

Biologically Inspired Design: Process and Products

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Biologically inspired engineering design uses analogies to biological systems to develop solutions for engineering problems. We conducted a study of biologically inspired design in the context of an interdisciplinary introductory course on biologically inspired engineering design in Fall of 2006. The goals of this study were to understand the process of biologically inspired engineering design and to provide insight into biologically inspired design as a type of design activity. This paper provides a descriptive account of biologically inspired design processes and products, and summarizes our main observations: 1) designers use two distinct starting points for biologically inspired design; 2) regular patterns of practice emerge in biologically inspired design; and 3) certain errors occur regularly in the design process.

Keywords: Biologically Inspired Design, Biomimetic Design, Engineering Design, Cognitive Study

Biologically inspired design uses analogies to biological systems to develop solutions for engineering problems. Biologically inspired design is gaining in importance as a wide-spread movement in design for environmentally-conscious sustainable development (e.g., Anastas & Warner, 2000; Benyus 1997; Papanek 1984; Wann 1990) that often results in innovation (Collins and Brebbia 2004; Forbes 2005; French 1998; Vogel 2000). Bosner (2006) and Bosner & Vincet (2007) trace the growth of biologically inspired design patents. From the perspective of design studies, a number of characteristics make biologically inspired design an especially interesting problem to study. (1) Biologically inspired design is inherently interdisciplinary. By definition, it is based on cross-domain analogies requiring expertise across two disparate domains (engineering and biology). (2) Since the objects, relations and processes in biology and engineering are very different, biologists and engineers typically speak a very different language, creating communication challenges. (3) Since biologists in general seek to understand designs occurring in nature while design engineers generally seek to generate designs for new problems, they typically use different methods of investigation and often have different perspectives on design. (4) Biological designs typically result in more multi-functional and interdependent designs than engineering designs. (5) The resources, such as materials and processes, available in nature to realize an abstract design concept typically are very different from the resources available in the engineering domain.

The literature in the design sciences contains many case studies of biologically inspired design. Vincent & Man (2002), for example, describe their imitation of the design of pinecones to design clothing that can help regulate body temperature. Other examples include design of micro robots that can walk on water mimicking the locomotion of the basilisk lizard (Floyd, Keegan & Sitti 2006), and design of nano-scale super-hydrophobic coatings inspired by the self-cleaning mechanism of lotus leaves (Zhu et. al. 2005), and dynamic server allocation for internet housing inspired by forager allocation in honey bee colonies (Nakrani and Tovey 2004). Beer et. al. (1999) and Bar-Cohen & Brazeal (2003) review several cases of biomimetic robot designs.

Recently, there also have been some attempts to build databases for supporting biologically inspired design. The Biomimicry Institute (<http://www.biomimicry.net/>), for example, provides the AskNature

(www.asknature.org/) online library of research articles on biomimetic design indexed by function. Chakrabarti et. al.'s (2005) SAPPHIRE tool provides English language descriptions of the structures, behaviors and functions of biological and engineering designs previously used in biomimetic design.¹ It also uses verbs to describe engineering design problems, and retrieves biological and engineering designs based on matches between the verbs used in the problem descriptions. Based on experiments with the SAPPHIRE tool, Sarkar & Chakrabarti (2007) discovered that diagrammatic representations of biological systems lead to generation of more and better design ideas than textual representations. Mak and Shu (2004) provide a taxonomy of verbs that relate biological and engineering designs. They (Mak & Shu 2008) have found that functional descriptions of biological systems in the form of flow of substances among components improve the quantity and quality of the generated design ideas. Nagel et. al. (2008) describe a small database of models of biological systems based on function flow. Linsey et. al. (2007) found that functional annotations on diagrams increase the chances of successful biological analogies.

However, at present there is little understanding of the *processes* of biologically inspired design as a design activity. Vincent et. al. (2006) provide one of the few information-processing models of the *how* of biologically inspired design instead of the *what*. However, their model, based on the TRIZ model of creative design (Altshuller 1984) is *normative*. The current paper provides a descriptive account of the biologically inspired design process through an *in situ* study conducted on the practices and products of designers in the context of doing biologically inspired design. The advantages of descriptive accounts of design include realism, and accuracy of predictions of design behaviors. In general, they are a precursor to developing more effective pedagogical techniques and computational tools for supporting design. Although not a focus of the current paper, this descriptive account is beginning to provide a detailed information-processing model of biologically inspired design that focuses on the cognitive processes or 'mechanisms' that facilitate and constrain the design practices and products (e.g., Helms, Vattam & Goel 2008; Helms et. al., 2008; Vattam, Helms & Goel 2008; Vattam et. al. 2008). This study was conducted in the context of an undergraduate

¹ The terms "function" and "behavior" have many meanings in the design literature. Following Goel & Bhatta (2004), we use the term function to refer to the purposes of a system, and the term "behavior" to refer to the internal causal processes of the system that result in the accomplishment of the system's functions.

interdisciplinary course on biologically inspired design at Georgia Institute of Technology (ME/ISyE/MSE/PTFe/BIOL 4803). Although this study was conducted in the context of a classroom, the goals of this study were both to understand the nature of biologically inspired design and to identify opportunities for enabling more effective practice of biologically inspired design at large.

1. The Context of the Study

ME/ISyE/MSE/PTFe/BIOL 4803 is a project-based undergraduate class, in which 45 students, 41 of whom were seniors, work in small teams of 4-5 designers on assigned projects. The class was very interdisciplinary, composed of 6 biologists, 25 biomedical engineers, 7 mechanical engineers, 3 industrial engineers, and 4 from other majors. The projects involve identification of a design problem of interest to the team and conceptualization of a biologically inspired solution to the identified problem. Each team writes a 15-20 page report and makes an oral presentation near the end of the semester. In Fall 2006, ME/ISyE/MSE/PTFe/BIOL 4803 was jointly taught by six faculty from Georgia Tech's Schools of Biology, Chemistry, Mechanical Engineering, Industrial & Systems Engineering, and Polymer, Textile and Fiber Engineering. The course also included guest lectures by several prominent researchers from other schools.

The ME/ISyE/MSE/PTFe/BIOL 4803 class was structured into *lectures*, *found object exercises*, *journal entries*, and a *final design project*. Most lectures focused on exposing the designers to existing biologically inspired design case-studies. Other lectures were devoted to the design processes involved in biologically inspired design work: reframing engineering problems in biological terms, functional analysis of a problem, optimization, and the use of analogy in design. Some lectures posed problems for the students to solve in small group exercises.

Although this study was conducted in the context of a classroom setting, we approached the study from a design cognition perspective as opposed to a learning sciences perspective. That is, we were less concerned about the pedagogical approach and the learning outcomes of the course. Although we believe that our research will have implications on the approach and conduct of the course, we were not directly involved in

the decision-making regarding the design of the course. From our perspective the classroom provided a setting where we could observe designers engaged in biologically inspired design.

Most instructors and lecturers had many years of practical biologically inspired design experience and focused classroom lectures on sharing their biologically inspired design experience through specific case studies. Most students, although new to biologically inspired design, had previous design experience. Out of the 45 students, at least 32 had taken a course in design and/or participated in design projects as part of their undergraduate education. Throughout this paper, we will refer to the students in the class as designers.

In addition to lectures, classroom activities included regular *found object exercises* that required designers to bring in biological samples and analyze the solutions employed by these samples. These exercises were intended to expand awareness of biology, provide hands on experience with biological systems, and encourage the designers to dig progressively deeper into the functions of biological systems. Additionally, *journal entries* required designers to write about their classroom experiences, including found object discussions, and to document their own design thinking.

The *final design project* grouped an interdisciplinary team of 4-5 designers together based on interest in similar problems or solutions. Each team had at least one designer with a biology background and a few from different engineering disciplines. Each team identified a problem that could be addressed by a biologically inspired solution, explored a number of solution alternatives, and developed a final solution design based on one or more biologically inspired designs. The teams presented their final designs during the final two weeks of class and submitted a final paper, which combined represented a majority of their semester grade.

As observers, we attended all the classroom sessions, collected all course materials, documented lecture content, and observed teacher-designer and designer-designer interactions in the classroom. We also observed a few of the interdisciplinary teams of designers engaged in their design projects. We minimized our intervention, only occasionally asking clarifying questions. Our observations focused on the processes and

the products of the designers. In terms of the practices, we observed and documented frequently occurring problem-solving and representational activities of designers. In terms of the design products, we observed and documented the “design trajectory” – the evolution of the conceptual design over time.²

2. Biologically Inspired Design Processes

While designers have used biology as an inspiration for thousands of years, no normative process exists specific to the practice of biologically inspired design. At the leading edge of the nascent but rapidly expanding community of practice of biologically inspired design, classroom instructors taught what they considered best practices gleaned from both the biologically inspired design community and from their own experience. The six step process outlined below was not taught explicitly, but is rather an organizing framework resulting from our retrospective analysis of the classroom lectures. The process in practice is very dynamic, with many visits to reformulate or deepen understanding of both the problem and solution spaces. This organizing framework focused primarily on the problem-driven process which was emphasized in classroom instruction, although a second, solution-driven process, described in more detail in section 5, emerged in practice.

2.1. Problem-Driven Biologically Inspired Design Process

The pattern of problem-driven biologically inspired design follows a progression of steps which, in practice, is non-linear and dynamic in the sense that output from later stages frequently influences previous stages, providing iterative feedback and refinement loops.

- Step 1: Problem Definition
- Step 2: Reframe the Problem
- Step 3: Biological Solution Search
- Step 4: Define the Biological Solution
- Step 5: Principle Extraction

² Additional details of the study are available in Vattam, Helms, & Goel (2007).

- Step 6: Principle Application

2.2 Step 1: Problem Definition

Designers were asked to find or invent a problem they care to solve and then were instructed to define their problem as a function. For example a group that began with the problem of preventing shark attacks on surfers defined their desired function as camouflaging a surfboard. Instructors emphasized two techniques to aid designers in thinking through their problem.

Functional Decomposition: As problem definition is carried out, initially simple-seeming problems become complex, often involving multiple, integrated functions. In the words of one instructor, “Biological systems are complex, inter-connected and multi-functional. It is difficult to extract a single concept to use from the tangled mess.” Functional decomposition takes a complex function and decomposes it into sub-functions.

Functional Optimization: Functional optimization defines a function or set of functions in terms of an optimization problem or equation. Designers then analyze potential new solutions by measuring performance against optimization criteria. Similarly, biologists can frame biological solutions in terms of optimization equations. Abstracted to this level, designers can more easily transfer engineering requirements to biological solutions (and vice versa). For example, in the analysis of moss in a found object exercise, the functional goals of the structure and placement of moss are to: (a) reduce water loss, (b) increase surface area for photosynthesis, (c) position relative to the sun, and (d) protect reproductive structures from environmental stress. However, the functions of reducing water loss and protecting reproductive structures oppose increased surface area and sunlight exposure functions. The structure and placement of moss must optimize the balance between these two opposing sets of functions.

2.3 Step 2: Reframing the Problem

Designers always initially defined problems in human terms, such as protecting police 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 “biologizing” the problem. As an example, instead of “stopping a bullet,” the biologized version of this function was “What characteristics do organisms have that enable them to prevent, withstand and heal damage?”

2.4 Step 3: Biological Solution Search

Instructors provided four general strategies/techniques for finding biological solutions relevant to a problem which are listed in Table 3.1.

Table 3.1 Solution Search Heuristics

Search Technique	Technique Description
Change Constraints	If the problem is narrowly defined, such as “keeping cool”, change the constraints to increase the search space, for instance to “thermoregulation”.
Champion Adapters	Find an organism or a system that survives in the most extreme case of the problem being explored. For instance, for “keeping cool”, look for animals that survive in desert or equatorial climates.
Variation within a Solution Family	Where multiple organisms have faced and solved the same problem in slightly different ways, e.g. bat ears and echo-location, look at the small differences in the solutions and identify correlating differences in the problem space.
Multi-Functionality	Find organisms or systems with single solutions that solve multiple problems simultaneously.

2.5 Step 4: Define the Biological Solution

Designers usually first identified the structures and superficial mechanisms from the biological system that were related to the reframed function, for example, the shell of the abalone for resisting impact. The initial understanding that abalone shell is hard, lightweight, resists impacts, and is regenerative, deepened over time into an understanding of the complex interactions of composite materials that are responsible for this

behavior. The same functional decomposition used in the problem definition step was often helpful in facilitating the understanding of the biological solution.

2.6 Step 5: Principle Extraction

After a solution was well understood, important principles were extracted into a solution-neutral form, which required a description that removed as many specific structural and environmental constraints as possible. For example describing the principles of the abalone shell in terms of “interactions between flexible proteins and hexagonal calcium carbonate deposits” may constrain design thinking to proteins, calcium carbonate, and hexagons. On the other hand “tightly coupled composite material formation from alternating flexible and rigid structures for resisting impact,” allows for the possibility of using arrangements of many different kinds of flexible and rigid material.

2.7 Step 6: Principle Application

After the principle was extracted from the biological solution, designers translated the principle into the new domain. This translation involved an interpretation from one domain space (e.g. biology) into another (e.g. mechanical engineering), by introducing new constraints (and affordances) to the biological problem. In the case of the bullet proof vest, new weight, flexibility, impact resistance and manufacturing process criteria were added, along with new affordances, for example in materials. Designers frequently created composite solutions by selecting the “best-of” multiple sources to meet competing demands, which we classified as *compound analogies*.

3. Biologically Inspired Design Projects

This section provides a summary of three of the final design projects submitted by the design teams that highlight practices of interest. In section 5 these practices are tabulated for all projects and emergent patterns of practice are noted.

3.1 Project 1: *i-Fabric*

The *i-Fabric* project followed the problem-driven approach prescribed in class by the instructors. The design team arrived at an ultimate formulation of the problem as conceptualizing “a thermally responsive and adaptive fabric that can be made into clothing in order to provide thermoregulation for the user in extreme temperature environments.” The problem was reframed, or “biologized,” as: “How are organisms in nature capable of maintaining consistent body temperatures using the least amount of energy?” The complex problem statement results in multiple functional requirements at the highest level of the problem statement, and we therefore classify this problem as a multi-functional problem. Note in the reformulation of the problem, a deeper understanding is reflected by the additional energy constraint in the reframed question. That is, that minimal energy use, though not explicit in the problem statement, is related to thermoregulation in extreme temperature environments.

From the reframed problem, the designers found six different sources of biological inspiration, including: penguins, wood storks, arctic wolves, bee hives, Kenyan chameleons, and humans. Each source was evaluated, and an initial solution was selected based on the bee hive, which uses the phase transition properties of a paraffin wax, called octadecane to store and release heat to moderate the temperature of the hive.

In the initial design solution the designers limited themselves to making a composite material with octadecane, rather than extracting the core principle of phase transition and applying it to other materials. Because of the reuse of the same physical components from source to solution, rather than application of the principle, we classify this as a project that was structurally focused. As was common, the designers also encountered a new problem -- in this case the problem of heat localization in the human body -- and required a solution that not only involved the storage and release of heat, but could shift heat from central to peripheral body locations (or vice versa). Thus the first solution offered a new sub-problem, which the team solved by iterating through the biologically inspired design process.

The second iteration of the design process yielded a counter-current bypass system found in several other biological cases (wood stork and arctic wolf) that could help manage heat distribution between parts of the body. Using this as their inspiration, the designers combined the phase transition material with heat conducting fibers that could manage heat distribution from one location of the body to another. Since the final design used two separate mechanisms, each to accomplish a separate function, we classify this as an example of compound analogy, but not as a multi-functional solution. Multi-functional solutions differ in that they use a single mechanism to accomplish two or more functions. For example, in this case paraffin wax may have been a good multi-functional solution if water resistance were an additional criterion for the problem.

3.2 Project 2: Abalone Armor

The abalone armor project provides an excellent counter-example to the problem-driven approach prescribed in class by the instructors. In this case, the team first determined that they wanted to use abalone shell (nacre) as their inspiration, and then formulated a problem that could be solved by the impact-resistant nacre. We classify this as an example of solution-driven biologically inspired design. Starting from the biological solution, the designers for this project quickly settled on the problem of conceptualizing a bullet-proof vest using the abalone nacre. Later, under a directive from the instructors to investigate other biological sources using the problem-driven approach, the team abstracted their problem specification to “using a material that combines the qualities of strength, toughness and self-healing”, and reframed their problem as the biologized question: “What characteristics do organisms have that enable them to prevent, withstand and heal damage?”

Using these more abstract problem definitions, the students investigated five alternative biological sources of inspiration: spider silk, lobster exoskeleton, sea star, rhino horn, and human bone. Each new alternative was dismissed after a short period of analysis, demonstrating a solution fixation that was common among all groups. That is, as soon as an initial biological source of inspiration was investigated, that source of inspiration tended to dominate all future solution development. Alternative sources of inspiration tended to

be dismissed as soon as a potential challenge was encountered, even despite the fact that some of those same challenges were also true of the initial, fixated source of inspiration. In the words of one designer “we’ve invested too much time in [our biological source of inspiration] to abandon it now.”

After quickly analyzing and dismissing other sources of inspiration, the designers initially focused on understanding the composite material of the abalone shell and the material organization at very small scales. As this initial analysis unfolded, an understanding developed that suggested to the designers that substances reaction to forces not only depended on the magnitude of the force, but also the duration. This created an elaboration of the problem to include resistance to both bullets and knife strikes, which apply different force magnitudes over different time frames and result in different and competing design constraints. Because there were now multiple functions which the solution needed to address (stopping bullets is a sufficiently different function than stopping knife strikes), we classified this as a multi-functional problem.

The designers analyzed how abalone nacre behaved when acted upon by different forces at different time scales, including fracture mechanics of response to bullet impact based on criteria such as fracture stress, surface energy, strength intensity, and minimum initial crack size. This analysis showed that body armor made from abalone shell would be one hundred times too weak to stop a bullet, and would weigh ten times more than conventional Kevlar body armor. Note that there is a light-weight criterion implied by the analysis of weight that was never made explicit in the problem definition. Despite three competing criteria – resisting a bullet, resisting a knife strike, and weight – this problem was never posed as an optimization problem.

All phases of design, initial through final, mimicked the components and materials of the abalone shell exactly, assuming the same composite of calcium carbonate and protein would be applied to the bullet-proof vest. Closely mimicking structure in this way was another common design practice highlighted by this case, even despite the well formed recasting of the problem space, and “biologizing” of the problem. Because the final design attempted to use a single solution to meet the needs of the multi-functional problem, we classified this as a multi-functional solution.

The self-healing mechanism of abalone shell was excluded from the scope of the problem because the mechanism was not well understood.

3.3 Project 3: BioFilter

The BioFilter project represented another example of problem-driven biologically inspired design. The initial goal of the project was to produce a portable, stand-alone, home air filtration unit to trap allergens and other harmful particles. Also important in the problem definition were the qualities of low power consumption, no degradation in filtration capacity over time, inexpensive or no replacement of parts, and environmental friendliness. The designers reframed the problem in terms of “What cleaning and filtration mechanisms are found in natural organisms?” and came up with the largest number of sources of inspiration. In fact some designers complained “there were too many biological sources to select from.” This is interesting in light of comments from other design problems stating that too few biological sources were available.

In the case of the BioFilter project, of the ten sources that were initially evaluated, the human lungs were selected for the first design attempt. This design examined the cleaning and filtration capabilities of the mucus and cilia present in the respiratory track, where the function of the mucus is to trap small particles before the air reaches the alveoli in the lungs and the function of the cilia is to transport the contaminated mucus. The initial conceptual design depicted in Figure 3.1 is taken directly from the designer’s final report. Ultimately, this design was rejected when the designers considered the problems of production and secondary filtration of mucous, a critical component to their system. This sub-problem was too difficult for the designers to overcome, so they scrapped their initial design, and began with completely different sources of inspiration. The second time through, however, the team demonstrated a deeper understanding of their problem, in particular with the production and removal of filtration medium.

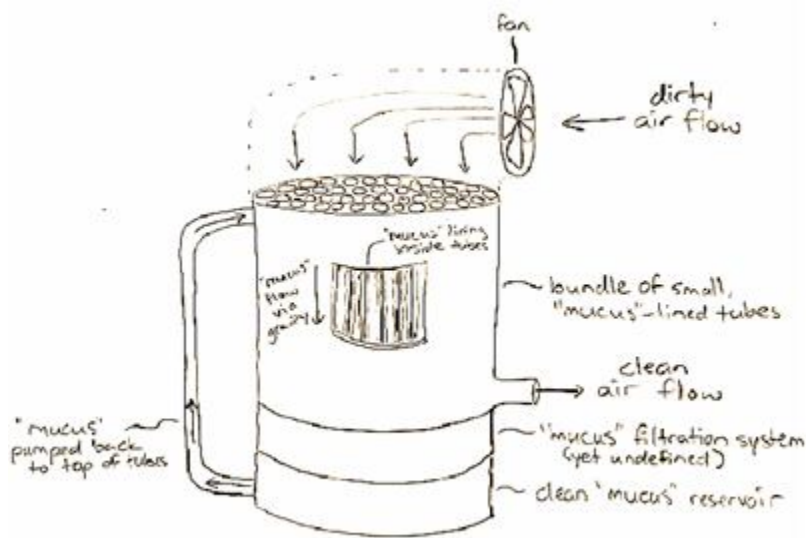


Figure 3.1

The second iteration of the design focused on a multi-stage filter using the adherent properties of spider-silk to remove large particles, and the fine, porous properties of diatoms to remove smaller particles. Spider silk was selected for its biodegradable properties, and its similarity to current first-stage filters. In the case of the diatoms which would do small-size filtration, the control of size, ease of replication, low cost, and environmentally friendly composition of the diatom structure (made of pure silicon) made for an ideal filtration medium. In this second design instance, the team showed a heightened awareness to the problem of secondary filtration, and ease of creation and disposal of expensive, fine filtration medium. This second solution showed how a single function, air-filtration, could be decomposed into large- and small-grain filtration, and solved again using compound analogies.

Especially noteworthy in this filtration example is the focus on structure. In the case of the analogy to human lungs, the design team focused on using a “mucous like material” for their design, which ultimately caused the termination of that design path. In the case of the use of spider silk and diatoms, the designers used the actual structures of spider silk and diatoms themselves, rather than extracting the useful principles and

applying them to the design. Designers continued to focus on and design around structure, despite many hours of instruction attempting to focus designers on underlying mechanisms and functions.

4. Analysis of Biologically Inspired Design Processes

In the previous section we provided examples of the types of observations made during the design process, and the classifications we employed to discern core biologically inspired design processes, common errors, and emergent patterns of practice. Here we provide a summary of our findings over all design projects and classroom observations.

4.1. Solution-Driven biologically inspired design Process

While the normative biologically inspired design process pointed to a problem-driven approach, we observed that the biologically inspired design process typically begins from one of two different starting points, the solution or the problem, and follows two distinct patterns, solution-to-problem or problem-to-solution (Helms et. al. 2008). Some classroom exercises, and many of the case-studies provided to the class, began with a biological solution, extracted a deep principle, and then found problems to which the principle could be applied. In general, the solution-driven biologically inspired design process follows the steps listed below (note again that this pseudo-algorithm only illustrates the high-level pattern of the problem-driven process; in practice, the actual process is not necessarily ordered linearly).

- Step 1: Biological Solution Identification

Here, designers start with a particular biological solution in mind.

- Step 2: Define the Biological Solution
- Step 3: Principle Extraction
- Step 4: Reframe the Solution

In this case, reframing forces designers to think in terms of how humans might view the usefulness of the biological function being achieved.

- Step 5: Problem Search

Whereas search in the biological domain includes search through some finite space of documented biological solutions, problem search may include defining entirely new problems. This is much different than the solution search step in the problem-driven process.

- Step 6: Problem Definition
- Step 7: Principle Application

4.2. Common Errors

Throughout the biologically inspired design process, we observed errors (as identified and critiqued by the instructors) that were common to a number of designers. Table 5.1 summarizes the main types of errors:

Error 1. Vaguely defined problems.

Problems that are nebulously defined, such as “lowering our dependence on oil,” or “protecting a cell phone,” are either too vague to yield to functional description, or result in too large a search space. Better examples are “more efficient allocation of resources to reduce energy consumed in transportation” and “forming a scratch-resistant coating for cell phones.”

Error 2. Poor problem-solution pairing.

Frequently, designers match problems to biological solutions based on vague or superficial similarity, such as matching “making a better dishwashing detergent” with the “cleaning properties of the lotus leaf.” While the function “cleaning” is similar, the lotus leaf relies on the structural details of the structure to be cleaned, which a detergent cannot manipulate.

Error 3. Oversimplification of complex functions.

Designers often miss the significance of an underlying principle because of simplifying assumptions, such as when using the term “simply writhing”, when in fact writhing is a very deliberate, complex motion.

Error 4. Using “off-the-shelf” biological solutions.

Commonly, designers seek to use an organism to “do what it does” instead of leveraging the principles of the organism. This is the equivalent of using fireflies themselves to produce light, rather than understanding and applying the complex chemistry involved in bioluminescence.

Error 5. Simplification of optimization problems.

Designers frequently fixate on a single biological function, rather than investigating complex and competing biological functions when formulating optimization problems. For example, designers viewed the structure of moss as a surface area optimization problem for gathering sunlight, while ignoring protection and water preservation requirements of the plant.

Error 6. Solution fixation.

Designers commonly fixated on the first inspiration source offered, initially focusing on it to the exclusions of investigating others, and then preferring it over all subsequent sources when instructors mandated comparative evaluations. Only one out of nine teams rejected their initial source in favor of an alternative.

Error 7. Misapplied analogy.

When making an analogy, superficial or high-level matches are often forced into an incongruent solution space, yielding flawed solutions. For instance, a two-way traffic optimization algorithm derived from ant foraging behavior, applied directly to a throughput traffic optimization problem yielded an erroneous model. Fixation on this erroneous model resulted in three design revision attempts prior to it being discarded.

Error 8. Improper analogical transfer.

During the process of transferring mechanisms from the inspiration source to the problem, mechanisms that are important in the source domain, but not applicable to the problem, are also transferred. For instance, while a dog nose is great at sorting through and identifying a multitude of different scents, if you’re looking for just one scent in particular, there are filters in the dog nose that are unnecessary to the solution, but were nevertheless transferred to the design.

4.3. Patterns of Practice

Designers submitted a total of nine final projects, five of which were covered in the previous section. We analyzed these nine projects using the following criteria: the number of sources investigated and used in the final design; whether or not the designers began with an initial solution fixation; whether the designers used a problem or solution driven process; whether the problems and solutions were multi-functional; whether the designers focused strongly on structure instead of function; and whether or not designers optimized to a specific function. Table 4.2 provides a summary of our findings.

Table 4.2 Project Summary

Project	Sources Used	Sources Investigated	Initial Fixation	Solution/ Problem	Multi-function problem	Multi-function solution	Structural Focus	Optimization
Bomb Detection	2	3	-	Problem	Yes	No	No	No
Traffic Routing	1	4	Ants	Problem	No	No	No	Yes
Body Armor	1	6	Abalone	Solution	Yes	Yes	Yes	No
Air Filtration	2	10	-	Problem	No	No	Yes	No
Visual Display	2	3	Morpho	Solution	Yes	No	Yes	No
U/W Stealth Vehicle	2	2	Copepod	Solution	Yes	No	Yes	No
Cell Phone Case	1	6	Abalone	Solution	Yes	Yes	Yes	No
Adaptive Garment	4	6	-	Problem	Yes	No	Yes	No
Surfboard Camouflage	2	4	Ponyfish	Problem	Yes	No	No	No

From this table it is interesting to note the following trends:

- While experts emphasized a problem-driven approach to biologically inspired design, 4 of 9 projects were solution driven.
- Although experts emphasized the importance of considering function, 6 of 9 projects focused on structure. All 3 projects that focused on function used a problem-driven design process.
- Only solution-driven projects generated multi-functional designs.

- Compound solutions were used in 6 of 9 solutions, in each case as a result of further elaboration of each problem from an initially proposed solution or source of inspiration. Each new source of inspiration was used to solve a new sub-problem or elaboration of the original functional requirements (Helms, Vattam & Goel 2008; Vattam, Helms & Goel 2008).
- Despite several weeks of instruction on functional optimization, only one project framed the problem as an optimization problem.
- In almost all cases, designers quickly honed in on target solutions already discussed at length during instructor presentations. Once a designer or group “locked onto” a solution, they stuck with their original solution even when looking for additional inspiration from other sources. All projects that used a solution-driven design process demonstrated fixation on an initial biological source, and included additional biological sources only when required to do so by instructors.
- During the search process, some designers noted that “there were far too many solutions applicable to their problem, and so choosing among the possibilities was very difficult”. Other designers noted exactly the opposite problem, saying they could find few, one or no applicable biological organisms for their problem space.

5. Conclusions

Biologically inspired design is a nascent but rapidly growing area of design research. In this paper, we have analyzed the biologically inspired design process in terms of the practices of the designers and their products. We noted the existence of two high-level processes for performing biologically inspired design based on the two different starting points – problem-driven and solution-driven process. We also noted how the problem-driven process was “given” to the designers by the experts as a normative methodology for biologically inspired design, while the solution-driven process emerged in practice. We draw three conclusions from our observations of the biologically inspired design process. First, once a biological solution is selected, that solution constrains the rest of the design process. When the design process begins with a biological solution, as in almost half the cases we studied, this solution fundamentally drives the design process, from problem definition through final design. In the problem-driven design process, the biological solution became a source

of design fixation, limiting the source of inspiration to that one source. Second, throughout the process of design, designers consistently fall prey to a common set of mistakes, ranging from ill-defined problems to improper analogical transfer. Third, patterns of practice emerge spontaneously in biologically inspired design, such as focus on structure, which differ from instruction. Each process, practice pattern, and cognitive error provides an opportunity both to enhance our understanding of the nature biologically inspired design and to develop strategies to improve the performance of designers engaged in biologically inspired design.

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