Compound Analogical Design, Or How to Make a Surfboard Disappear

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Abstract

Biologically-inspired design uses analogous biological systems to develop novel solutions for human needs. In this paper we describe an *in situ* cognitive study of biologically inspired engineering design. We found that biologically inspired engineering design often involves compound analogies in which a new design concept is generated by composing the results of multiple cross-domain analogies. This process of compound analogy relies on an opportunistic interaction between two processes: problem decomposition and analogical transfer. Based on this cognitive study, we also present an information-processing account of compound analogies.

Keywords: design, cognitive study, biologically inspired, engineering, analogical design.

1. Introduction

One of the conundrums in research on creativity is that any solution to any problem has to start from what one already knows: so, how is it possible to create novel solutions? One way of trying to answer this question is to conduct *in situ* (or *in vivo*) cognitive studies of creativity in naturalistic settings (e.g., Darden & Cook 1994; Dunbar 1995; Kurz-Milcke, Nersessian & Newstetter 2004; Christensen & Schunn 2008). Kurz-Milcke, Nersessian & Newstetter (2004), for example, describe an *in situ* cognitive study of scientific research laboratories in bio-medical engineering. We have conducted an *in situ* cognitive study of biologically inspired design, and in this paper we describe one of the (many) findings from the study.

Biologically inspired design is a growing movement in design, driven in part by the need for environmentally sustainable development (e.g., Benyus 1997). Although applications of biologically inspired design can be found in many design domains such as engineering, architecture and computing, our focus is on biologically inspired engineering design (and in the rest of this paper we will use the term biologically inspired design to refer to biologically inspired engineering design only). A recent example from textile engineering is the design of thermally self-regulating clothing based on the design of pinecones (Vincent & Mann 2002). By definition, biologically inspired design is based on cross-domain analogies. We chose this particular domain for study because of our interest in understanding the role, process and content of analogies in creativity.

2. Cognitive Study

Our study was conducted in the context of an interdisciplinary course on biologically inspired design offered by Georgia Tech's Center for Biologically Inspired Design in the fall of 2006. At least 32 of the 45 students in the class had already taken a course in design and/or participated in design projects as part of their undergraduate education. In the rest of this paper, we will refer to the students in the class as designers.

The instructors of the interdisciplinary course taught biologically inspired design using a problem-based learning approach. Design projects grouped an interdisciplinary team of 4-5 students together, where each team had one student from biology and the rest were from different engineering disciplines. Each team was responsible for identifying a problem that could be addressed by a biologically inspired solution, exploring solution alternatives, and developing a final solution design based on biological design solutions. As observers, we attended the classroom sessions, collected course materials, documented lecture content, and observed teacher-student and student-student interactions in the classroom. We had no influence on the course design or pedagogical approach. We also did *in situ* observations of a few of the teams engaged in their design projects. We minimized our intervention, only occasionally asking clarifying questions.

Our observations focused on the cognitive practices and products of the designers. We observed and documented the frequently occurring problem-solving and representational activities of designers as part of the design process. Some of these activities were part of the design process explicitly taught by the instructors. Others emerged during practice. In terms of the design products, we observed and documented the natural evolution of the conceptual design over time. We also attended the final oral presentations of the design teams to the class, and read the design briefs the teams submitted with their projects. Vattam, Helms & Goel (2007) provide details of the cognitive study.

Table 1. Design projects from the cognitive study.

Project Name	Design	Solution Type	Source of Inspiration
Abalone Armor	Bullet-proof vest using strength, toughness and self-healing qualities of composites.	Non-compound	Abalone Shell
Traffic Control	Congestion reducing traffic regulation system.	Non-compound	Ants
Shell Phone	Scratch-, Shock-, and Shatter resistant cell phone case.	Non-compound	Abalone Shell
BioFilter	Portable, stand-alone air-filtration system.	Compound	Diatoms, Spider Silk
BriteView	Monitor screens that remain visible in strong sunlight.	Compound	Hummingbirds, Butterflies
Eye in the Sea	Underwater, stealth micro-robot	Compound	Squid, Copepod
InvisiBoard	Surfboard that does not produce a silhouette when seen from below to prevent shark attacks	Compound	Pony Fish, Brittle Star
iFabric	A thermally responsive adaptive fabric for clothing, providing thermo regulation for the wearer.	Compound	Bee Hive, Artic Wolves
RoboHawk	Aerial bomb detection device	Compound	Seagull, Dog

3. Compound Analogical Design

Table 1 gives a high-level description of the design projects in the interdisciplinary course on biologically inspired design. Again, additional details about each project are available in Vattam, Helms & Goel (2007).

One of the major finding of our cognitive study is that a majority of the biologically inspired designs were based on compound analogies: the final design solutions were compositions of multiple partial solutions, where each partial solution was based on a different analogy. In particular, as indicated in Table 1, we found that six of the nine (or 66%) of the biologically inspired designs in our cognitive study were based on compound analogies.

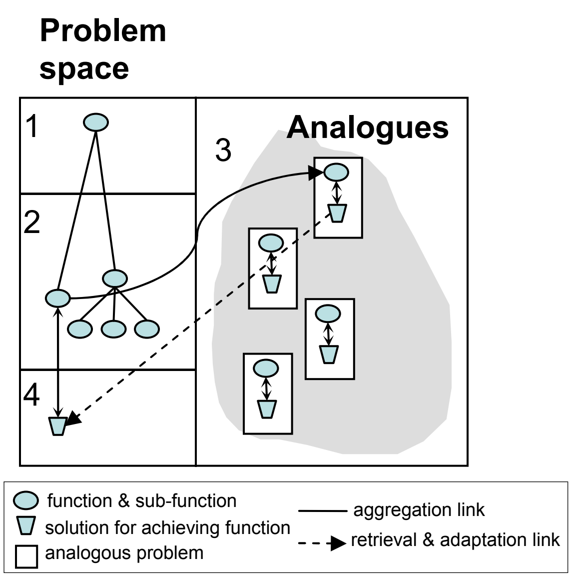

Figure 1. A simple case of compound solution generation: 1) presentation of the problem, 2) elaboration of the problem space, 3) retrieval of the analogue, and 4) application of the analogous solution. Repeat for each leaf in the problem decomposition (not shown).

4. Interplay between Problem Solving and Analogical Reasoning

An examination of our documentation of the design process used in the projects involving compound analogies showed a complex interplay between the processes of problem decomposition and analogical transfer. Of course, that a design team decomposed a large, complex design problem into smaller, simpler problems is unsurprising. However, a deeper examination of the interplay between problem decomposition and analogical transfer revealed the opportunistic process of compound analogies.

Figure 1 illustrates our interpretation of the designers' problem solving in generating their design solutions. In the simplest case of compound analogical design, the designer, once presented with a problem, decomposes the problem into sub-problems to create a problem hierarchy. Assuming that the problem is decomposed along functional lines (alternative decompositions are possible) each node in this hierarchy is a function to be achieved. Each function is used as a cue to retrieve known solutions that achieve that function. Solutions are transferred to the current problem, and aggregated to generate the overall solution. For illustrative purposes, we make the simplifying assumption that solution aggregation does not produce new sub-problems, although this is rarely the case. Note, in this case, the problem decomposition is known when the problem is presented.

In other cases, where it is not obvious to the designer how to decompose a problem, the designer can search for an analogous solution based on the high-level problem itself. This retrieved analogical source provides both a potential solution and, through a more explicit understanding of the workings of that solution (a solution decomposition), insight into the further decomposition of the problem. This solution decomposition in the source design can be brought into the current problem space as shown in Fig. 2.

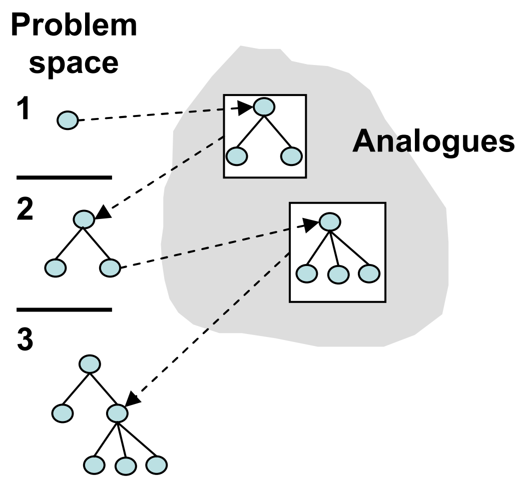

Figure 2. Iterative analogical generation of a problem space: 1) presentation of the problem and retrieval of the analogue, including the solution decomposition, 2) elaboration of problem space, and retrieval of a new analogue, 3) continued elaboration of problem space.

Each new node from the source solution decomposition that is integrated into the problem space can act as an additional cue for retrieving another set of solution analogues. This process can continue iteratively leading to the incremental development of the problem space. At every stage of this iterative process, the designer can evaluate the partial solutions available and decide to take further actions.

The iterative feedback between these two processes accounts for the both incremental evolution of design problems, as well as for our observed compound design solutions. Specific examples of compound analogical design are presented in the next section.

5. Illustrative Examples

In this section we will apply the conceptual framework of *compound analogical design* developed in the previous section to analyze two of the compound designs observed in our study.

5.1. Eye in the Sea

The goal of this project was to design a small underwater robot with locomotion modality that would ensure stealth. The initial research for the underwater robot focused on the copepod (a small crustacean, 1-2 mm in length) as a source for understanding stealthy locomotion. In exploring this concept, designers became aware that the copepod used two distinct rhythms of appendage movement for achieving motion underwater. A slow and stealthy rhythm was used when foraging for food and a quick but non-stealthy rhythm was used when escaping from predators. This understanding led the designers to decompose their original problem into two separate functions, one for slow movement, and one for rapid movement, both of which required stealth. *This new problem decomposition was based solely on the understanding gleaned from the copepod analogy.* The knowledge of the slow, stealthy mechanism used by the copepod, known as a "metachronal beating pattern" was also transferred from the copepod source.

Next, the designers had to address the second sub-function: fast, stealthy motion. They identified squid locomotion as an inspiration for achieving this function. The squid mechanism, jet propulsion, is both much *faster* and *stealthy,* matching its wake with external disturbances that naturally occur in the surrounding water. Notice the stealth achieved here (wake matching) is different from the stealth achieved by the copepod (wake minimizing).

Fig. 3 develops a model of the generation of this solution using the framework of the compound analogical design. Step 1 depicts the nature of the problem space early in the design. The main function is to move underwater stealthily, and the copepod is identified as a solution analogue. In Step 2, *based on knowledge from the copepod analogy*, the function of moving underwater is decomposed into sub-functions. The solution to the function of moving slowly by minimizing wake is adapted from the copepod to generate a partial solution. But the function of moving fast, yet stealthily remains unresolved in Step 2. In step 3, the squid analogue is retrieved to address this function. Its solution of using jet propulsion for movement is transferred to the current problem to generate the remaining solution. These two partial solutions are aggregated to achieve the trial design.

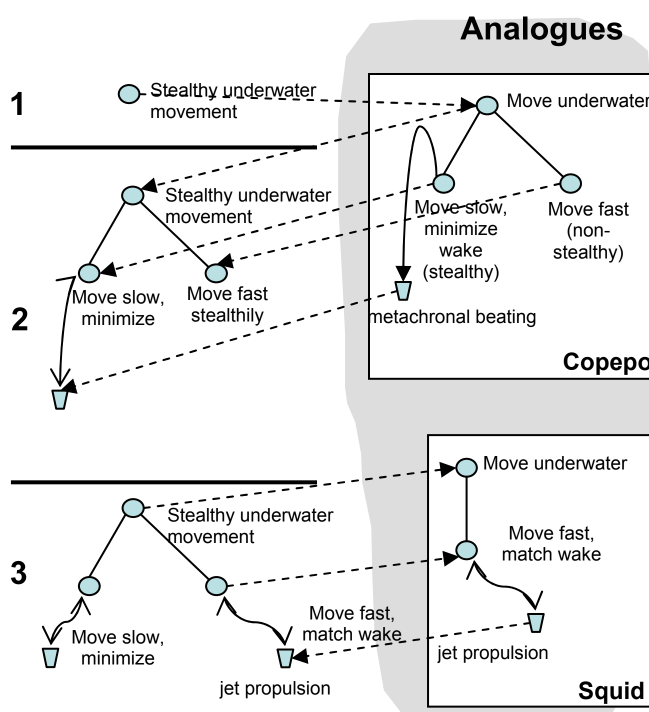

Figure 3. Design Trajectory of the Eye in the Sea.

5.2. InvisiBoard

The goal of this project was to conceptualize a surfboard that minimized its silhouette to prevent "hit-an-run" shark attacks. Designers chose the pony fish, which produces counter-illumination by producing light that is directly proportional to the amount of ambient light, as their source of inspiration. Using this analogy, the function of silhouette camouflage required the sub-function of producing a glow on the ventral side of the surfboard to match the ambient light. Based on a more detailed understanding of the mechanism employed by the pony fish, function of producing ventral glow was decomposed in the sub-functions: produce light, channel and disperse light.

In order to produce light, a light source and a power source onboard the surfboard was considered an inferior solution. The search for alternate means of producing light led them to an organism called a brittle star (a kind of a star fish). The dorsal side of the brittle star is covered with thousands of microscopic lenses. This suggested a design in which the top of the surfboard would be covered with (suitably distributed) lenses to collect the sunlight incident upon the surfboard. Dispersion of the light would occur via optic fibers. Additional design steps include adding a layer of "pattern light diffusers" on the bottom of the surfboard, which disrupts the pattern of light from the optical fibers to mimic the wavy pattern of the ocean surface. Fig. 4 demonstrates the generation of this solution using the framework of the compound analogical design.

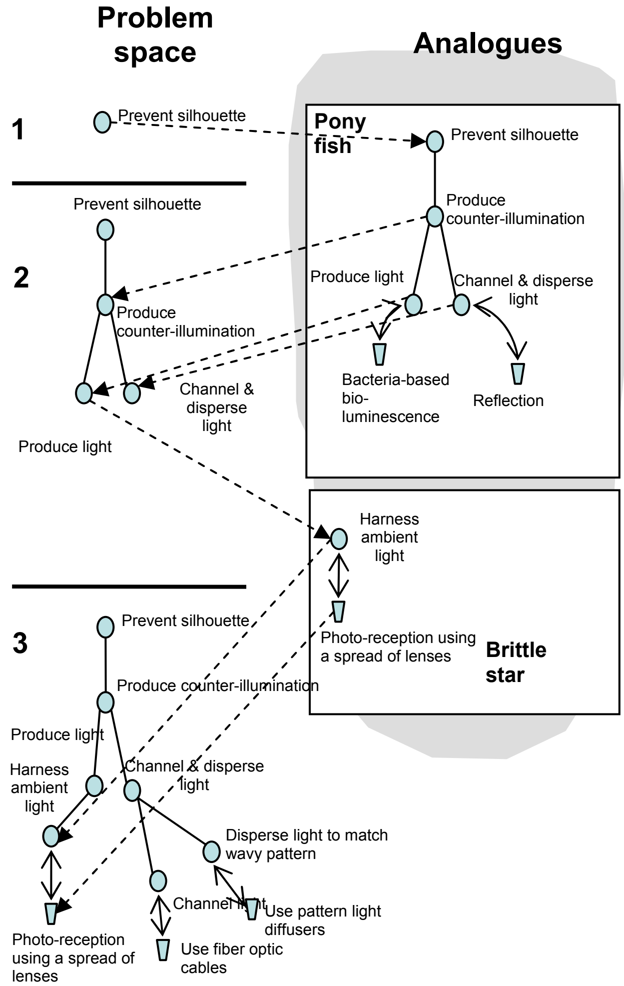

Figure 4. Design trajectory for the InvisiBoard.

6. Related Research

Of course, neither problem decomposition nor the use of analogies in design is new. Brown & Chandrasekaran (1986) provide an early account of problem decomposition in design. Much of the work on use of analogy in design has focused on case-based design (e.g., Zhao & Maher 1988; Wills & Kolodner 1994; Smyth et. al., 2001). Goel & Craw (2005) provide a recent review of this work. However, there also has been considerable work on cross-domain analogies in design (e.g., Goel 1997; Goel & Bhatta 2004; Qian & Gero 1996).

In a different context, viz., software design, Smyth et al. (2001) have described Déjà Vu, a system that uses hierarchical case-based reasoning for generating design solutions. Their model of design does combine problem decomposition and analogy. One important difference between our work and theirs is that, ours easily explains cross-domain analogies, whereas they do not. Additionally, in Déjà Vu the problem decomposition is already compiled into the cases, whereas in our model, the problem decomposition is generated dynamically and incrementally, and is interleaved with the process of analogy.

There are few cognitive accounts of biologically inspired design available in the literature. The available studies focus mostly on the effect of external representations on the number and quality of generated designs. For example, Linsey, Wood & Markman (2008) have found that when compared with using only diagrammatic representations of biological systems, combining diagrams with functional descriptions increases the chances of successful analogies. Sarkar & Chakrabarti (2008) have found that the use of external visual representations such as diagrams, animations and videos increases the number of design ideas generated in biologically inspired design. In contrast, our work provides a more descriptive account of the process of biologically inspired design, with a focus on the use of compound analogies.

Recently there have been a few attempts to build computational tools for supporting biologically inspired design. Chakrabarti et al.'s (2005) Sapphire tool represents the structure, behaviors and functions of biological and engineering systems in a uniform representational scheme. It retrieves biological and engineering designs based on matches between functional abstractions of the systems and functional abstractions used in a problem description. Chiu and Shu (2007) use latent semantic indexing to find a match between functional abstractions. Insofar as we know, none of these efforts have been extended to address the issue of compound analogies in biologically inspired design.

Christensen & Schunn (2008) have conducted an *in situ* cognitive study of engineering design in a different context, viz., product design in industry. They have found that designers make abundant use of analogies, with about the same number of within and cross-domain analogies. Of course, biologically inspired design is based on cross-domain analogies.

7. Conclusion

In our goal to understand the cognitive basis of biologically inspired design, we first conducted a study of designers engaged in design and then identified the salient aspects of the design process. A closer look at the design products and processes in biologically inspired design revealed a complex interplay between solution knowledge, analogical references and problem understanding, leading to the incremental, iterative development of compound solutions. In this paper we developed a high-level conceptual framework of *compound analogical design.* This framework extends the traditional accounts of analogical design by incorporating the interaction between two related processes, analogy and problem decomposition. We have applied this framework to analyze sample compound solutions from our study of biologically inspired design.

We draw two main conclusions from our analysis. First, successful biologically inspired design requires that designers carry rich representations of previous solutions during design. These rich representations are organized at different levels of abstraction and aggregation that facilitate the decomposition of solutions and allow solution analogues to be retrieved with cues taken from each level. Second, once a mapping is established between the problem space and a target solution, transfer can include both potential new solutions *and inferences about problem decomposition*. This opportunistic interplay between problem decomposition and the analogy-making process is the key to the evolution of problem space in design and the creation of successful compound solutions.

Since the submission of the first version of this paper to the Cognitive Science conference, we have had the chance to analyze the results of a second cognitive study we conducted in fall 2007. The second study used the same classroom laboratory and the same observation methodology as the first study in fall 2006. The second study confirms that biologically inspired design often involves compound analogies: about half of the designs created by the design teams were based on compound analogies. More importantly, the conceptual framework for compound analogies described above appears to cover the compound analogies found in the new study as well.

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