# Problem-Driven and Solution-Based Design: Twin Processes of Biologically Inspired Design

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## Abstract

Biologically inspired design uses biological systems as analogues to develop solutions for design problems. We conducted a cognitive study of biologically inspired design in the context of an interdisciplinary introductory course on biologically inspired design in Fall of 2006. The goal of this study was to understand the processes of biologically inspired design. This paper provides a descriptive account of twin biologically inspired design processes, problem-driven and solution-based, and highlights the similarities and differences between them.

## 1 Introduction

Biologically inspired design uses analogies to biological systems to develop solutions for design problems, often results in innovation (e.g., Benyus 1997; Vogel 2000). A number of typical characteristics make biologically inspired design an especially interesting problem to study. (1) By definition, biologically inspired design is based on analogies requiring expertise across two disparate domains (e.g. architecture and biology), and thus is inherently interdisciplinary. (2) Since the objects, relations and processes across domains are very different, design collaborators speak from different lexicons. (3) Since biologists in general seek to understand the functions of designs occurring in nature whereas designers generally seek to generate designs for human needs, they use different methods of investigation and have different perspectives on design. (4) The resources, such as materials and processes, available in nature to realize an abstract design concept are very different from the resources available in the human 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. Aldersey-Williams (2004) reviews several case studies of biomimetic architectural design, for example, the Kunsthaus in Graz, Austria, the Singapore Arts Center, and 30 St.Mary Axe in London.

While designers have used biology as an inspiration for thousands of years (Vogel, 2000), we are unaware of any normative process specific to the practice of biologically inspired design. This paper provides a preliminary descriptive account of biologically inspired design processes through a study conducted on the practices and products of designers in the context of doing biologically inspired design. Additional details about the study can be found in Vattam, Helms, & Goel, 2007.

## 2 The Context of the Study

ME/ISyE/MSE/PTFe/BIOL 4803 is a project-based learning class at Georgia Tech, in which 45 students work in small teams of 4-5 designers on assigned projects. The projects involve identification of an engineering design problem and conceptualization of a biologically inspired solution to the identified problem. At the end of the semester each team made an oral presentation of their design and provided a 15-20 page final report. The final report defined the engineering problem, provided market research for existing solutions to the problem and potential market size, identified at least five potential biological sources of inspiration, and provided specifications of the final design, including technical quantitative analysis.

Each team had one biologist and a three or four from diverse engineering disciplines. The designers 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 solutions.

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 the interdisciplinary teams during the process of design, documented design trajectories, and evaluated the final design reports

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. Some researchers have examined pedagogical issues related to teaching biologically-inspired design (e.g. Vogel, 2000). Although our research on understanding how designers integrate biological and engineering knowledge can inform teaching strategies, this was not our central focus. From our perspective the classroom provided a setting where we could observe designers engaged in biologically inspired design.

## 3 Problem-Driven Biologically Inspired Design

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

- Step1: Problem Definition
- Step 2: Reframe the Problem
- Step 3: Biological Solution Search
- Step 4: Define the Biological Solution
- Step 5: Principle Extraction
- Step 6: Principle Application

### 3.1 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. Problem elaboration typically occurred throughout the design process, creating more refined functional requirements and constraints.

### 3.2 Step 2: Reframing the Problem

Designers defined problems in human terms such as protecting police or avoiding shark attacks. To find solution analogues in biology, designers redefined their problems in more biological terms, often in the form of a question such as "How do biological solutions accomplish xyz function?" As an example, instead of "stopping a bullet," the reframed version was "What characteristics do organisms have that enable them to prevent, withstand and heal damage?"

### 3.3 Step 3: Biological Solution Search

Instructors provided the four general search strategies found in Table 3.1.

### 3.4 Step 4: Define the Biological Solution

Designers first identified structures and surface 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. We note that 66% of the all of design teams, and 100% of the design teams using the alternative solution-driven approach, focused on structure and surface characteristics in this way.

**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 dessert or equatorial climates. |
| Variation within a Solution Family | Find organism “families” that have faced and solved the same problem in slightly different ways. For instance, the many variations on bat ears suggest deeper solution principles for echo-location. |
| Multi-Functionality | Find organisms or systems with single solutions that solve multiple problems simultaneously. |

### 3.5 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 with alternating flexible and rigid structures for resisting impact,” allows for the possibility of using arrangements of many different kinds of flexible and rigid material.

### 3.6 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. 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. This process often created new sub-problems, which designers frequently solved with new biologically inspired solutions. Designs that used multiple biological analogies we classify as *compound analogical designs* (Vattam et al, 2008).

## 4. Sample Problem-Driven Design Project: i-Fabric

The i-Fabric project followed the problem-driven approach prescribed in class by the instructors. The design team arrived at the problem of 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 designers found six different sources of biological inspiration, including arctic penguins, wood storks, arctic wolves, beehives, Kenyan chameleons, and humans. These choices illustrate the effectiveness of reframing the problem in biological terms. Not only do the biological entities come from different environments, they represent a wide range of behaviors at a number of different levels of biological organization, e.g. organism systems, to collections of organisms, Each source was evaluated, and an initial solution (Figure 2a) was selected based on the beehive, which uses the phase transition properties of a paraffin wax to store and release heat to moderate the temperature of the hive.

The designers initially limited themselves to making a composite material with wax. Because of the use of the same physical components from source to solution, rather than application of the principle, we classify this as a structurally focused project. 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 could shift heat from central to peripheral body locations. New sub-problems, of which this is one example, occurred in all of the observed design problems. As solutions were tried, obstacles to their implementation (new requirements), deficiencies in the solution (partial-solutions, as in this case), or inspiration from the source analogue provided a deeper insight into the problem, and resulted in additional design iterations.

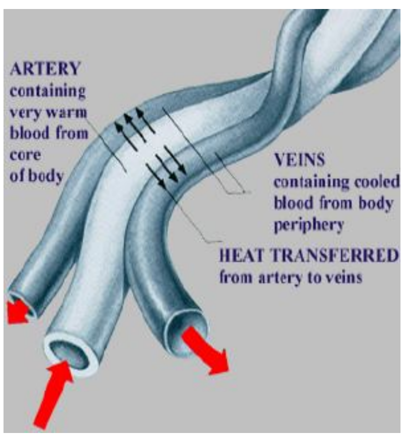
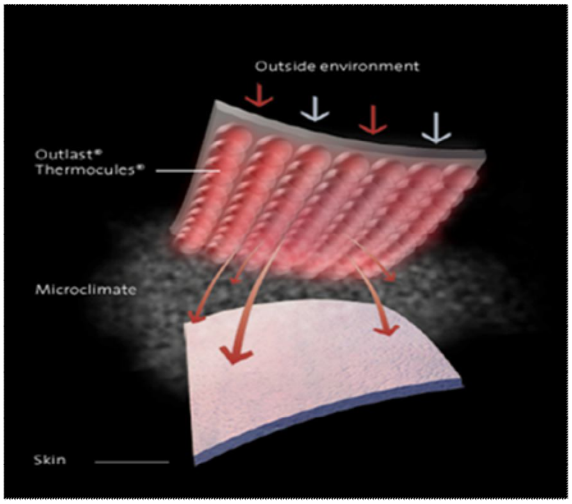
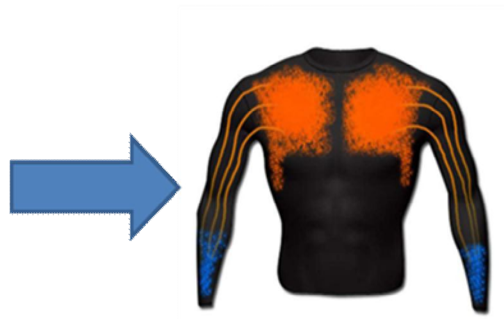



**Figure 1. Counter-current bypass system**

The second iteration of the design process yielded a counter-current bypass system (Figure 1) found in several other biological cases (wood stork and arctic wolf) that could redirect heat to other parts of the body. Using this inspiration, the designers combined the phase transition material with heat conducting fibers that could channel heat from one location of the body to another (Figure 2b). Note here the designers more away from the literal, structural translation of moving a fluid, to moving only the essential substance, heat. 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.



b) Final Design Concept, incorporating beeswax and counter-current systems.

a) Initial Design Concept, from Beeswax

**Figure 2. Problem-driven design trajectory for the i-Fabric**

## 5. Solution-Driven Biologically Inspired Design Process

Whereas the normative biologically inspired design process taught in the class was problem-driven, we observed that in practice the design process often began with a biological solution. In fact, we note that 4 of 9 projects in 2006, and 5 of 10 projects in our follow up study in 2007, were solution-driven. A literature review of 70 cases of biologically inspired design showed that the solution-driven process appears to be at least as common as the problem-driven process (Vattam, Helms, Goel, 2007). It is difficult to make more precise characterizations as the actual design process in most literature of this kind is retrospective and more concerned with describing the final design than the process of getting to it. Some classroom exercises, and many case-studies of biological design, 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.

- Step 1: Biological Solution Identification

  Designers start with a particular biological solution in mind.

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

  Reframing forces designers to think in terms of how humans 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 biological solutions, problem search may include defining entirely new problems.

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

## 6. Sample Problem-Driven Project: Abalone Armor

The abalone armor project provides an excellent example of the solution-driven approach. The team first determined that they wanted to use abalone shell (Figure 3), in particular, nacre, as their inspiration, and then formulated a problem that could be solved by the impact-resistant nacre. The designers had an initial understanding of the superficial characteristics of nacre, and quickly settled on the problem of conceptualizing a bullet-proof vest using the abalone nacre. Later, 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 question: "What characteristics do organisms have that enable them to prevent, withstand and heal damage?"

Using these more abstract problem definitions, the students were instructed to investigate other sources. They looked at 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 were dismissed as soon as a potential challenge was encountered, despite the fact that some of those same challenges also were true of the initial, fixated source of inspiration.

As the designers understood the behavior of the abalone shell better, an understanding developed that suggested to the designers that the way substances react 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. Because there were now multiple functions which the solution needed to address we classified this as a multi-functional problem.

The analysis of abalone nacre, including fracture mechanics of response to bullet impact based on criteria such as facture stress, surface energy, strength intensity, and minimum initial crack size, showed that body armor made from abalone nacre would be one hundred times too weak to stop a bullet, and would weigh ten times more than conventional Kevlar body armor. The analysis in this project was mostly technical and quantitative, and did not result in a conceptual design.

**Table 7.1 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 |

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. 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.

## 7. Conclusions

The two high-level processes for performing biologically inspired design are based on the two different starting points – the problem or the biological solution. Many of the design steps in the two are the same though their ordering varies between the two processes. Table 7.1 provides a summary of all observed projects. The projects are evenly divided between the two processes, a pattern that we continued to note in our follow up study in Fall of 2007. When the process of design is solution-driven, structural focus occurred 100% of the time, whereas problem-driven design teams focused more often (60%) on the functions and behaviors of biological systems. Additionally, whereas solution-driven teams always incorporated multiple functions in their design problem-driven design teams only did so 60% of the time. This suggests that whichever starting point is used for the biologically inspired design, designers tend to fixate on that initial point, to the exclusion of alternatives.

## 8. Acknowledgements

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