Chapter 2
The Biomimicry Design Process: Characteristics, Stages and Main Challenge

There exist many perspectives about design processes in general [52]. The introduction of biomimicry adds to this complexity and variety. In order to understand this setting, this chapter describes the characteristics of the biomimicry design process, its stages and main challenges. It becomes clear that one significant issue in realizing the process is the language gap between engineering and biology.

2.1 Characteristics of the Biomimicry Design Process

2.1.1 Bidirectional Design Process

Two biomimetic design processes are identified according to their starting point. We can start from technology or engineering with a design problem and locate a solution in biology (from a problem to biology). An example is the bullet train in Japan that was redesigned after the beak of the kingfisher to solve the noise problem. First, the problem was identified as the noise the train produced every time it came out of a tunnel, due to a change in air pressure. Then, a solution in biology was found in the kingfisher which dives from air into water with little splashing. The front of the train was redesigned using the beak of the kingfisher as a model. The result is a quieter, faster and more energy efficient train [5]. However, the kingfisher was found coincidentally and not by a search process that is usually required to support a biomimetic design process from a problem to biology.

We can also start from biology with a biological solution and move to locate an application for an analogical problem (from biology to an application). One example follows the discovery of the self-cleaning mechanism of the lotus, which is based on small epidermis protrusions causing the droplet to collect pollutants while it rolls off the leaf. Several applications were found for this biological effect including a self-cleaning paint, glass and fabric [53].

Y.H. Cohen and Y. Reich, *Biomimetic Design Method for Innovation and Sustainability*, DOI 10.1007/978-3-319-33997-9_2

Table 2.1 Biomimetic design directions terminology

	From biology to an application	From a problem to biology	Source	Year
1	Solution driven	Problem driven	Helms et al. [54]	2009
2	Organism driven	Mechanism driven	Hesselberg [55]	2007
3	Bottom up	Top down	Speck and Speck [56]	2008
4	Biology push	Technology pull	ISO Biomimetic committee [57]	2012
5	Biomimetics by induction	Biomimetics by analogy	Gebeshuber and Drack [58]	2008
6	Biology to design	Challenge to biology	Biomimicry 3.8 [5]	Unknown

Helms et al. [54] identified these bidirectional design processes as "Problem-driven" and "Solution-driven" biologically inspired design. Other researchers called these directions with different terminology as presented in Table 2.1. Whether we start from biology and end with technology or vice versa, at the end, knowledge is being transferred from biology to technology to solve technological problem, generate a new capability that may solve the problem, or replace other inferior solutions. In the first case, interesting biological phenomenon sparked the process, and in the second case, a technological need sparked the process.

Each one of these design directions is a biomimetic design process, while the direction "from biology to an application" is more common according to our research database described in Sect. 5.4. It might be easier to find analogical design problems to a given biological solution then finding an analogical biological model to a given problem among the millions of potential biological sources.

2.1.2 Analogical Based Design Process

Biomimicry by definition is an analogical transfer of design knowledge between biology (the source) and technology (target), or others domains of applications [17]. Biologically inspired design often involves compound analogies when a design concept is generated by multiple cross-domain analogies [59]. In this case, different organisms may be sources for different functions that at the end will be integrated in one technological system. This integrative approach [55] was demonstrated by a case of developing an endoscope inspired by rag worms which can move on slippery surfaces.

2.1.3 Interdisciplinary and Multidisciplinary Design Process

Mutidisciplinary study involves different disciplines, where each one provides a different perspective on the subject under study, but these perspectives are not integrated. Interdisciplinary study on the other hand, involves an integration of theoretical, conceptual and methodological approaches of different disciplines [60]. Thus, an interdisciplinary process requires more flexibility and blurring of boundaries so a new body of knowledge can emerge.

Every design process incorporates multidisciplinary teams involving at least marketing people, engineers, and customers. Biomimetic design involves also biologists thus the level of complexity is even greater. However, biomimetic design process goes beyond the level of viewing the design challenge from different perspectives (multidisplinary), as it involves also an integration of disciplinary knowledge (interdisciplinary). It is clear that each discipline benefits from this interdisciplinary process. Studying a biological system in the context of biomimetic design may extend biologist's understanding of an observed mechanism. For example, Full [61] studied the gecko's movement and evoked interest about the role of the tail. He provided biologists with a hypothesis about the role of the tail, one they did not considered. Thus, collective discoveries emerged beyond any single field. Full called this mutual benefit for both disciplines 'Biomutualism'. Reich et al. [62, 63] called the process where multiple disciplines are integrated and enrich each other over several cycles a bootstrapping effect.

Parvan et al. [64] offered a collaboration model between biologists and engineers referring to their tasks and roles in the process. Schmidt [65] suggested that biomimetic knowledge starts from a zone of communication between an engineer and a biologist, where a circulation of knowledge occurs rather than a unidirectional knowledge transfer. This circulation of knowledge, leading also to knowledge extension, is again a form of bootstrapping. Another collaboration model developed by Swedish biomimetics 3000 [66], the $V^2IO^®$ model, is said to be an innovation accelerating model that integrates multiple disciplines, organizational issues, cultures and their corresponding global challenges. However, its details are not disclosed, hence it cannot be assessed. Nevertheless, the idea of creating a model that accounts for the impact of the social and organizational aspects to the innovation process is valuable. PSI—product, social, institutional—is a general framework that considers all these issues [67–69].

2.2 Biomimetic Design Process Stages—From a Problem to Biology

Figure 2.1 describes the biomimetic design stages from a problem to biology. When we start from a problem we first need to define the problem (stage 1). This stage is not unique to biomimetic design as every design process starts with a problem definition task; a good definition of a problem is considered to be a major part of the solution. However, in the context of biomimetic design a problem definition has even a greater impact of bridging to biology (stage 2). After the problem definition, we follow with three core stages of every biomimetic design process that are unique

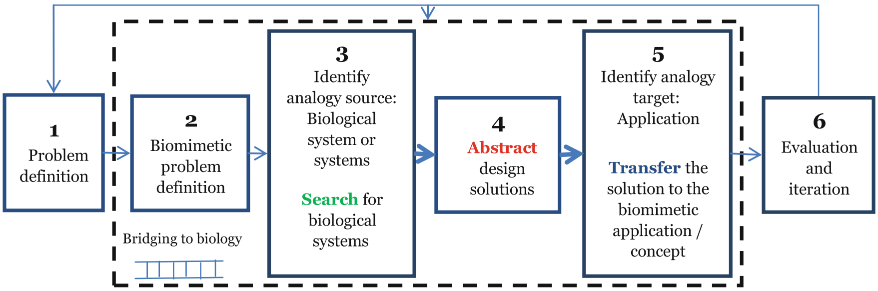

Fig. 2.1 The biomimetic design process—from a problem to biology

to biomimetic design and are derived from the biomimetic analogy: Identify analogy source—the biological system or systems in case of compound analogy (stage 3), abstraction of the biological solution (stage 4), and transfer the solution to the application (stage 5). These three core stages were also suggested as a base to define a biomimetic product, as part of the ISO standardization initiative that is based on VDI Guideline 6220 [70].

At the end of these three core stages, there is an evaluation and iteration stage (stage 6). This stage is also not unique to biomimetic design, and characterizes every design process. A designer may want to repeat each one of the previous stages, including the problem definition, location of the biological system, abstraction, or transfer to biomimetic concept or application. The dashed box in Fig. 2.1 includes the stages unique to biomimetic design. Outside the dashed box are the initial and final general design stages of problem definition and evaluation. The bolded arrows between the source (biology) and target (application) represent the connecting bridge between these two domains.

2.2.1 Problem Definition (Stages 1 and 2)

Problem definition is derived from customer needs or from some observed opportunity and transformed by designers to a technical definition that drives the design process. The result of this stage could be several problem definitions according to different technical views or different interpretations of the initial needs. In order to search for relevant solutions in nature, we need to move from a technical definition to a biomimetic oriented definition that supports the biological search. We call this process bridging to biology as we set here the foundation for the bridge that is being built later during the abstraction (stage 4). Therefore, problem definition in biomimetic design process from a problem to biology has an implicit role in the retrieval process of biological systems.

Biomimicry 3.8 [5] offered to ‘biologize’ the problem by redefining problems with biological terms. Helms [54] suggested to reframe the problem by biological terms and ask "How do biological solutions accomplish xyz function?". Other problem definition approaches directed designers to define clearly the function of interest, assuming that a clear function could lead the search process and clarify the design target. Sartori et al. [71] provided guidelines for this problem definition/analysis phase: (i) identify the required function from problem description and (ii) identify the most important requirements and conditions. All these suggestions are clear but too general and opened to personal interpretations without tools to 'biologize' the problem.

Mckeag [72] did offer a tool, the Bio-design cube to accomplish the translation to biology. Each side of a cube represents a problem definition space: What it is (form, process, system), what is the key parameter (information, energy, structure), and where it can be applied (Science, Design, Business). All the aforementioned ideas and tool are merely proposals for bridging. They need to be further investigated in relation to biomimetic problem definition to assess their value.

2.2.2 Identify the Analogy Source: Search for Biological System (Stage 3)

In a biomimetic design process from a problem to biology, we first need to perform a retrieval process in order to find a biological system that demonstrates a required solution for an analogical problem. This process requires searching algorithms and techniques to retrieve relevant information from biological databases. Elaboration on this issue is presented in Sect. 3.1. The result of this searching process is an identification of a biological system. The identification occurs when the designer acknowledges the analogical relation of the biological system to the given problem.

2.2.3 Abstraction—Abstract Design Solutions (Stage 4)

Abstraction in the context of biomimetic design is the process of refining the biological knowledge (design solutions) to some working principles, strategies or representative models that explain the biological solution and could be further transferred to the target application. It may be understood also by the word 'Simplify' the biological complexity into some transferable design mechanisms or principles. During the abstraction stage, the bridge between biology and technology is built and the biological system is presented in the context of analogical reasoning. This bridge creates the language that allows a designer to go back and forth, detaching from one domain and moving to the other to transfer the required knowledge. Therefore, the abstraction stage is the core of the biomimetic design process.

Abstraction is considered to be one of the most difficult steps in the biomimetic design process [56]. In fact, the transfer of knowledge is done from a model of a biological system to a model of a technological system [71] so during the abstraction stage, we aim to create a model of the biological solution. This model should explain how the problem is solved in biology and may include references to functions, structures, behaviours, design principles or strategies in case they are related to the solution. Indeed, abstraction often involves representation of the biological solutions by models. Representation of knowledge is a natural cognitive process executed when trying to understand a phenomenon. In relation to biological phenomena, representations can facilitate understanding the functional mechanism and support the transfer to technology [73, 74]. Vattam et al. [75] conducted a class experiment in a course of bio-inspired design. Most of the 45 students were senior students from engineering background. They found out that the students used rich mental representations at different levels during the biomimetic design process, and suggested that it had an advantage in creating biomimetic analogies.

Mak et al. [17] demonstrated the importance of abstraction to the sequential transfer stage of biomimetic concept. They found out that abstracted principles regarding biological solutions tend to evoke more biomimetic concepts, comparing to information about forms and behaviours of biological systems. However, the advantage in quality of these concepts was not discussed extensively. They also reported on difficulties with the analogical mapping due to superficial analogies and fixation problems when a designer tends to stick to the first biological solution he encounters [76].

Abstraction requires knowledge about the biological solution in order to model it. Therefore, the biological system should be first analysed and understood. However, the available knowledge in the literature might not be sufficient to understand the biological mechanism. In this case, there is a need for further investigation.

2.2.4 Transfer the Solution (Stage 5)

Following the abstraction stage, the abstracted knowledge should be transferred to technological or other domains of applications. We transfer the knowledge that is relevant to the solution we aim to imitate. There are different levels of knowledge transfer including forms, structures, processes, functions, systems or principles [77].

Schmidt [65] identified three levels of knowledge transfer including (i) Structures, forms and materials (ii) Functions and (iii) Processes and information. Sartori et al. [71] identified four levels of knowledge transfer from the biological to the technological system, based on the SAPPhIRE model: (i) Parts—same materials in the same arrangement; (ii) Organs—same or similar organs including the physical effects related to these organs; (iii) Attributes—same attributes (properties of the parts); and (iv) State of change—the state change of a biological system is transferred but implemented with technical means, without using the same organs or physical effects like in biology. Sartori et al. [71] reported that the transfer most often was carried out at the physical effect level that is more related to the organs of the system, i.e., the system structures. Jacobs et al. [78] reached a similar conclusion regarding the question of what is being transferred from biology to the applications. They performed a quantitative and qualitative analysis of the BioM database of biomimetic innovations and found out that the majority (61.8 %) of biomimetic designs incorporate elements of biological form, most of which (51.3 %) include only Form.

The knowledge may be extracted from different levels of organization of living things, from the cell, to organs, organisms and ecosystems. There are many examples of transfer of forms and structures such as biomimetic materials, coatings, adhesives and functional structures. There are also examples of transfer of processes, such as genetic algorithms and swarm intelligence algorithms.

2.2.5 Evaluation and Iteration (Stage 6)

Following the transfer stage, a designer should evaluate the results and repeat the process again if required. The initial biomimetic design concepts may be abandoned later due to various reasons such as technological or manufacturing constrains, costs and complexity. In this case, a designer may go back to nature to generate new design concepts that will hopefully meet the expectations this time.

Biomimetic design process is not linear but iterative. This iterative nature is expressed by the biomimetic spiral diagram of biomimicry 3.8 [5], that integrates feedback loops within the design process. Gramann [79] offered three evaluation steps that lead to either transfer to biomimetic application or repetition to a previous stage in the process. (i) Evaluate the analogy—the initial analogy might be superficial, inaccurate, or lead to a dead end. For example, when InterfaceFLOR® searched for substitutes to replace the glue they used to fix the modular carpets to the floor, they first searched analogies for glues in nature. This level of analogy led them to a dead end as they observed complicated adhesion mechanisms that required significant R&D effort. When they rephrased the analogy and searched for principles to stay attached in nature they extracted the principle of using gravity for attachment. That led to their novel TacTiles technology that adhere modular carpet tiles to each other rather than to the floor, and let gravity holds them in place [31]. (ii) Evaluate the abstracted model—the abstracted model may be short in description and we may want to consider adding more aspects. For example, if we initially based the model on the organism itself, we may want to include its interaction with other environmental elements. (iii) Evaluate the organism—we may conclude that the organism search was not accurate and define a new objective search that would lead to new biological models. This iteration is important because sometimes the initial biological system being observed is not the most suitable solution. A tendency to fixate on the initial biological phenomena was observed by Helms et al. [54] in a research conducted on students. Iteration may address this fixation but other means might be necessary.

2.3 Biomimetic Design Process Stages—From Biology to an Application

Figure 2.2 describes the biomimetic design stages from biology to an application. When we start from biology and move to the application, we have similar core stages with slight modifications. First, we encounter a biological system with a unique characteristic or mechanism (stage 1) and we identify it as a suitable analogy source when we realize its potential benefit to innovate. When we encounter several biological systems with unique characteristics, we may form compound analogy.

Many biomimetic innovations sparked in a moment of wonder from a biological mechanism. The lotus effect was discovered after the wonder of observing a clean lotus leaf in a dirty environment. The mystery of how penguins stay ice-free though they live in very cold temperatures led to a biomimetic research to prevent ice formation on airplane wings [80]. The fast process of building a new crayfish skeleton in freshwater environment aroused the curiosity of a crayfish farmer. The research led to a discovery of an Amorphous Calcium Carbonate (ACC), a base of a new bioinspired calcium supplement [81]. Metaphorically, we may call this moment the Bio-WOW (stage 1), the wonder stage that sparks the biomimetic innovation process.

Following the Bio-WOW stage, we define which problem is actually being solved at this biological system that sparked our wonder (stage 2), in order to identify analogical challenges in technology and possible applications (stage 3). At this stage we do not choose the specific biomimetic application but we do acknowledge the relation to some possible applications. This relation motivates us to keep on with the analysis and abstraction process to gain better understanding of the biological solution. Therefore, stages 1–3 are interrelated as we do not proceed with the process of analysing and abstracting the biological solution, unless we respect its value to spark innovation. Compared to a biomimetic design process that

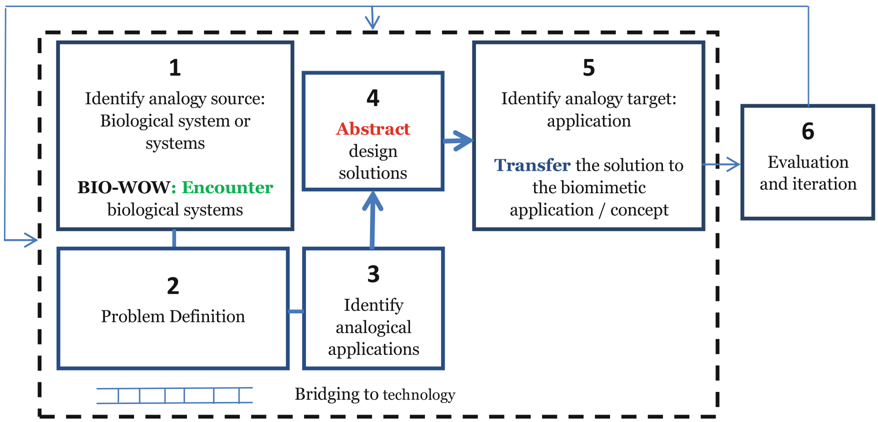

Fig. 2.2 The biomimetic design process—from biology to an application

starts with a problem (2.2), here we do not need to perform a retrieval process as we start from the biological system we encountered (stage 1). Next, we move to build the bridge to the application by the abstraction stage (stage 4) that enables to transfer design solutions between the domains. Then, we transfer the biological solution to a suggested biomimetic concept or application (stage 5). At this stage, we have deeper understanding of the biological solution and we are able to define a specific application. Finally, we evaluate and perform iteration to each one of the previous stages if required (stage 6). Elaboration on the abstraction, transfer and evaluation stages (4–6) in Sect. 2.2 is also relevant to this design direction.

The dashed box in Fig. 2.2 includes the core and unique stages to biomimetic design. Outside the dashed box is the final general design stage of evaluation. The bolded arrows between the source (biology) and target (application) represents the connecting bridge between these two domains.

2.4 The Synapse Design Model Charts

The above mentioned design processes from a problem to biology and vice versa, are presented in a more appealing way in the two following synapse design model charts. Synapse, the space between nerve cells where signals are passed, is named after the Greek word synapsis that means a conjunction or point of contact. The following biomimetic design model charts are named after the synapse conjunction concept, as they aim to connect biology and engineering (see Figs. 2.3 and 2.4).

The synapse design charts steps, one by one, lead the designer in the conjunction of biology and technology. As the model suggests, iterations forward and backward may be required during the process.

Fig. 2.3 The synapse design chart: from a problem to biology

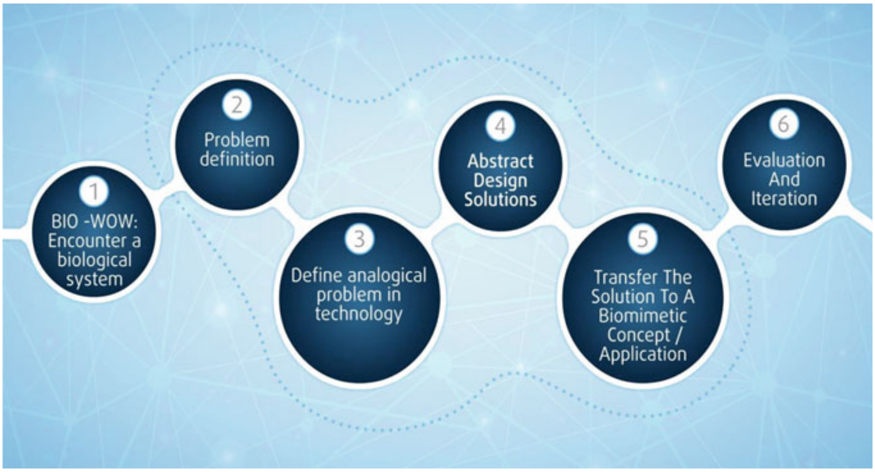

Fig. 2.4 The synapse design chart: from biology to an application

2.5 Biomimetic Design Process Stages—Literature Review

The stages we described in Sects. 2.2 and 2.3 as our suggested model for the biomimetic design process appear in the literature in various sources. For example, the stage of biological system search appears as 'Biological solution search' [54] or 'Search for examples of relevant biological systems' [79] for a problem to biology direction. The stage of encountering a biological system appears with partial similarity as 'Biological solution identification' [54] for a biology to application direction. The stage of abstraction appears as 'Identify solution principle in the biological example' [71] or 'Analyze the biological systems' [79]. The stage of transfer appears as 'Technical implementation' [79] or 'Transfer the principles into the new domain' [54].

Our conclusion about repeated stages in the literature corresponds with Sartori et al. [71] study. They reviewed several biomimetic design processes from the literature and identified stages that are common in various descriptions including problem definition, biological system search, analysis of the biological system and the transfer.

2.6 Biomimetic Design Process—Main Challenge

The main challenge of the biomimetic design process is related to its analogical and interdisciplinary nature: bridging the gap between biology and technology. Biology and technology are based on different terminologies and ways of thinking.

In general, knowledge structure and mapping in different disciplines is different [82], although there is notable exception, namely, the Interdisciplinary Engineering Knowledge Genome (IEKG) that bridges between seemingly distinct disciplines [62, 83, 84]. The difference between biology and engineering was previously discussed. In addition, functional terminologies in both domains may be different. For example, the function 'Transport' may have different meaning in biology. While plants do not move they can be a source of inspiration for transportation by exploring the way they disperse their seeds [85]. We elaborate on functional terminologies difference in Sect. 6.1.2.

The difference between biology and technology is also manifested by the way engineers and biologists are trained and think. Biologists are trained to investigate phenomena and search for details. They do not tend to abstract or formulate rules. Engineers are trained to solve problems by synthesis and they investigate possible solutions. In general, biologists lack engineering and design knowledge and engineers lack biological knowledge. The main challenge therefore is bridging these two domains and creating an infrastructure for fertile knowledge transfer and communication.

http://www.springer.com/978-3-319-33996-2

Biomimetic Design Method for Innovation and
Sustainability
Helfman Cohen, Y.; Reich, Y.
2016, XXVII, 254 p. 77 illus., 44 illus. in color., Hardcover
ISBN: 978-3-319-33996-2