be dispersed widely. Inspired by this burr, de Mastral used nylon to create Velcro fasteners (Fig. 3b). To enhance its adhesive abilities, Velcro consists of a strip with round loops and a strip with burr-like hooks. For its small surface area, Velcro has exceptional adhesive strength and is used extensively as a simple and practical substitute for buttons or hooks in clothing and shoes (Hwang, et al. 2015).

Fig. 3 – Example of bio-inspired design at form level:
a) Burr (Xanthium strumarium); b) Velcro fasteners

WhalePower

WhalePower has developed a new fan and wind turbine blade design using tubercle technology. Frank E. Fish noticed that the leading edges of humpback whale flippers have tubercles or bumps (Fig. 4a). This did not make sense to him because it went against the normal way of thinking. By means of wind tunnel tests, Fish discovered that the tubercles on the flipper delay the stall angle by approximately 40%, while increasing lift and decreasing drag. Current wind turbine blades require a steady, high wind to generate electricity. The efficiency of the electric fan depends on how much energy it needs to move air. Blades designed using tubercle technology (Fig. 4b) are more energy efficient. The wind turbine blade requires lower wind speeds, increasing the amount of time and the number of locations where they can actively generate electricity (Baumeister, et al. 2011).

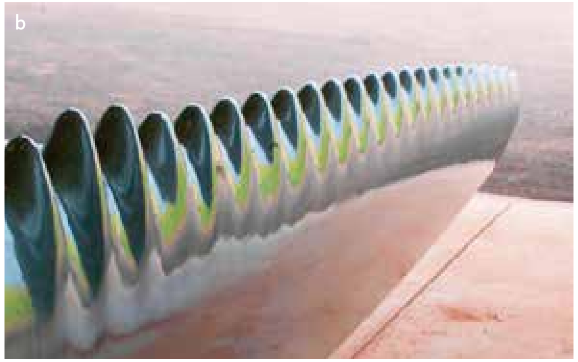


Fig. 4 – Example of bio-inspired design at form level:
a) tubercles or bumps on the leading edges of whale flippers;
b) blade designed using tubercle technology (whalepowercorp.wordpress.com/wind-turbines)

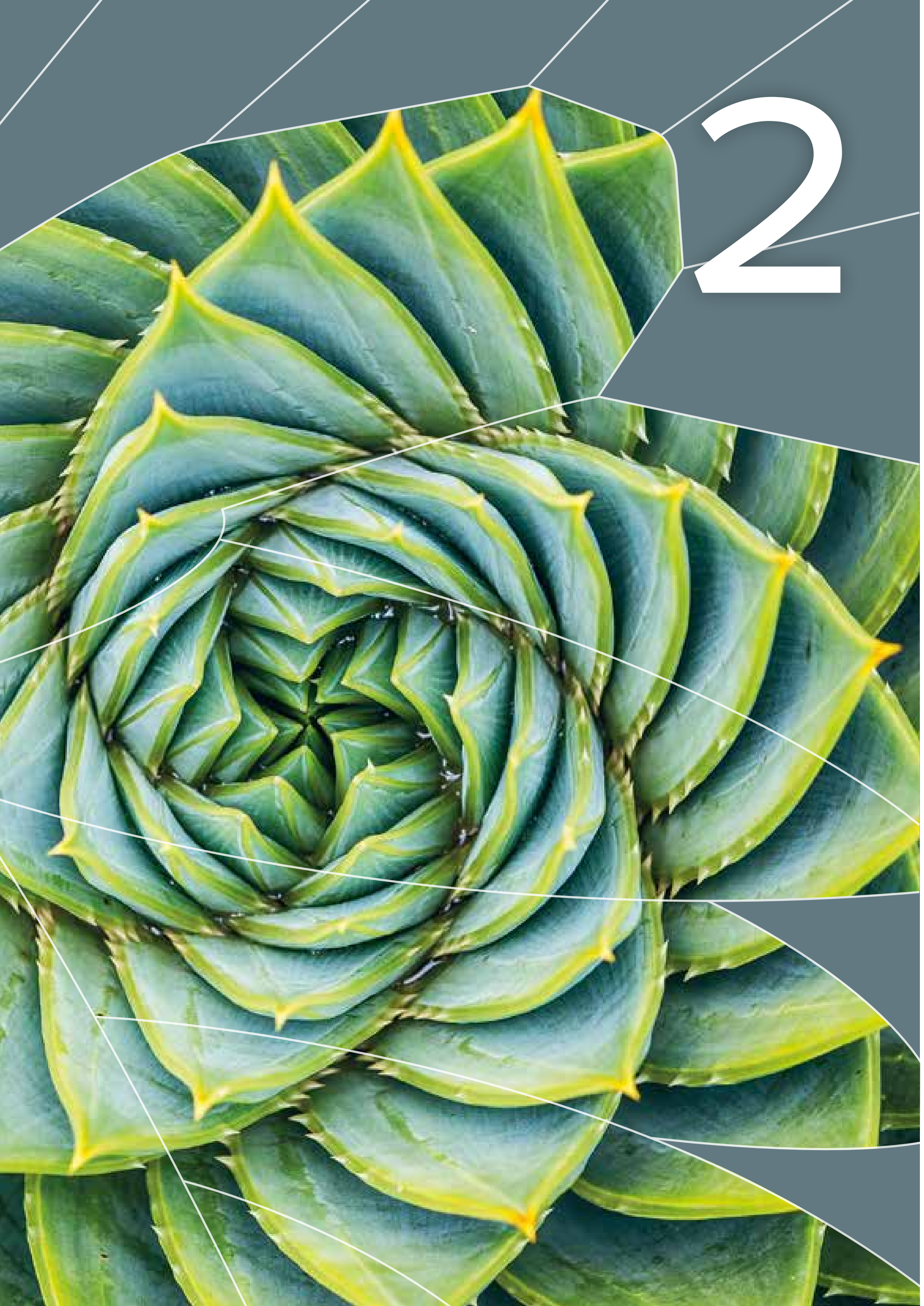
Calera

To make conventional cement, industries extract limestone, heat it to 1450°C to form clinker, which is then pulverised. This energy-intensive process uses fossil fuels and releases CO_2 previously captured on a geological time scale. Calera Corporation has developed an alternative biomimetic process for producing cement that mimics the creation of limestone deposits. First there is the biological phase: coral makes aragonite, a polymorph of $CaCO_3$, in saturated salt water by crystal nucleation – a small crystal of $CaCO_3$ acts as a seed from which the other crystals form. The second phase is geochemical: coral aragonite exposed to freshwater is unstable and spontaneously converts to calcite, a different, yet stable $CaCO_3$ polymorph. Calera produces aragonite from carbon dioxide in saturated brine. By spraying supersaturated brine through flue gas, it converts gaseous CO_2 to carbonic acid and bicarbonate ion. The pH is then raised to precipitate aragonite out of the solution, which dries using waste heat from flue gas. When this aragonite is mixed with fresh water during concrete production, it changes into the more stable calcite and hardens (Baumeister, et al. 2011). Calera's process sequesters CO_2 instead of releasing it, making it not just carbon neutral, but even carbon negative (Fig. 5).

Fig. 5 – Example of bio-inspired design at process level: Calera's concrete production

Kalundborg Industrial Symbiosis

Symbiosis means co-existence between different organisms with a mutually beneficial realtionship between them. In the ancient harbour town of Kalundborg, Denmark, various processing companies, a waste handling company, and the Municipality of Kalundborg participate in industrial symbiosis. All participants exploit each other's residual or by-products. The symbiosis is cooperation self-organised over a number of decades and today comprises some 20 projects (Baumeister, et al. 2011).



Biologically inspired design

The previous section has shown some very inspiring examples of biomimicry and it is worth noting that most of them have been achieved without any systematic approach to design. They have been obtained either by serendipity or via very long and frustrating 'trial and error' processes. As biomimicry is a new emerging discipline, the development of a systematic approach to bio-inspired design is still a lively and dynamic field of research. Initially, biomimicry has mainly attracted the interest of designers and engineers who, by questioning nature, aim to discover more creative and efficient solutions to their challenges. For this reason the design processes and methodologies have been developing mainly in technology and engineering. Interdisciplinary, abstraction and functional modelling are the main characteristics of bio-inspired design. In addition, these aspects are not dependent on the specific disciplines, thus the methodologies and processes described in the following sections can also be adopted to solve problems in a diverse field such as social sciences. The next section illustrates the philosophy underlying bio-inspired design. The current framework for bio-inspired design and the related supporting tools will then be shown. This section ends with a discussion of the approach we intend to adopt to teach, learn and practice biomimicry.

2.1 Design philosophy and life's principles

The biomimicry design philosophy has been conceived by thinkers such as the biologist Janine Benyus and the economists Amory and Hunter Lovins. According to Benyus, nine principles can be identified as underlying nature's designs. Nature, Benyus argues, (i) runs on sunlight, (ii) uses only the energy it needs, (iii) fits form to function, (iv) recycles everything, (v) rewards cooperation, (vi) banks on diversity, (vii) demands local expertise, (viii) curbs excesses from within, and (ix) taps the power of limits (Benyus 1997). If we designed our industry and our built environment in accordance with these principles, Benyus suggests, we would be well on the way to living within the ecological limits of nature, and thus achieving our goal of sustainability. Given the descriptive nature of life's principles, they represent for the designers a sort of guideline for bio-inspired design. Life's principles such as 'bank on diversity' or 'nature runs on sunlight' serve to define the designer's *modus operandi*, but they do not make nature more intelligible to us. Only when we have understood why nature runs on sunlight and why it banks on diversity, can we truly get inside nature's mindset and design our world, non-dualistically, from inside this mindset. Mathews identifies two main principles underlying biomimetic design (Mathews F. 2011). The first is defined as autopoiesis or conativity and refers to the ability of a natural organism to reproduce and maintain itself. The striving to preserve own integrity and existence is the hallmark of all living things. However, there is another hallmark of living systems. It pertains to the very particular manner in which they pursue their conative ends. They do so in a way that involves the least expenditure of effort on their part. Mathews proposes to call this the principle of least resistance. Whenever organisms meet resistance they are inclined, if circumstances permit, to turn aside, seeking to avoid obstacles rather than meet them head-on. The path of least resistance is thus a path by which one seeks to fulfil one's own conativity while, as far as possible, accommodating the conativity of others. As living systems ourselves, we humans are also essentially conative beings: our fundamental impulse is to strive to preserve the integrity of our own existence and maintain ourselves in existence. In this respect, we are basically 'part of nature'. However, because we are endowed with reflexive awareness, we can reflect on our own nature, and, by reflecting on it, modify it. Moreover, against the immediacy of gratification, we can choose to depart from the principle of least resistance and act instead in an 'impose and control' mode, that effectively places us 'outside nature'. In modern civilisation, science has enabled technologies to provide unlimited supplies of energy in the form of electricity, nuclear power, thermal power, etc. As this power generation comes from the exploitation of external (natural) energy resources and not from our own life force, we do not perceive any self-depletion. This gives us the apparent freedom to act with impunity on the environment but, without being fully aware, we are depleting the environment in which we live and, in the long term, this kind of behaviour will have serious effects on our life on earth.

2.2 General aspects of bio-inspired design

Usually design activities start with the need to solve a problem. Indeed, the first step of 'traditional' design process, depicted in Fig. 6, is problem definition. This step is followed by the identification of requirements that the device has to meet, then the creative part of the design process starts: concepts generation. In the 'traditional' design process these concepts are generated within the designer field of the expertise (mono-disciplinary approach). The designer selects the most promising concept based on criteria previously defined, then the operations related to testing and implementation follow.

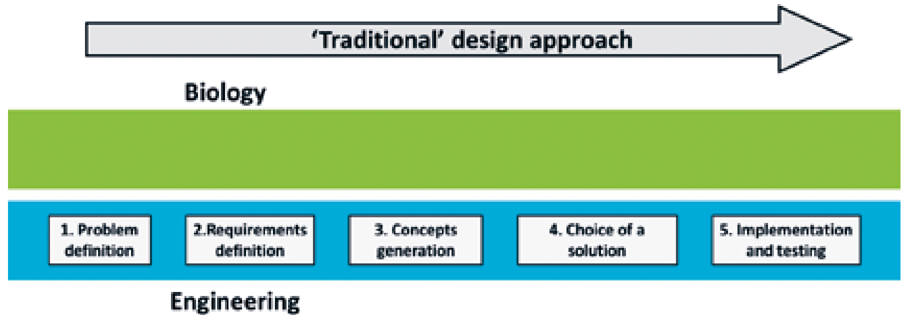


Fig. 6 – Main steps of the 'traditional' design process

The main difference between 'traditional' and bio-inspired design is the creative part of the design process: concepts generation. While in the 'traditional' design approach the concepts are generated by using the experience and specific knowledge of the designer, with the bio-inspired approach the concepts are generated in the biological domain: a discipline not familiar to designers who typically have a background in engineering and/or industrial design. With bio-inspired design, the designer has to find solutions to the problem by going beyond her/his field of expertise and crossing the boundary of the biological domain. The designer needs to enter into the biological domain and must identify the biological systems to be emulated to generate the concepts. Similar to the 'traditional' approach, the concepts are evaluated on the basis of predefined criteria and the final concept is then chosen. The bio-inspired design process, so far described, is defined as a problem-driven approach in which a given problem motivates the search for biological analogies that could support the problem solution. Together with the problem-solving approach, bio-inspired design is also affected by another holistic design approach, i.e. the solution-driven approach: an interesting biological phenomenon inspires the search for potential applications.

Regardless of the type (problem-driven or solution-driven) of holistic approach adopted, the main challenge in bio-inspired design process is access to the biological domain. So far the science has developed with a very reductionist approach. Engineers, designers, architects, planners, social scientists, chemists, material scientists, biologists, etc. have been trained with a mono-disciplinary approach. This has created the development of a different mindset and scientific jargon which have made communication and knowledge sharing between different domains impossible. Biology is largely descriptive and creates classifications, whereas engineering is the result of decision-making; it is prescriptive and generates rules and regularities. As to the scientific language, for example, for biologists, 'stress' represents extreme conditions such as heat, lack of water, or predators, to which organisms must respond using physiological, behavioural, genetic, developmental, or

other mechanisms. For mechanical engineers, 'stress' is the measure of force per unit area on a deformable body. Such differences occur even within the broad field of engineering, but become increasingly significant as more disciplines are involved (Yen, et al. 2014).
Functional modelling and abstraction are 'tools' that designers and biologists can use to make connections and parallels between biological and engineered systems. Abstractions allow one to capture the essence of a product, process, or component as well as of a biological system within a succinct phrase, diagram, image, or domain-independent terms (Nagel, et al. 2010). The use of functional modelling by designers and biologists allows the transfer of biological systems and technical challenges in a 'neutral and abstract environment' (Fig. 7). The technical challenges and biological systems are expressed in their true form without any scientific jargon. This 'neutral and abstract environment' is therefore the place where it is possible to create analogies and metaphors leading to creative leaps.

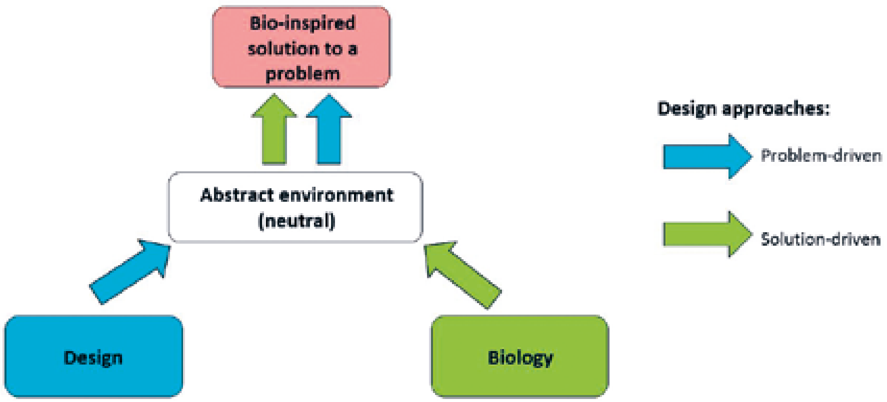


Fig. 7 – Schematic of the problem-driven and solution-driven design approach

The following two examples related to the solution-driven and problem-driven design approach are described with the aim of emphasising the key role of functional modelling for bio-inspired design.

Example a): solution-driven design approach
Consider a leaf as an interesting biological system which can potentially lead to a solution in the technical domain. Definition: *a leaf is an organ of a vascular plant and is the principal lateral appendage of the stem. The leaves and stem together form the shoot. Although leaves can be seen in many different shapes, sizes and textures, typically a leaf is a thin, dorsiventrally flattened organ, borne above ground and specialized for photosynthesis* (Wikipedia 2018). The descriptive definition of the biologist does not stimulate the interest of the designer because the definition, barely understandable for a non-biologist, does not explicitly state the functions that can inspire a solution for a technical problem. Actually the main function of the leaf is present in the definition and is expressed by the word *photosynthesis* which is the process used by plants and other organisms to convert light energy into chemical energy. Therefore, a synthetic functional definition of a leaf could be: *energy conversion system (light energy → chemical energy)*. This kind of functional definition enables the transfer of the biological system (leaf) from the biological domain to the abstract environment (Fig. 7) and catches the interest of the designer, who will look at the leaf as a possible biological solution for technical problems involving energy conversion processes.

Example b): problem-driven design approach
Consider a team of engineers/designers addressing the following technical challenge: *development of a new recuperator design for a combined cycle power plant*. The challenge formulated in these terms is not comprehensible for the biologist. Indeed, the term 'recuperator', denoting the component to be upgraded, is understandable for experts in energy conversion systems, but could be a misleading term for the biologist who may wonder: What do we have to recuperate? Water, material, energy? In order to answer this question, the designers have to present the challenge in terms intelligible for the biologist. Therefore the designers can describe the recuperator in functional terms saying: *the recuperator is a device in which heat transfer takes place between a hot and cold fluid*. This kind of description enables the transfer of the technical challenge to the abstract environment (Fig. 7) and enables the biologist to understand the main function (heat transfer) and then to identify the biological domain strategies adopted by organisms to fulfil this function.

2.2.1 Solution-driven design approach

Based on observation of the design processes of students, Helms, Vattam and Goel have extrapolated the main steps involved in the solution-driven design approach (Helms, Vattam and Goel 2009). A biological system that arouses the curiosity and interest of the students triggers the design process.

1. *Biological Solution Identification:* Designers start with an interesting biological phenomenon in mind.

2. *Define Biological Solution:* This step involves designers moving from structures and superficial mechanisms to a deeper understanding of the biological system. If, for example, an abalone shell is chosen as an inspiring biological system, the students have to move from the easily detectable functions/properties such as hard, lightweight, resists impact to an understanding of the complex interactions of composite materials that are responsible for this behaviour. Functional decomposition typically used for engineering problem definition can also assist understanding of the biological solution.

3. *Principle Extraction:* Once the biological phenomenon is sufficiently understood, principles are extracted into a solution neutral form, which involves removing reference to structural and environmental entities of the biological domain. For example, instead of describing the abalone shell as 'interaction between flexible proteins and hexagonal calcium carbonate deposits', the principle is expressed as 'tightly coupled composite material formation by alternating flexible and rigid structures for resisting impact'.

4. *Reframe Solution:* Reframing the solution involves considering how humans would view the usefulness of the function achieved by the biological phenomenon.

5. *Problem Search:* After reframing the biological phenomenon as its usefulness to humans, human problems to which the principle can be applied are identified.

6. *Problem Definition:* An identified problem is defined using tools such as functional decomposition and optimisation.

7. *Principle Application:* The biological principle is translated into the engineering domain by introducing new constraints (and affordances), e.g. weight, flexibility, impact resistance and manufacturing process criteria. The principle is then applied to develop a solution to the identified problem.

Fig. 8 shows the main steps of the solution-driven approach to bio-inspired design. As can be seen, to achieve a bio-inspired solution for a technical problem and/or an innovative way of fulfilling a technical task, during the design process it is only necessary to cross the boundary between the technical and the biological domain once.

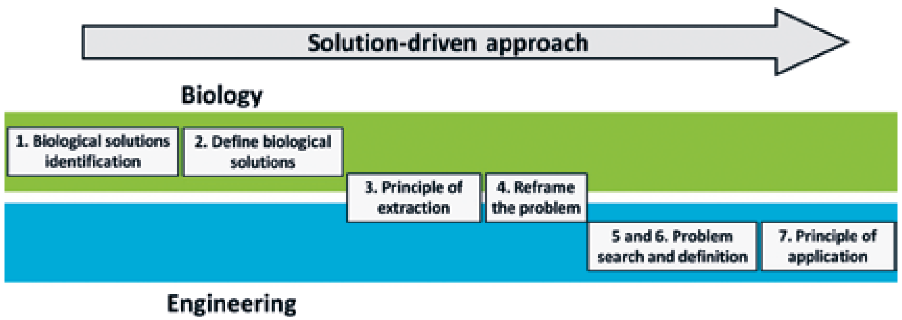


Fig. 8 – Steps of the solution-driven design approach

2.2.2 Problem-driven design approach

The main steps involved in the problem-driven approach are illustrated in the following (Helms, Vattam and Goel 2009). The description of some steps such as '*define the biological solution*', '*principle of extraction*' and '*principle of application*' is omitted as these steps are identical to those described in the previous section 2.2.1.

1. *Problem Definition:* Designers start with the definition of a problem they need to solve. For example, the problem may be to design a surfboard capable of preventing shark attacks.

2. *Reframing the Problem:* Designers have initially always defined problems in human terms, such as protecting policemen or avoiding shark attacks. In order for designers to find solution analogues in biology, designers redefined their problems in more broadly applicable biological terms, often in the form of a question such as 'How do biological solutions accomplish xyz function?' Instructors termed this reframing step as 'biologising' the problem. As an example, instead of 'stopping a bullet,' the biologised version of this function was 'What characteristics do organisms have that enable them to prevent, withstand and heal damage?'

3. *Biological Solution Search:* The designer seeks in the biological domain possible biological systems whose functions can be potentially adopted to solve the problem. Some of the tools used to support the biomimetic design are illustrated in the following section.

4. *Define the Biological Solution*

5. *Principle of Extraction*

6. *Principle of Application*

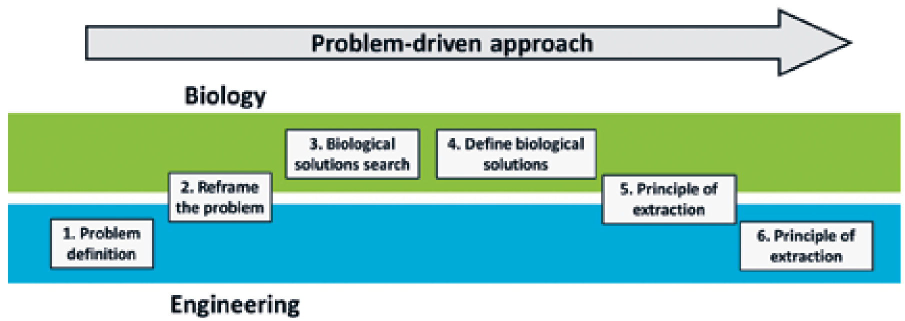


Fig. 9 – Steps of the problem-driven design approach

Fig. 9 shows the main steps of the problem-driven approach to bio-inspired design. As can be seen, to obtain a bio-inspired solution for a technical problem, during the design process it is necessary to cross the boundary between the technical and the biological domain twice.

It is important to emphasise that in practice both the solution-driven and the problem-driven approach are non-linear and dynamic in the sense that output from later stages frequently influences previous stages, providing iterative feedback and refinement loops.

2.3 Tools to support bio-inspired design

Making connections between the biological domain and the other disciplines is a meta thinking challenge. Indeed, new ways of thinking and reasoning are necessary to cross the boundaries of different domains. Visual thinking (the ability to think through images), analogical thinking (the ability to use information from one domain to solve problems affecting a different domain) and speaking a common language are important skills that designers have to develop for the search of analogies between the biological domain and other disciplines. The following sections describe some practice-oriented strategies to aid the search for biological solutions.

2.3.1 Invite a biologist to the design table

An obvious way of finding potential biological analogies for solving problems related to a different domain is to ask a biologist. The advantage of simply asking biologists is that the designer, typically with no or very limited biology knowledge, does not have to look for potential biological solutions with the risk of misinterpreting the biological information. The disadvantage of this approach is the access to biologists. To overcome this problem, the online biological database AskNature.org provides a team of biologists who can be consulted for this purpose. A further critical disadvantage of this approach is the lack of objectivity in the proposed solutions identified by the biologists because these solutions will be biased towards the biologist's specific field of expertise.

2.3.2 Search through a database

An approach able to capture the biological information necessary to solve a problem in a more objective way is the use of a database (Shu, et al. 2011). Within the database the biological systems are classified by using keywords which are also used to categorise past engineering solutions. Therefore, the relevance of information found is assured because the same keywords are used as database classification method and to access the database. Keywords are usually verbs capable of capturing the main functions of the biological systems. The main disadvantage of searching through a database specifically developed to support biomimetic design is that the search results are limited to what was entered into the database. Depending on how the database is structured, bias may be imparted during the categorisation of information as it is entered. A simple example is that since Velcro was developed from burrs, should the biological entity of a burr be categorised under the engineering function of fastening? If so, other potential functions or strategies that can be extracted from the burr may be lost. In addition to the database collecting biological systems for engineering use, another valuable source for building a database is the vast biological information already available in the form of articles, texts and books. This approach, called natural-language based search, avoids the enormous and subjective work necessary to classify the biological phenomena within a database. The initial source of a natural-language database is crucial. This source should: a) be written in a language easy to understand for designers with no or very limited biology background; b) give an overview of all the biological systems ranging from microorganism to ecosystems. A natural-language database, designed in this way, can be a valuable tool to identify the more relevant biological phenomena. If further details are required, they can be found in more advanced biological literature. However, searching through more advanced sources will initially generate results that are in more technical language and thus more difficult to understand. This is then frustrating for the designer and consequently these results are more likely to be overlooked, even if they are relevant. Finding relevant analogies in a natural-language database depends on the word choices made by the authors of the various natural-language sources, i.e. multiple terms can describe and thus locate the same concept. In the same way as for databases for engineering use, in natural-language databases verbs should be preferred as keywords because the use of nouns tends to restrict the variety of possible biological solutions. For example, searching with the verb keyword 'protect' will identify several biological phenomena that involve protection. However, searching with the noun keyword 'cuticle' will only identify information related to cuticles, thus overlooking other potential solutions for protection.

2.3.3 Patterns from nature

A more systematic and objective approach to bio-inspired design can be achieved through the discovery, identification and classification of patterns in the solution of problems in nature. The concept of 'pattern' is abstract and not bound to a specific discipline and/or context.

An exhaustive definition of pattern is provided by Alexander (Alexander, Ishikawa and Silverstein 1977):

> *"Each pattern is a three part rule, which expresses a relation between a certain context, a problem, and a solution. As an element in the world, each pattern is a relationship between a certain context, a certain system of forces which occurs repeatedly in that context, and a certain spatial configuration which allows these forces to resolve themselves. As an element of language, a pattern is an instruction, which shows how this spatial configuration can be used, over and over again, to resolve the given system of forces, wherever the context makes it relevant."*

The structure, interconnecting the problem, the solution and the context, explicates according the following template (Salustri 2005):

1. *Pattern Name:* A short, descriptive name that quickly conveys the intent of the pattern.

2. *Problem Statement:* A concise statement of the problem, including the context in which the pattern can be applied and the forces or drivers that create the problem and that must be resolved to obtain a successful solution.

3. *Therefore:* The solution (including any required tasks), how the outcome is used, why the solution works, and relationships to other patterns. The solution resolves the forces or drivers, moving the system from an undesirable to a more preferred state. Examples from different fields can demonstrate that the problem/solution set is recurrent and broadly relevant.

4. *But:* The consequences of implementing the solution, to help avoid 'surprises'. Can also show how the solution changes the context of the problem, either by eliminating contradictions between forces/drivers or by working at a different level than the original problem (sub-system or super-system).

5. *See Also:* Pointers to related patterns not mentioned in other sections of the pattern.

A pattern is not an isolated entity, but is included in a context of interacting patterns. Usually the patterns within the context are characterised by a hierarchical structure, therefore the interaction can take place at a similar level (our pattern interact with other patterns at the same level), at a higher level (encompassing our pattern) and at a lower level (component). This network of patterns is defined as pattern language and the rules underlying their interaction can be considered as the 'grammar' (Hoeller, et al. 2007). The search for patterns in the technology domain has enabled the development of a systematic and standardised methodology for the technical design named TRIZ, acronym of Teorija Reshenija Izobretatel'skih Zadach (loosely translated as 'Theory of Inventive Problem Solving'). This design methodology is also acknowledged for its successful transfer of various inventions and solutions from one field of engineering to another. Genrich Altshuller developed this design methodology by means of the identification and classification of patterns underlying human design (Altshuller 1999). Based on the analysis of more than three million patents, Altshuller has identified the patterns governing the solutions of technical challenges. By analysing these patterns it is also possible to determine the resources (energy, material, information, time, etc.) utilised by humans to solve their technical problems (Fig. 1a). Vincent pioneered the pattern identification in the context of biology by analysing 500 biological systems with the aim of transfering the TRIZ design methodology to the biology domain BioTRIZ (Vincent, et al. 2006). These first patterns from nature enabled a preliminary comparison between the strategies adopted by humans and nature to solve problems, and they noted a very limited overlap. This means that our method of problem solving is very different to that used by nature. This is also highlighted by the diverse and more sustainable use of resources needed by nature for solving problems (Fig. 1b). In order to provide bio-inspired design with a systematic framework similar to that developed for the TRIZ it is necessary:

- to identify patterns in the solution of problems in technology (the original TRIZ system);
- to identify patterns in the solution of problems in biology (develop a modified, BioTRIZ, system);
- to make these patterns compatible within a new general Biomimetic TRIZ.

2.4 Teaching, learning and practice

Biomimicry is multidisciplinary as it calls for collaboration between very different disciplines (engineering, economy, chemistry, material sciences, biology, etc.). Over the years they have evolved with a reductionist approach and developed different jargon, perspectives and mindsets which obstruct knowledge sharing between them. In order to express itself, biomimicry needs to be approached with an interdisciplinary process developed by crossing the boundaries of various disciplines. In general terms, a boundary can be considered as a socio-cultural difference causing discontinuity in action and interaction, while boundary crossing is related to a person's transition and interactions across different domains (Akkerman and Bakker 2011). Therefore, teaching biomimicry cannot disregard the answer to the question: What dialogical learning mechanism takes place at the boundaries? In their review article on boundary crossing and boundary objects, Akkerman and Bakker have identified four learning mechanisms that take place at the boundaries: identification, coordination, reflection and transformation. In this context learning, in the broad sense, encompasses new understandings, identity development and change of practices. The learning mechanism that fits better with biomimicry is transformation. It leads to profound changes in practices, potentially even to the creation of new, in-between practices usually defined as boundary practices. Therefore in this framework biomimicry can also be defined in this way. Transformation always starts with a *confrontation* process in which a lack or problem forces the intersections of different domains to change their current practices and interrelations. A second process that takes place is the *recognition* of a shared problem space which is bounded by the confrontation. For biomimicry the shared problem space is the environment (biome, ecosystems) which is affected by several interconnected problems rather than a single biological system with a specific problem. A third process in the transformation is *hybridisation*. Given a certain problem space, practices that can cross their boundaries engage in a creative process in which something hybrid – that is, a new cultural form – emerges. In hybridisation, ingredients from different contexts are combined to form something new and unfamiliar. A fourth process found in the descriptions of transformation is the *crystallisation* of what is created. The reasoning is that it is one thing to create something hybrid at the boundary, but quite another to embed it in practice so that it has real consequences.

The second part of this section illustrates the biomimetic design process we would like to adopt in the projects of the biomimicry lectorate. The projects will be carried out by students, lecturers and researchers coming from various fields of expertise. In the projects the holistic problem-driven approach is used so that the teams are challenged with a technical problem. The problem will be expressed in terms pertaining to the field of the problem. The team therefore has to translate the problem into a 'language' understandable for all team members by using functional modelling. In this phase supervision of the biologist is extremely important because he/she is responsible for ensuring that the problem is expressed in terms, functions and keywords meaningful for the biological domain. The outcome of this step is the generation of keywords; these keywords will be used for the preliminary identification of possible biological solutions by searching in a biological database currently available such as Asknature.org. The main goal of this phase is not to generate solutions to our problem immediately, but to identify the organism size or scale in which the biological solutions of the problem can be found (cells, organisms, plants, ecosystems). With this preliminary search the team has to identify in which size or scale the potential solutions to the problems lie and then look for a biology specialist: microbiologist, plant biologist, ecologist, etc. Together with the biology specialist, the team has to identify the set of biological systems which can represent a potential solution to the problem. The biology specialist has to go through the scientific literature describing the potential biological solutions and advise the team on the best candidate to provide a bio-inspired solution to the challenge.
The involvement of a biology specialist, capable of understanding the language of the specific scientific literature, will prevent the risk of losing useful biological information relevant for the problem solution. The potential solutions to the problem are to be found among the champion adapters which are the organism or systems that survive in extreme environments relevant for the problem, for example an organism living in the desert or a tropical environment. Once the team together with the biology specialist has identified the biological system that is the best candidate for the problem solution, the biological system needs to be translated in terms and functions understandable for the field of the problem. This phase is then followed by product realisation and assessment. It is of utmost importance that during the whole design process researchers observe the interaction among the team members; this will enable them to extrapolate methodologies and strategies aimed at facilitating knowledge sharing with the biological domain. Bio-inspired design, described in detail in the previous sections, can contribute to the realisation of products capable of fulfilling their tasks in a more efficient manner. An example is the wind turbine blade inspired by the tubercles of the humpback whale. It can convert wind energy into electricity more efficiently with a significant noise reduction. These advantages are pointless if the wind turbine blade manufacturing process is energy intensive and polluting and/or if the materials used are toxic and not recyclable. This makes the disposal process very polluting for the environment. Therefore, in the design process it is necessary to take into account issues pertinent to the sustainability of the product manufacturing and of the disposal process; it is then possible to assess the actual impact of the product on the environment. In this more holistic design approach, bio-inspired design and biomimicry can play a key role in the transition from linear to circular economy.

Biomimicry as an innovation tool for the agrifood sector

The lectorate "Biomimicry: Learning from nature for sustainable solutions" is the result of a collaboration between three universities of applied sciences: Aeres UAS Wageningen, Inholland UAS Delft, and Van Hall Larenstein UAS Leeuwarden. Given the common green DNA of the three universities of applied sciences, the lectorate research activities aim to demonstrate that biomimicry can represent an innovation tool that can be used to increase sustainability in the agrifood sector through the development of bio-inspired products and processes. Moreover, the nature-inspired design can be used to devise new strategies and models to improve the management and logistics of agriculture companies.

3.1 Challenges in agrifood

A fundamental challenge of the 21st century will be to provide food for the ever-increasing world population, while maintaining the integrity of our natural ecosystems through preservation of biodiversity. Today most of our food and fibres are produced by annual-based arable agroecosystems (Fig. 10a) which include far fewer species of plants and animals as compared with the native ecosystems (Crews, et al. 2016). A second broad distinction between native and agricultural ecosystems is that of succession. Following disturbance, native ecosystems regain functionality through successional changes that strengthen a range of internal, regulating feedbacks. In contrast, due to recurring tillage events or herbicide applications, annual crop ecosystems remain arrested in a disturbed, less regulated state of early secondary succession (Smith 2014). As a result, degrading processes of soil erosion (Montgomery 2007), nutrients and water leaching (MEA 2005, Vitousek and Reiners 1975), soil organic matter decline (Davidson and Ackerman 1993), and extensive weed establishment (Liebman and Mohler 2001) compromise the agricultural ecosystems. Therefore, in order to satisfy the ever increasing demand for food, it is necessary to shift the annual-based agricultural models to more sustainable models, such as permaculture (Fig. 10b), which aim at strengthening biodiversity in agriculture.

Fig. 10 – Agricultural ecosystems: a) monoculture (low diversity); b) permaculture (high diversity)

Agricultural models with high diversity result to be more resilient and productive in the long term than agricultural ecosystems based on monoculture (AskNature.org 2016). A low diversity system has high productivity in the short term, but is severely affected by a fluctuation in conditions (Fig. 11a). This is because these changes could cause the entire system to lose all functions, resulting in low or no productivity.
A high diversity system containing members that serve multiple, overlapping functional roles may not be as productive in the short term, but shows long-term stability and productivity. If there is any fluctuation in conditions (Fig. 11b), the conditions only impact a small part of the system. As a result, these changes only affect productivity briefly as the remaining members and replacement members continue to provide all the ecosystem functions.
If on the one hand strengthening biodiversity in agriculture is the roadmap to a more resilient and sustainable agrifood sector, on the other hand the shift to agricultural models with high diversity such as permaculture poses a number of relevant problems. If these problems are not solved, they can prevent the large diffusion of

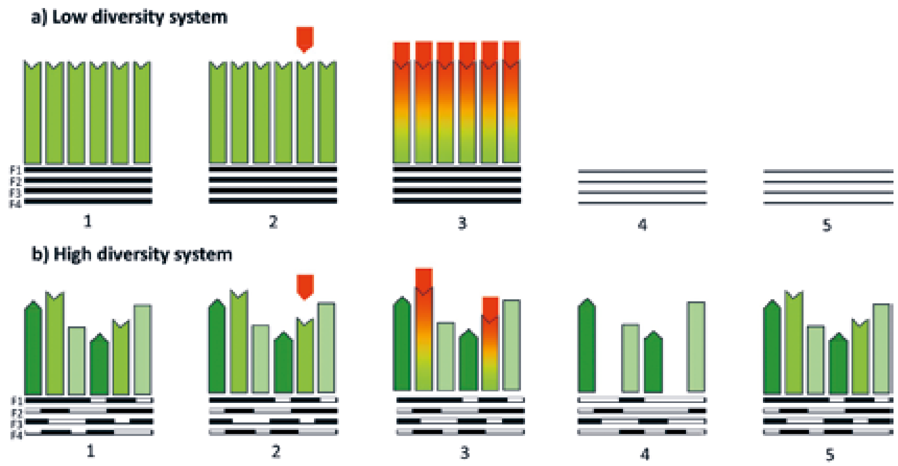


Fig. 11 – Comparison between low diversity a) and high diversity b) agricultural systems

more biodiverse agricultural ecosystems. These problems concern management which includes activities such as harvesting, monitoring plant growth, measuring the amount of nutrients in the soil, etc. As these activities are not optimised and are mainly carried out manually, the biodiverse agroecosystems are not as cost-effective as agroecosystems based on monoculture.

3.2 Bio-inspired robots in agriculture

The introduction of automation in biodiverse agroecosystems by means of the realisation of bio-inspired robots can improve cost effectiveness. The robots can be equipped with bio-inspired grippers for harvesting, with sensors and vision systems to monitor the health and growth of the plants as well as the nutrient level in the soil. In addition, the behaviour of insect swarms is a source of inspiration for the development of algorithms to control and pilot swarms of robots deployed on the field.

3.2.1 Grippers

One of the major challenges in the realisation of robots for harvesting is the design of grippers capable of harvesting fruits and vegetables without damaging them. Soft biological materials can inspire new concepts for the grippers (Kim, Laschi and Trimmer 2013). The vast majority of animals are soft bodied, and even animals with stiff exoskeletons such as insects have long-lived life stages during which they are almost entirely soft (maggots, grubs, and caterpillars). Studying how animals use soft materials to move in complex, unpredictable environments can provide invaluable insights for emerging robotic applications not only in agriculture but also in medicine, search and rescue, disaster response, and human assistance. Soft materials are essential for the 'mechanical design' of animals because they enable them to conform to surfaces, distribute stress over a larger volume, and increase contact time. A simple example is the soft finger pads and skin of arboreal animals that assist climbing by conforming to surfaces for better grip or adhesion. Another source of inspiration for a completely soft manipulator is based on the anatomy and mechanism of the arm movement of an octopus. Each octopus arm is endowed with a highly complex muscular system which allows the arm to articulate the shape by shortening, elongation, bending, or torsion, and to distribute forces by localised or global stiffening. A research group from the University of Pisa (Laschi, et al. 2012) have built a robotic arm that resembles an octopus arm. They used a plastic fibre braid to make the highly deformable mechanical structure of the robot arm, whereas soft actuators comprised of shape memory alloy (SMA) springs (Follador, et al. 2012) are arranged transversely and longitudinally to produce the local deformations (Cianchetti, et al. 2012) shown in Fig. 12. Global bending is achieved by means of longitudinal cables that can elongate, shorten, bend, and stiffen.

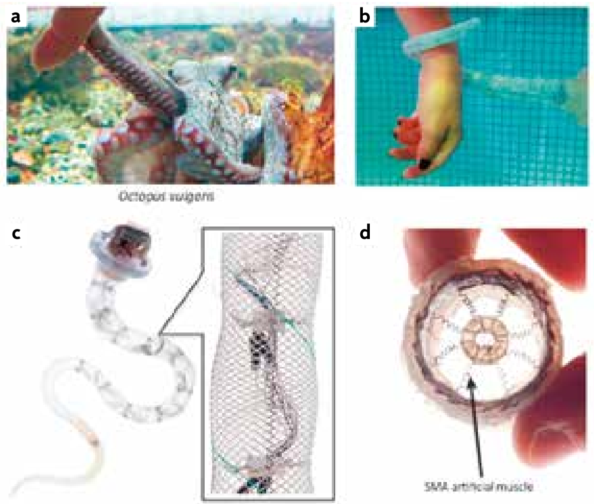


Fig. 12 - Octopus-inspired robot. a) Octopus (Octopus vulgaris) grasping a human finger with one arm.
b) An octopus-like robot arm wrapping around a human wrist, in water.
c) Details of an octopus-like robot arm. The external braid represents the mechanical structure of the arm, enabling local and global deformation while keeping the arm shape.
d) Details of the SMA springs that generate local diameter reductions (Kim, Laschi and Trimmer 2013).

3.2.2 Self-organising robot swarm

The development of algorithms is crucial to allow robot swarms to operate autonomously in the field. If a swarm of robots has been designed to harvest tomatoes in a field where tomato plants are not the only plants cultivated, the function of the algorithm is to instruct the robots how to identify the type of fruit to be harvested, how to distinguish the fruit ready to be harvested from that which is still immature and how to converge to the areas of the field with the highest concentrations of fruit to be harvested.
By observing the aggregation behaviour of young honeybees, Schmickl has developed a very simple, yet robust and flexible algorithm able to impart the above-mentioned instructions to robot swarms (Schmickl 2011). The idea for this algorithm originates from the observation of young honeybees in the beehive where the newly emerged honeybees have a preferred temperature of approx. 36°C. These young bees tend to locate themselves in a collective way in the warmest central areas of the hive. Experiments with single young honeybees in a temperature gradient (approx. 30°C - 36°C) showed that most bees cannot locate themselves in the warmest zone permanently. Instead, most of them wander around aimlessly and frequently leave warm areas soon after they have entered them (Fig. 13a). Thus, a 'swarm effect' seems to be responsible for the bees' well-functioning collective temperature-finding behaviour. Further experiments with a specialised arena provided insight into this behaviour (Kernbach, et al. 2009): single honeybees usually wandered around in the arena randomly, but stopped when they collided with another bee and then waited there for a duration that correlated with the temperature at this place.
Low temperatures resulted in a short waiting time of the bee, whereas warmer temperatures resulted in longer waiting times. Thus, clusters of bees formed all over the arena, but in the warmer zone these clusters lasted longer than in colder zones. Finally, all clusters merged into one big cluster near the global temperature optimum (Fig. 13b-d).

The algorithm extrapolated by the honeybees' behaviour can be translated for the robots used for harvesting. The robots need to aggregate in the zones of the field with a high concentration of fruit to be collected. When during the random wandering two robots collide, they will stop in that area for a time dependent on the amount of fruit present in that area. The amount of fruit present in the collision area is estimated by using the vision systems installed on the robots. The smaller the amount of fruit, the shorter the robot clustering time, whereas the larger the amount of fruit, the longer the robot clustering time. Therefore, analogously to the bees, the robots tend to aggregate in the area with the highest concentration of fruit.

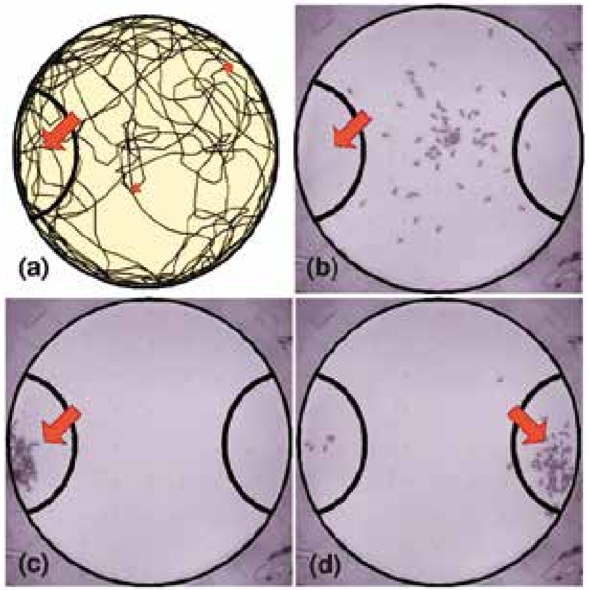


Fig. 13 - Experiment with bees in a specialised arena (Schmickl 2011). a) A single bee does not find the 36°C temperature optimum to the left, indicated by the red arrow.
b) Initial state of an experiment with 64 bees. The 36°C (global) optimum is to the left, indicated by the red arrow. The 32°C sub-optimum is to the right. c) Bees collectively clustered at the optimum.
d) After the 36°C optimum to the left was switched off, the bees were able to decide again and cluster at the new 32°C (global) optimum to the right, indicated by the red arrow. Ambient temperature: approx. 30°C.

3.3 Bio-inspired water filtration in agriculture

About 2.5% of the total amount of water on earth is freshwater and of this only about 0.007% is available for human consumption. Out of all global freshwater withdrawal, about 70% is used in agriculture, 20% for industrial (including energy) use, and 10% for water-related needs of households, institutions, municipal systems, and small-medium size industries (Gonzalez-Perez and Persson 2016, Gleick 1993). As agriculture withdraws the majority of the freshwater available, it comes as no surprise that the main source of water contamination originates from agricultural activities which require 140 million tons of fertilisers and several million tons of pesticides per year. During the last decade, in addition to the conventional (namely nitrogen compounds, phosphorus, microorganisms, etc.) and non-conventional pollutants, such as heavy metals and hydrocarbons, a further source of pollutants has emerged, i.e. pharmaceuticals and personal care products. Due to high polarity and low volatility, most pharmaceuticals tend to be easily transported and discharged into the water compartment.

In the following two bio-inspired filtration systems are described. The first, the living filtration system, has been designed for agricultural applications, whereas the second, the liquid-gated system, has a much wider field of application.

3.3.1 Living filtration system

At the University of Oregon (US), a design team has developed the living filtration system (LFS): a bio-inspired water filtration concept designed to mitigate the environmental impact of agriculture (Earthworm-inspired innovation 2016).
The designers developed this concept by taking inspiration from the form and function of earthworms, wetlands and the human small intestine. This transitional technology was created to replace conventional agricultural drainage systems and capture excess nutrients in runoff, reducing fertiliser use and improving soil health.
The living filtration system is a multilayer pipe (Fig. 14). The inner layer, made of wood-plastic material, mimics the intestinal villi to perform the function of decelerating the water flow. A second layer is made of biochar and, by imitating the earthworm's digestive system, is capable of retaining the nutrients. The last two layers are formed by the organic fabric and plants roots. They have a twofold function: a) to give the nutrients back to the plants; b) to sustain a beneficial relationship between the plant roots and the soil microorganisms. It is worth noting that LFS can drastically reduce nutrient leakages in the waterways and therefore can also prevent eutrophication, a phenomenon responsible for aquatic fauna depletion.

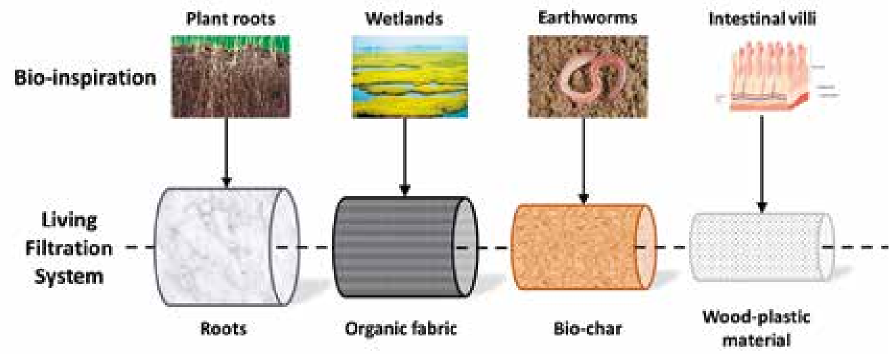


Fig. 14 – Living filtration system

3.3.2 A biomimetic liquid gating system

Plant stomata are liquid gated openings that cover leaves and stems allowing the exchange of air, water and microbes between the plant and its environment (Fig. 15). The ability of such pores to coordinate multiphase transport, in a highly selective and subtly triggered fashion and without clogging, has inspired interest in synthetic gated pores for applications ranging from fluid processing/filtration to 3D printing and lab-on-chip systems (Hou, et al. 2015).

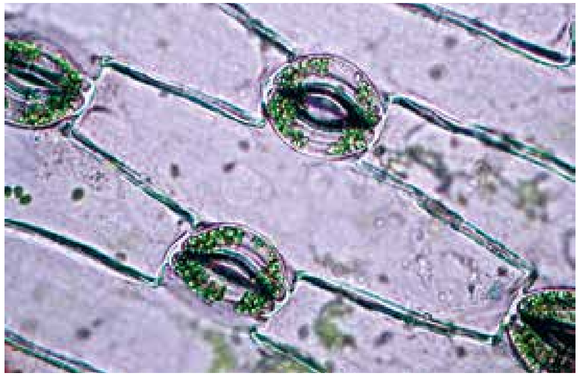


Fig. 15 – Plant cells and stomata with green chloroplast

A gating mechanism uses a capillary-stabilised liquid as a reversible, reconfigurable gate that fills and seals pores in the closed state, and creates a non-fouling, liquid-lined pore in the open state (Fig. 16). Matching the gating liquid to the feed stream enables filtration at a lower trans-membrane pressure than a conventional filter of the same pore size. This liquid gating strategy enables efficient long-term operation and can be applied to a variety of pore structures and membrane materials, and to both microscale and macroscale fluid systems.

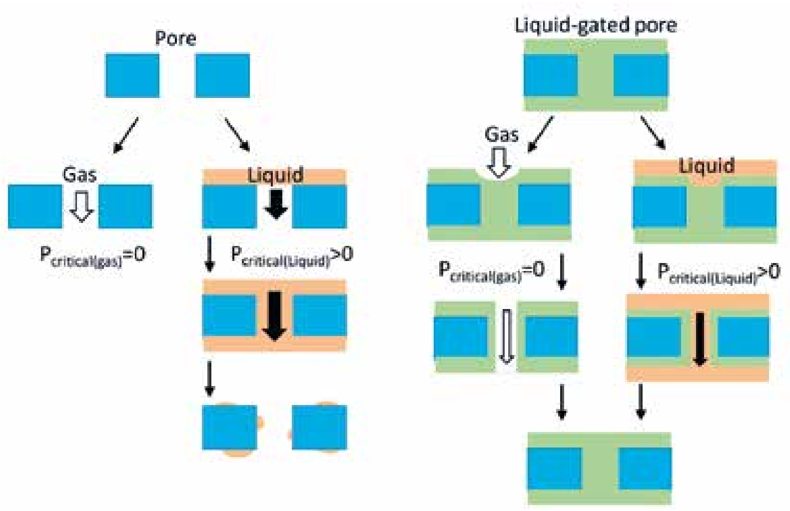
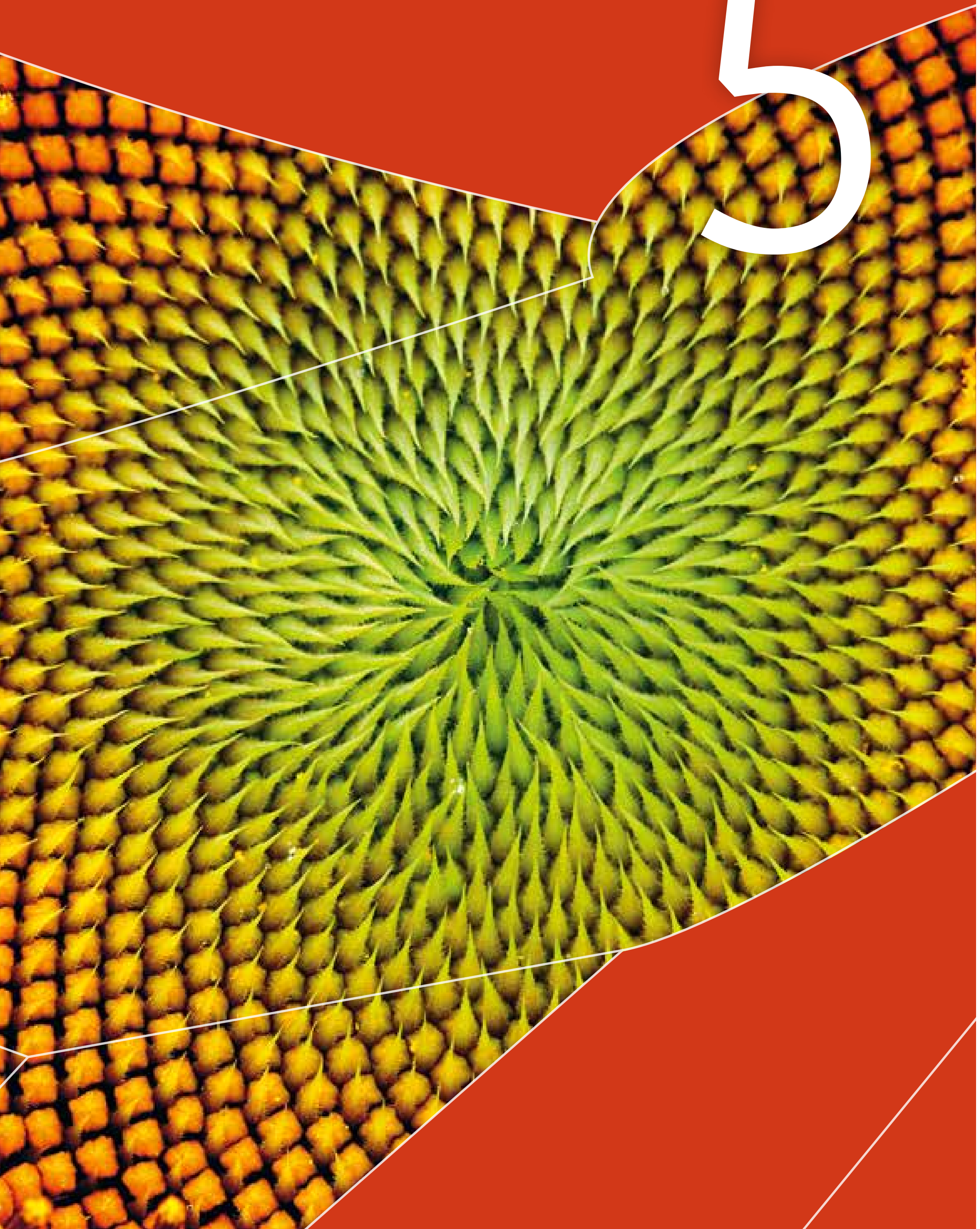


Fig. 16 – Liquid-gated membrane: comparison between simple pores and liquid-gated pores

Biomimicry for social innovation

Biomimicry is also potentially effective for social innovation. Ecosystems, insect swarms and animal behaviour are potential inspiration sources to boost innovation in organisations (communities, companies, industry, academic and government institutions) and to develop more effective models for leadership. Currently most of the activities concerning the adoption of biomimicry for social innovation are carried out by biologists who act as consultants for companies that wants to explore new creative ways of tackling their problems. Most of the time the proposed solutions lack scientific rigor and the recommended strategies seem to be based on common sense rather than nature. Therefore, in this field too, it is very important to devise a systematic approach to solve problems for the organisations based on more consolidated scientific grounds.

A preliminary literature survey of the use of biomimicry for social innovation showed that in this field the scientific output is rather poor (McGregor 2013, Patel and Mehta 2011, Richardson 2010). This means that the application of biomimicry for social innovation is almost an unknown research field. Therefore, the lectorate research activities in this field will first focus on a deeper survey of the literature and at the same time companies and organisations will be interviewed in order to understand their problems. This twofold approach will allow us to formulate better the research questions for this biomimicry field of application.
Companies, industry, academic and government institutions are not isolated entities and typically have a complex organisational structure. For instance, a company may be made up of several interconnected components. The interaction between these components explicates through flows of information, materials, employees, etc.
In addition, a company is embedded in a higher level structure encompassing market, society, suppliers, etc. Therefore, innovative strategies to improve responsiveness or to make companies more resilient to market variations can be obtained from a deeper understanding of the natural ecosystems, as shown in Table 1. Models describing the behaviour of ecosystems, especially those characterised by abrupt and/or changes in the environmental conditions, once properly translated, can be adopted by companies to develop new business models and to increase their resilience and efficiency.



5 Biomimicry lectorate research lines

The main research lines of the biomimicry lectorate are summarised below:

- bio-inspired robots for a more sustainable agrifood sector;
- bio-inspired filtration systems to improve water quality in agriculture;
- bio-inspired strategies to enhance the responsiveness of organisations;
- development of methodologies to enable knowledge transfer in multi/interdisciplinary environments.

The development of the mentioned research lines will benefit from the collaboration with the other lectorates of the three universities of applied sciences (Aeres, Inholland, Van Hall Larenstein). In addition to scientific and technical support, they give the opportunity to compare the performance of ‘bio-inspired products’, developed within the projects associated with biomimicry research lines, with those obtained using the ‘traditional’ design approach.

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Mauro Gallo
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