Nature of Creative Analogies in Biologically Inspired Innovative Design

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ABSTRACT

Analogy is a fundamental process of creativity. Biologically inspired design by definition entails cross-domain analogies, and in practice has led to many innovative designs. Thus, biological inspired design is an ideal domain for studying creative analogies. In this paper, we describe an intricate episode of biologically inspired design that unfolded over an extended period of time. We then analyze the episode in terms of *Why, What, How* and *When* questions of analogy. This analysis provides a content theory of creative analogies in biologically inspired design.

Author Keywords
Cognition, creativity, analogy, design, innovation, bioinspiration, biomimetics.

ACM Classification Keywords
I.2.0 General: Cognitive simulation. I.2.6 Learning: Analogies. J.2 PHYSICAL SCIENCES AND ENGINEERING: Engineering

General Terms
Design, Human Factors

INTRODUCTION: ANALOGY, CREATIVITY, COGNITION

Analogy is a fundamental process of creativity [3, 24, 35]. Polya [35] noted that “Analogy seems to have a share in all discoveries, but in some it has the lion’s share” (p. 17). Boden [3] states that “a psychological theory of creativity needs to explain how analogical thinking works” (p. 76). Hofstadter views analogy as central not only to creativity but to the whole of cognition itself [24, 25].

Development of a cognitive theory of creative analogies immediately raises the issue of the task domain in which to study analogy. Cognitive science has often studied analogies in the context of scientific discovery and engineering innovation, in part because these tasks symbolize human creative problem-solving abilities, and in part because there is anecdotal evidence of scientists and engineers who have made breakthrough discoveries and innovations using analogies. Thus, Clement [6] describes a classic study of physicists engaged in creative problem solving. Similarly, Kurz-Milcke, Nersessian & Newstetter [29] and Christensen & Schunn [5] describe recent studies of biomedical engineering scientists in their research laboratories and engineering product designers in plastics industry, respectively.

Here we describe an inquiry into creative analogies in the domain of biologically inspired design. Biologically inspired design uses analogies to biological systems to develop innovative solutions for engineering problems [39]. A classic example of creative analogy in biologically inspired design is George de Mestral’s design of Velcro in the 1940’s inspired by the attachment mechanism found in burr seeds. In practice, biologically inspired design has led to numerous innovative products [4]. Recent examples in engineering include design of micro robots that can walk on water mimicking the locomotion of the basilisk lizard [11], design of dry adhesives similar to how gecko’s foot adheres to various surfaces [19, 30], and design of self-cleaning materials inspired by a similar mechanism found in lotus leafs [37, 44].

A second issue in developing a cognitive theory of creative analogies concerns the method of study. One common method is to study human subjects engaged in creative analogies *in vitro* (e.g., [6]). In practice, this method allows formal experiments with control and subject groups, and instrumentation of the subjects for collecting a wide variety of data such as verbal protocols and eye tracking data. A disadvantage is that the human subjects typically work on rigid, static and isolated problems. A second common method is to study human subjects *in vivo* as they go about making analogies in their “normal” activities in their “natural” settings (e.g., [5, 29]). Although this setting does not easily allow for formal controlled experiments and does not permit collection of certain types of data, it does enable observation of problem solving by teams of humans subjects as well as problem solving over an extended period time. Perhaps more importantly, in contrast to the *in*

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vitro method that observes human performance on rigid tasks in artificial settings, the *in vivo* method observes human behavior in natural settings where problems evolve over times, human subjects collect new information in the course of problem solving, and the problem solving is characterized by opportunity as well as serendipity. Dunbar [8] has shown that humans exhibit different problem-solving behaviors in *in vitro* and *in vivo* settings. In particular, humans appear to make more abundant analogies in their natural environments than when given a static problem in an artificial setting [9]. In the inquiry presented here, one of the researchers (in particular, the first author) was part of a design team engaged in an extended biologically inspired design project that we describe below. This approach is similar to the *in vivo* approach, but the researcher not only observed but also participated in the design effort.

A third important issue in developing a cognitive theory of creative analogies is the level of resolution of the analysis. Some theories of analogy begin with a cognitive architecture such as the production system architecture [1], and express the theory of analogy in terms of the constructs of the architecture such as production rules, short-term memory, focus of attention etc. Other theories of analogy develop general-purpose information-processing mechanisms of realizing analogies such as constraint satisfaction mechanism based on various types of constraints [26], and structure mapping mechanism, a kind of heuristic graph matching [12, 10]. Yet other theories emphasize the content of analogies (e.g., [25]). A content theory of analogy entails answering the four core questions of *Why, What, How,* and *When* (e.g., [14]). The *Why* question refers to task or the use of an analogy; *What* pertains to the knowledge contents of the analogical transfer; *How* is concerned with the method for the analogy; and *When* pertains to the stage of problem solving at which the analogy occurs. Clearly, these four questions are closely linked. Thus, although a content theory posits a method of analogy, the method is at the same level of resolution as the use and the contents of analogy (and very different from that of a general-purpose mechanism such as, say, structure mapping). In this paper, we analyze creative analogies in biologically inspired design in terms of the *Why, What, How* and *When* questions. From the perspective of our content theory of creative analogies, cognitive architectures such as production systems and information-processing mechanisms such as structure mapping are powerful substrates for realizing the content theory.

STUDYING BIOLOGICALLY INSIPIRED DESIGN

The design objective of biologically inspired design is to use the wisdom of nature (*results* of natural evolution) as source cases for engineering target problems, utilizing principles of efficiency, adaptability, and multi-functionality that characterize many biological systems [43]. Much of the literature on biologically inspired design describes the technical details of cases of biologically inspired design (e.g., [19, 37]). However, there also is small but growing body of literature on cognitive studies of biologically inspired design (e.g., [23, 31, 33]). Our work as described in this paper seeks to add to this growing understanding of the cognitive basis of biologically inspired design. Our goals are to (i) develop computational tools for aiding designers in making successful and useful analogies between engineering problems and biological systems, and (ii) develop content and process theories of creative analogies.

In this paper, we first briefly summarize a finding from an earlier study of biologically inspired design that we conducted in Fall 2006 [22, 38]. In the remainder of the paper, we describe in detail our current study of biologically inspired design conducted in Fall 2008. Both studies were conducted in the context of a senior-level interdisciplinary course on biologically inspired design offered by Georgia Tech's Center for Biologically Inspired Design. This course typically attracts about 45 students from diverse disciplines, including biology, engineering, architecture, and computing. It employs a project-based approach, engaging teams of students in semester-long design projects. Each design project groups an interdisciplinary team of 4-6 students, with each team having at least one student from biology and the rest from different design disciplines. Each team is responsible for identifying a problem, exploring solution alternatives, and developing a final design solution based on one or more biological sources of inspiration.

SUMMARY OF AN INITIAL STUDY

We conducted our initial study of biologically inspired design in Fall 2006. We found that more than half of all design projects in our study used *compound analogies*. In contrast to single analogies, in *compound analogical design*, multiple source cases are used in the design generation process: the overall solution is obtained by combining solutions to different parts of the problem where solution to each part is derived from a different (biological) source.

Figure 1 illustrates the design trajectory in one of the design projects as an example of compound analogical design. The goal of this project was to design a underwater microbot with locomotion modality that would ensure stealth. The problem was "biologized" as: "how do marine animals stalk their prey or avoid predators without being detected?" Two marine biological systems were considered as sources of inspiration, copepods (small shrimp-like crustaceans) and squid.

The initial research for the underwater microbot focused on the copepod as a source for understanding stealthy locomotion. In exploring this concept, designers became aware that the copepod used two rhythms (of leg-like appendage movement) for achieving motion underwater. A slow and stealthy rhythm was used during foraging for food, and a quick but non-stealthy rhythm was used during escaping from predators. This understanding led the designers to decompose their original problem into two separate functions, one for slow and stealthy movement, and one for rapid, yet stealthy movement. Helms, Vattam & Goel [22] and Vattam, Helms & Goel [38] describe the initial study in detail.

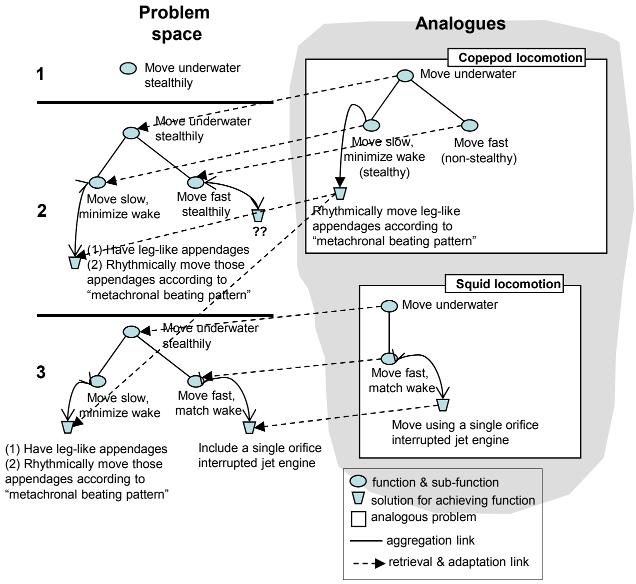


Figure 1: Design trajectory of one of the projects that exemplify compound analogical design (adapted from [38]).

CURRENT STUDY

Our second study, conducted in Fall 2008, focused on the design activities of one particular team called Team FORO. Team FORO, which included the first author of this paper, was composed of six team members including four undergraduates (two biology majors and two mechanical engineering majors) and two computer science graduate students. Each team member maintained an idea journal and made journal entries throughout their design process. Their journal entries contained research on biological systems and documented their design ideas. The idea journal of the first author was used as data for this study. Various other documents produced by the team at different stages of the design process like the problem definition document, abstracts of biological systems researched, initial design document and a final design report was also part of the data analyzed. This data was used to analyze the activities of the team and the evolution of their design ideas and sources of many of those ideas.

Cross [7] among others has analyzed complex design problem solving in terms of many design stages or phases such as preliminary design, detailed design, etc. Our analysis of Team FORO's design activities suggest that their design process consisted of the following six phases: problem definition and elaboration, search for biological analogues, initial design development, design evaluation, redesign, and design analysis.

Problem Definition and Elaboration

All design teams in this course were responsible for choosing a problem meaningful to them. Team FORO decided to address the problem of increasing water shortage on a global scale by designing a novel water desalination technology that converted ocean water into a drinkable supply of fresh water. Initially, they surveyed five existing desalination technologies. Three among the five, *multi-stage flash evaporation*, *multi-effect distillation* and *vapor compressed distillation*, were thermal based processes, and two, *reverse osmosis* and *electrodialysis*, were membrane-based processes. In the course of their survey they learnt that current desalination technologies employed processes that were very energy intensive, which prevented their widespread adoption. Therefore, designers added a new constraint to their design problem: their solution should use significantly less energy compared to the existing technologies.

The process of analogy played a central role in the survey. The function of desalination was used as a cue to retrieve existing technologies. At other times, a subset of the retrieved sources led them to other similar technologies.

This survey served two cognitive purposes. First, the different sources in their survey helped infer different mechanisms (or physical processes) for achieving the function of desalination.

Second, the different sources helped designers to elaborate their problem by suggesting alternate problem decompositions, which were related to each other through a hierarchy of functions that would lead them towards their design goal, producing a problem elaboration schema. Problem decomposition requires knowledge of the form $D \rightarrow D_1, D_2, \ldots, D_n$, where D is a given design problem, and D_is are smaller sub-problems. In many instances, this knowledge was inferred from the design patterns abstracted from the current technologies surveyed. By design patterns we mean shared generic abstractions among a class of designed systems. For instance, all membrane-based desalination technologies share common functions, mechanisms and principles.

Evidence for these design patterns come from diagrams, like the one shown in Figure 2(a), reproduced here from team FORO's design report. The evidence for the problem elaboration schema, a higher-level knowledge structure that relates design patterns and other abstractions to each other, also comes from a diagram, shown in Figure 2(b), which was reported in the team's problem definition document.

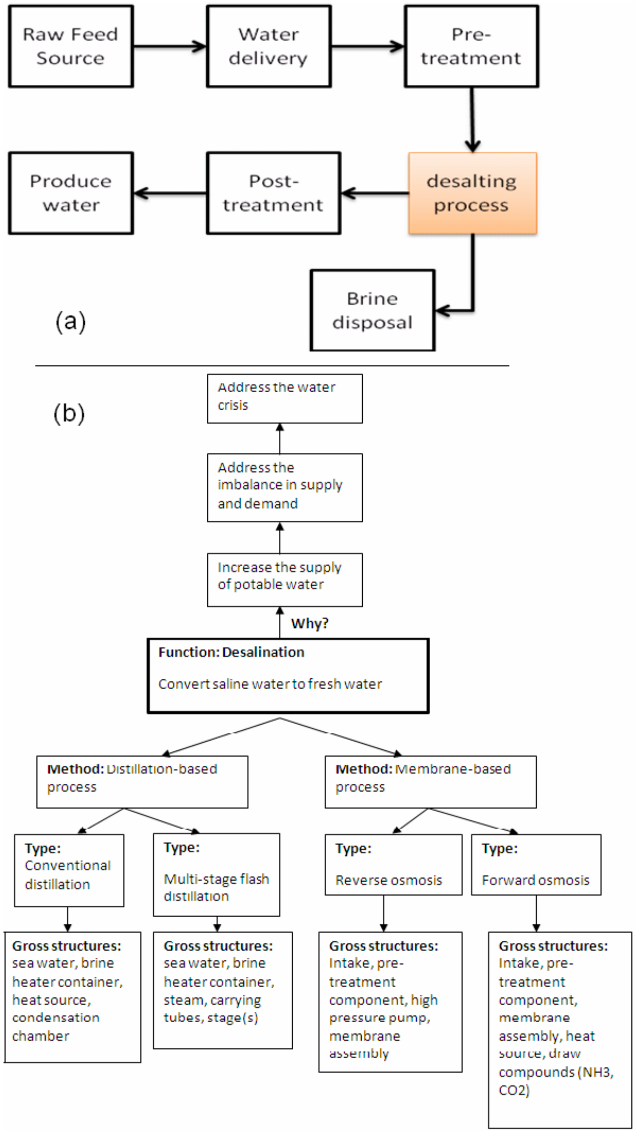


Figure 2: (a) Design pattern for membrane-based processes, (b) problem elaboration schema

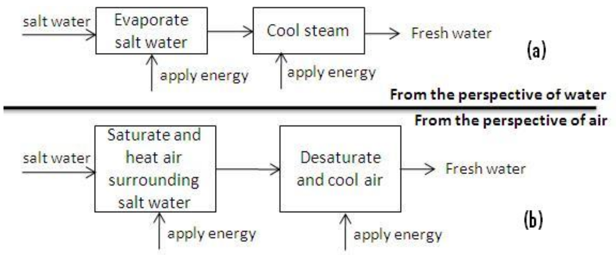


Figure 3: Pattern transformation to aid analogical retrieval

Search for Biological Analogues

Designers used their developing knowledge of the desalination problem to find biological analogues that were applicable to their problem. As can be expected, the problem elaboration schema from earlier activity provided the foundation for the search process. Paying attention to different aspects of the problem elaboration provided different cues for the retrieval process. A total of 24 biological systems were identified at various stages of this biological exploration activity that spanned almost one third of the semester. However, around ten systems were given serious consideration: *supra orbital salt glands in penguins, salt glands in marine reptiles, gills in salmons, respiratory tract in camels, kidneys, root systems in mangroves, esophagus in Gobius Niger fish, esophagus in eels, aquaporins, small intestines* in humans and other animals.

Analogy to biological systems again helped designers infer different mechanisms for achieving a desired design goal. However, three different methods of analogical retrieval were observed here. First, functional cues from the elaborated problem were directly used to retrieve biological sources. For instance the function of desalination or the related “removal of salt” was used to retrieve sources like supra orbital salt glands in penguins, salt glands in marine reptiles, gills in salmons, etc. Second, the general abstractions in the problem elaboration, like the aforementioned design patterns, were used to retrieve biological sources. This explains how a certain source like the small intestine was retrieved when there was no reference to salt anywhere in the intestine process (the intestine source included sugar solutions and not salt solutions). Third, design patterns were sometimes transformed and those transformed patterns were used to retrieve biological sources. This explains the curious case of the camel analogy to the thermal desalination process. The function of camel’s respiratory tract is to (1) saturate and warm the inhaled air so that it is suitable for the lungs to process and (2) desaturate and cool the exhaled air so that the moisture and heat are conserved and are not lost to the environment. This system, which had no relation to concepts like desalination or salt or solutions or energy expenditure, was still suggested to as an analogy to the thermal desalination process. This can be explained by the transformation of the design pattern for thermal process shown in Figure 3a (seen from the perspective of what is happening to the water) to a pattern shown in Figure 3b (seen from perspective from what is happening to the air surrounding the water) and by comparing the camel’s case to transformed pattern.

Initial Design Development

Developing a biologically inspired design solution involves retrieving a suitable biological system, understanding how that system works to a sufficient degree of depth, extracting mechanisms and principles associated with that system into a solution-neutral form, and applying those mechanisms and principles in the target domain of engineering. Team FORO had identified a subset of promising biological analogues. These systems were understood by the designers to varying degrees of depth. Based on their understanding, those systems were classified as using *active transport* (requiring external energy in the form of ATP) or not. This classification was used as an elimination criterion -

biological systems that used active transport were deemed unfavorable (because the goal was to achieve desalination with minimal energy expenditure). This eliminated all sources but the small intestine, camel nose and mangrove roots. Not enough was understood about the mangrove roots, and it was not readily apparent how the camel nose mechanism could be implemented as a solution. Therefore, team FORO developed an initial design solution based on the mechanism of the small intestine.

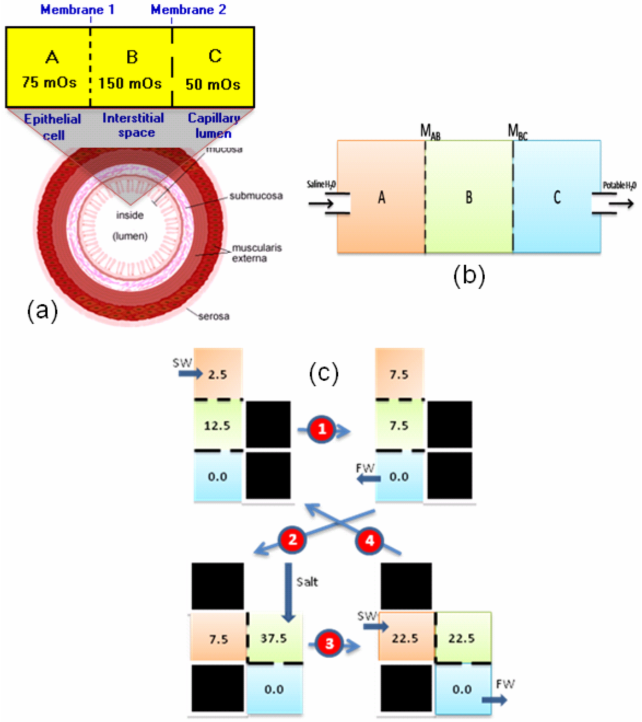


Figure 4: (a) Biological source (intestine), (b) the initial design solution, (c) redesigned solution.

The small intestine reabsorbs water using a conjunction of forward- and reverse-osmosis principles, called the three chamber method. This mechanism was transferred to the target problem to produce an initial design solution. Figure 4(a) and 4(b) shows a side-by-side comparison of the biological source and the initial solution developed.

Design evaluation

Team FORO now had produced a conceptual design of a desalination technology that was not only novel, but also eliminated the need for applying external energy (except for the energy required to feed the ocean water), which was too good to be true. They took their solution to an expert with several years of research experience in membrane technology for evaluation. The expert suggested that their initial design would not work. This was because the flow of fresh water in their design depended on the salt concentration gradients in the three chambers. But their design worked in such a manner that the salt concentrations in each chamber would change, over time, to offset the gradient, reaching equilibrium and stopping the flow of water.

The expert came to this conclusion with the help of an analogy of the initial design to a piston pushing liquid from one end of a cylinder, which has a membrane attached to its other end. The flow is maintained as long as one is applying force on the piston. The reaching of the equilibrium in their design was akin to someone taking their hands off of the piston. The cognitive purpose of the expert's analogy was to evaluate the design and identify any potential problem in it.

Redesign

Now the challenge for the designers was to redesign their system so that it did not reach equilibrium. They redesigned their system by coupling two three-chamber systems and by configuring those two to work cyclically. When the first three-chamber system reached equilibrium, it would create non-equilibrium conditions in the second three-chamber system, ensuring that the water would flow from the second one, and vice versa. The redesigned system is depicted in Figure 4(c), reproduced from the team's design report. The use of analogy in redesign is an open question.

Design analysis

Team FORO decided to do a quantitative analysis of their design in terms of estimating the flow rate of the fresh water produced. If the flow rate was of the order of cubic centimeters/hour, as was the case with the intestine, then their design was not viable. They had to determine how well the designed system scaled up compared to its biological counterpart. Since the biological model did not contain a flow analysis, the equations had to be derived from first principles. None of the designers knew fluid mechanics and had to rely on the expert, who was not available. So they put their analysis on hold till they could find another expert.

A few days later, one of the designers came across a paper by Popper et al. [36] by chance. This paper presented a novel mechanical system for desalination that was both similar to and different from their design. Popper's system was similar because it used forward-osmosis in conjunction with reverse-osmosis to achieve desalination. At the same time, it was different because its structure was different and did not utilize a three chamber method, it was prone to reaching a steady state resulting in the stoppage of flow, and was not biologically inspired. However, Popper's paper had a flow analysis of that mechanical system. Recognizing that Popper's mechanical system was analogous to their design, designers transferred the flow equations from Popper's situation to their current design situation, estimating a peak flow performance of 139.967 l/sec.

COGNITIVE ANALYSIS

We now turn to our analysis of the data we collected from Team FORO. As mentioned in the introduction, our analysis is in terms of the *Why, What*, *How* and *When* questions of analogy.

When?: Phases of Problem Solving

The when question refers to the stage of problem solving during which an analogy occurs. We already have analyzed TEAM FORO's design process as composed of the six phases described above.

Why? & What?: Uses and Contents of Analogy

We can identify at least three distinct uses of analogies in the above episode of biologically inspired design: *solution generation*, *evaluation,* and *explanation.* Further, we found that the analogies used for solution generation can entail transfer of knowledge of causal mechanisms or knowledge of problem decompositions. Accordingly, we have the following four classes of analogies based on the uses and the contents of analogical transfer: mechanism analogies, problem decomposition analogies, evaluative analogies and explanatory analogies.

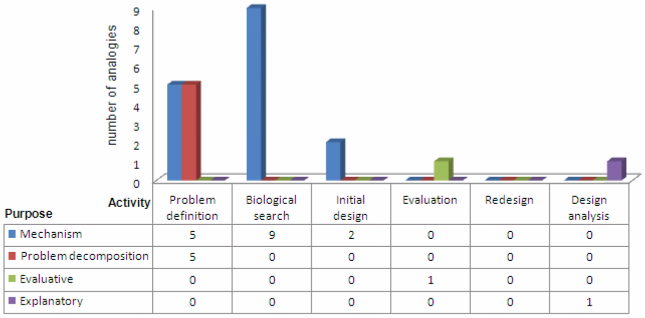
Mechanism analogies are generative analogies in which a mechanism is transferred from the source to achieve a particular function in the target problem. Mechanism analogies can be within domain (e.g. analogies in the problem definition activity) or cross-domain (e.g., analogies in the biological solution search activity).

Problem decomposition analogies are also generative analogies wherein the analogical transfer produces knowledge of how to break a complex problem into smaller sub-problems. Different sources for the same problem can suggest different decompositions as we saw during the problem definition activity (thermal- and membrane-based systems produced different decompositions for the problem of water desalination).

Evaluative analogies are used to infer if something works or not. During the evaluation phase, we saw the expert use the analogy of a piston to show that the team's design would not work.

Explanatory analogies are important in the development and justification of explanatory hypotheses. We saw an example of this kind of analogy during the design analysis when the team was trying to develop flow equations. Their recognition that Popper's system was analogous to their design allowed them to derive the required equations. Their flow equations were hypotheses that need justification.

Figure 5 summarizes our analysis of the different uses of analogies that occurred in our study of biologically inspired design. We gathered a total of seventeen analogies used by team FORO from the data and classified them along the dimensions of activity and use. In some cases a single analogy had to be classified into more than one category. The columns in Figure 5 correspond to the six major design activities described above. The rows correspond to the three main uses: generation, evaluation and explanation, where the generative analogies as divided into mechanism and problem decomposition analogies as described above.



Purpose \ Activity	Problem definition	Biological search	Initial design	Evaluation	Redesign	Design analysis
🟦 Mechanism	5	9	2	0	0	0
🟥 Problem decomposition	5	0	0	0	0	0
🟩 Evaluative	0	0	0	1	0	0
🟪 Explanatory	0	0	0	0	0	1

Figure 5: Uses of analogies distributed across different design phases.

Figure 5 shows that generative analogies that aid transfer of causal mechanisms are the most frequently occurring analogies (sixteen across the six design activities). It also shows that in the initial stage of problem definition, the number of mechanism and problem decomposition analogies were comparable (five each). This indicates that the biological sources encountered in the initial stages of exploration, in addition to indicating specific mechanisms for given functions, were also helping designers better understand and elaborate their problem by suggesting different ways of decomposing the problem

How?: Methods of Analogy

Literature on analogy suggests many different models of analogical reasoning, five of which were observed in this design study. Of course, that we did not directly observe other methods of analogy in this study does not imply that they absolutely did not occur or that we would not find them in other design episodes. In particular, our data from team FORO provides little information about substrates such as production systems, constraint satisfaction, and structure mapping for realizing any of these methods.

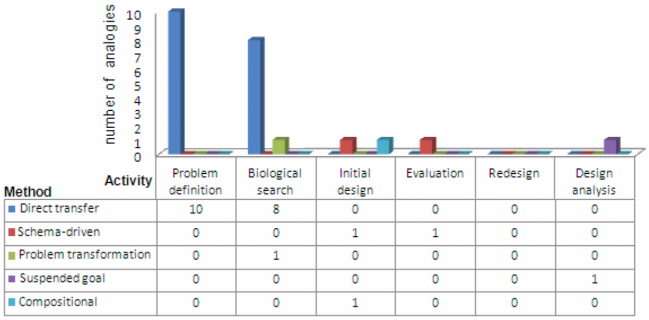
Direct transfer model: In this case-based method [28], first a designer attempting to solve a target problem is reminded of a similar source problem for which the solution is known, and then the target problem is solved by transferring and adapting the solution of the source problem to provide a solution for the target problem. (e.g., [16, 17, 18, 32]). Most analogies we noticed in this study conformed to this method. For instance, in the earliest activities of survey and search of biological solutions, function cues from the target problem were used to infer mechanisms from many different sources.

Schema-driven model: According to this model of analogy [13], an attempt to solve a target problem produces an abstract schema that then serves as a powerful retrieval cue for finding a source that provides a solution to the target problem [2, 15]. We saw this occur when the survey of existing technologies led to the development of the problem elaboration schema. The design patterns from this schema were used to retrieve biological sources there were otherwise probably inaccessible.

Problem transformation model: In this model (e.g. [6, 20, 21]), when an attempt to solve the target problem fails, the target problem is transformed using a variety of limiting case strategies [34]. The transformed problem then allows the problem-solver to recall a source problem that provides a solution. During search for biological analogues, the transformed design pattern of the thermal process led to the camel nose analogy.

Deferred goal model: In this model [40] reminding works in the opposite direction, from source to the target. When an attempt to solve a target problem has failed, the problem solver leaves it aside. Later, the problem solver serendipitously encounters a solved problem that can serve as a potential source, and this new source prompts recall of the unsolved target problem. We saw an instance of this during design analysis, when one of the designers encountered Popper's paper by chance and was reminded of the unresolved problem of deriving flow equations.

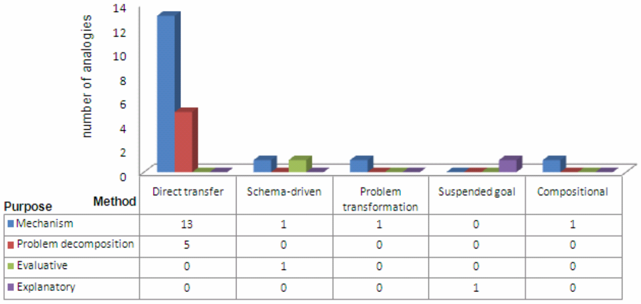
Compositional analogy: In this model (e.g. [41, 42]), target and source situations are represented at many different levels of abstraction and often associated with different modalities. For instance, the small intestine source may be represented in designer's mind at multiple levels of abstraction, starting from the more abstract functional and mechanism information towards the top (in verbal form) to shapes and composition of shapes near the bottom (in pictorial form). Compositional analogy suggests mapping and transfer at one level can potentially influence mapping and transfer in other levels. An example of this can was seen during the initial design development. The initial design not only works like the intestine, but also looks like the intestine model (see Figure 4).



Method \ Activity	Problem definition	Biological search	Initial design	Evaluation	Redesign	Design analysis
Direct transfer	10	8	0	0	0	0
Schema-driven	0	0	1	1	0	0
Problem transformation	0	1	0	0	0	0
Suspended goal	0	0	0	0	0	1
Compositional	0	0	1	0	0	0

Figure 6: Models of analogies distributed across different design activities.

Figure 6 summarizes our analysis of the different models of analogies that occurred in our study of biologically inspired design. Results in Figure 6 indicate that the large frequency of analogies that occur during the first two stages of the design used the direct transfer method. This could be attributed to the exploratory nature of those activities where one is trying to be as inclusive as possible and there are fewer constraints on what to match. But further along in the design process, the knowledge needs becomes more specific and more constraints get introduced. Therefore, alternative methods of analogy that take into account these additional constraints and knowledge types are required to find the right analogue.



Purpose \ Method	Direct transfer	Schema-driven	Problem transformation	Suspended goal	Compositional
Mechanism	13	1	1	0	1
Problem decomposition	5	0	0	0	0
Evaluative	0	1	0	0	0
Explanatory	0	0	0	1	0

Figure 7: Distribution of models of analogies to purpose of analogies.

When one looks at the distribution of models of analogies to purpose of analogies summarized in Figure 7, we note that an overwhelming majority of analogies are mechanism analogies, most of which employ the direct transfer method. These analogies correspond to the earlier activities of problem definition and biological solution search. However, analogical transfer of mechanisms may also require other methods in later stages of design activities. Finally, problem decomposition analogies almost exclusively employ the direct transfer method. One possible reason could be that other methods need generic abstractions (e.g. design patterns), which is bootstrapped by problem decomposition analogies.

CONCLUSIONS

This paper provides a descriptive account of one team's effort to produce a bio-inspired, novel water desalination technology, followed by an analysis of the nature and purposes of analogies used in the solution generation process. Our first conclusion however is from the initial study we only briefly summarized in this paper. Although the literature on biologically inspired design typically talks only of single source analogies (e.g., design of dry adhesives inspired by the hair on a gecko's foot), our observations indicate that many cases of biologically inspired design in fact involve compound analogies.

Returning to main study described in this paper, secondly, we found several different types of analogies (direct transfer, schema induction, problem transformation, deferred goal, and compositional) and several different uses of analogies (solution generation, evaluation, and explanation, where generative analogies may transfer of causal mechanisms or problem decompositions) at different stages of the design (problem definition, biological solution search, etc.). We note again that the fact we did not observe other methods of analogy in this study does not necessarily mean that they did not occur at all or that we would not find them in other design episodes.

Thirdly, we noted certain patterns of distribution of analogies. For example, (i) most of the analogies that occur during the first two stages of the design (problem definition and initial search for biological solutions) used the direct transfer method, (ii) generative analogies that aid transfer of causal mechanisms are the most frequently occurring analogies, (iii) majority of analogies used to infer a mechanism employ the direct transfer method, etc. In addition, we found that except for the redesign phase, analogies occurred in every major phase of the design process (problem definition, solution search, initial design, design evaluation, and design analysis).

Our content theory of creative analogies is based on a knowledge-level analysis of an extended episode of biologically inspired design. Klein et al. [27] have recently called such accounts macrocognitive theories, and have argued that they are critical for (i) understanding how cognitive agents do their "normal" work in their "natural settings", and (ii) developing computational tools for supporting the work of cognitive agents.

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