On the Analogical Roots of Biologically Inspired Design

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Short title: The Analogical Roots of Bio Inspired Design

Total number of pages: 40

Number of tables: 0

Number of figures: 9

On the Analogical Roots of Biologically Inspired Design

ABSTRACT

Biologically inspired design is an approach to design that espouses the adaptation of functions and mechanisms in biological sciences to solve engineering design problems. Biologically inspired design is inherently analogical in nature, yet our understanding of its analogical basis is limited. In this paper we present an observational study that describes an intricate episode of biologically inspired design that unfolded over an extended period of time. We then analyze our observations in terms of *Why*, *What*, *How* and *When* questions of analogy. This analysis contributes toward a content theory of creative analogies in the context of biologically inspired design.

KEYWORDS: Analogy, creativity, biologically inspired design, cognitive theory, observational study

1. INTRODUCTION

Analogy is a fundamental process of creativity (Boden, 1994; Hofstadter, 1996; Holyoak & Thagard, 1995). Polya (1954) noted that "analogy seems to have a share in all discoveries, but in some it has the lion's share" (p. 17). Boden (1994) states that "a psychological theory of creativity needs to explain how analogical thinking works" (p. 76). Hofstadter (1979, 1996) views analogy as central not only to creativity but to cognition itself.

We describe here an inquiry into the nature of creative analogies in the context of biologically inspired design. Biologically inspired design is inherently analogical in nature, in that it uses analogies to biological systems to develop innovative solutions for engineering problems (Yen & Weissburg, 2007). Biologically inspired design is a rapidly growing movement and the literature is abound with successful case studies of biologically inspired design ranging from the design of bio-inspired clothing (Vincent & Man, 2002) to biomimetic robot designs (Bar-Cohen & Brazeal, 2003). However, there are only a few studies that have examined biologically inspired design from a cognitive perspective. Our work as described in this paper seeks to add to this growing understanding of the cognitive basis of biologically inspired design.

1.1 Methodology of Inquiry

One important issue related to our inquiry concerns the method of study. A customary approach used to study processes like analogy in cognitive science involves studying human subjects engaged in analogy-making in laboratory-type experimental settings. This method allows formal studies with control and subject groups, and instrumentation of the subjects for collecting a wide variety of precise data such as reaction times, 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 situ* as they go about making analogies in their "normal" activities in their "natural" settings (e.g., Christensen & Schunn, 2008; Kurz-Milcke *et al.*, 2004). 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 real teams of people as well as problem solving over an extended period of time. Perhaps more importantly, in contrast to the experimental method, *in situ* method observes human behavior in natural settings where problems evolve over time, human subjects are exposed to external information in the course of problem solving, and the problem solving is characterized by opportunity as well as serendipity. Dunbar (1995) has shown that humans exhibit different problem-solving behaviors in these different settings. In particular, humans appear to make more abundant analogies in their natural environments than in artificial settings (Dunbar, 2001). In the inquiry presented here, we adopt the *in situ* approach where one of the researchers (in particular, the first author) not only observed but was part of a design team engaged in an extended biologically inspired design project that we describe and analyze below.

1.2 The Level of Resolution of the Analysis

Another important issue related to our inquiry concerns the choice of the level of resolution of the analysis required to develop our account of analogies in biologically inspired design. Some accounts of analogy begin with a cognitive architecture such as the production system architecture (Anderson & Thompson, 1989), 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 (Holyoak & Thagard, 1995), structure mapping mechanism (Gentner, 1989, Falkenhainer et al., 1989), etc. Yet other theories develop content accounts of analogies (e.g., Hofstadter, 1996) focusing on the core questions of *Why*, *What*, *How*, and *When* (e.g., Goel, 1997). The *Why* question refers to the *task* (or the goal) for which analogy is used in biologically inspired design. The *What* question pertains to the *content of knowledge* that is transferred from biological source to the design situation at hand. The *How* question is concerned with the *methods* for the analogical reminding and transfer. Finally, the *When* question pertains to the stage of problem design problem solving at which the analogy occurs. Our work described here seeks to develop a content account of analogy in the context of biologically inspired design.

1.3 Related Research

Some researchers have investigated different aspects of biologically inspired design employing experimental methods. For instance, Mak & Shu (2008) report on studies that have revealed that that subjects have design fixation problems and have difficulties with analogical mapping during idea generation using biological phenomena. They also 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. Similarly, Linsey et al. (2007) found that learning about analogous products with more general linguistic representations that apply across the problem and target domains improves an engineer's ability to use the analogous product in the future. They also found that functional annotations on diagrams increase the chances of successful biological analogies. Chakrabarti et al. (2005), focusing on the issue of aiding biologically inspired design, have proposed a structured representation to support idea generation for product design using the analogy between the knowledge of natural and artificial systems. This model, consisting of concepts to represent function, behavior, and structure of systems, is implemented as a software program called IDEA-INSPIRE. This program supports the designer with an automated analogical search. Sarkar & Chakrabarti (2008) have also studied and found that the representation of idea *triggers* (e.g., the sources of inspiration suggested by IDEA-INSPIRE) ranging from video/animation and audio, to text, to explanation, have a significant influence on the representations, number, and quality of the resulting ideas that were generated.

Other researchers have investigated the more general issue of analogy in design using *in situ* approaches similar to ours. For instance, Christensen & Schunn (2008) studied analogy in real-world engineering design. They too found several different uses of analogy in the context of design: identify problems, solve problems and explain concepts. They also found that problem identifying analogies were mainly within-domain; explanatory analogies were mainly between domain; while problem solving analogies were a mixture of within and between domain analogies.

2. BIOLOGICALLY INSPIRED DESIGN *IN SITU*: THE CONTEXT OF OUR INQUIRY

Our current and previous studies of biologically inspired design were conducted in the context of ME/ISyE/MSE/PTFe/BIOL 4803, a project-based introductory course on biologically inspired design that is offered in the Fall semester of every year at Georgia Tech. This course attracts 45 to 50 students every year, most of whom are seniors. The class composition is usually interdisciplinary, comprising mostly of students majoring in biology, biomedical, mechanical and industrial engineering disciplines. Typically, the course is taught by faculty members from

Georgia Tech's Schools of Biology, Chemistry, Mechanical Engineering, Industrial & Systems Engineering, and Polymer, Textile and Fiber Engineering. Many external guest lectures by several prominent researchers in biologically inspired design are also included.

This course is structured into lectures, found object exercises and a semester-long biologically inspired design project. Most *lectures* are focused on exposing the designers to case-studies in biologically inspired design. Other lectures are 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, etc. Some lectures also pose problems for the students to solve within class in small group exercises. 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.

The semester-long *design projects*, which is the focal of our analysis, groups an interdisciplinary team of 4-6 designers together based on similar interests. It is ensured that each team has at least one designer with a biology background and a few from different engineering disciplines. Each team identifies a problem that can be addressed by a biologically inspired solution, explores a number of solution alternatives, and develops a final solution design based on one or more biological sources of inspiration. All teams present their final designs during the last two weeks of class and submit a final design report.

3. OUR INITIAL STUDY

We conducted our initial study of biologically inspired design in Fall 2006. Additional details of this study can be found in Helms *et al.* (2009) and Vattam *et al.*, (2008). In 2006, the ME/ISyE/MSE/PTFe/BIOL 4803 course attracted 45 students, 41 of whom were seniors. The class was composed of 6 biologists, 25 biomedical engineers, 7 mechanical engineers, 3 industrial engineers, and 4 from other majors. 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. The students were grouped into nine design teams, with at least one biologist in every team, to work on their semester-long biologically inspired design project.

In this study, as observers, we attended almost all the classroom sessions, collected all the course materials, documented lecture content, and observed teacher-designer and designer-designer interactions in the classroom. But the focal point of our investigation was the design projects. We attended the design meetings of selected teams many times to observe firsthand how the design process unfolded. We took field notes, collected all the design related documentation produced by the teams, and also collected their idea journals. We analyzed the gathered data focusing 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. Some of our major findings are described below.

3.1 Biologically Inspired Design Processes

Insert Figure 1 here

We observed the existence of two high-level processes for biologically inspired design based on two different starting points – *problem-driven* and *solution-driven process* (DS1 paper). As depicted in Figure 1(a), in a problem-driven approach, designers identified a problem which formed the starting point for subsequent problem-solving. They usually formulated their problem in functional terms (e.g., stopping a bullet). In order to find biological sources for inspiration, designers "biologized" the given problem, i.e., they abstracted and reframed the function in more broadly applicable biological terms (e.g., what characteristics do organisms have that enable them to prevent, withstand and heal damage due to impact?). They used a number of strategies for finding biological sources relevant to the design problem at hand based on the biologized question. They then researched the biological sources in greater detail. Important principles and mechanisms that are applicable to the target problem were extracted to a solution-neutral abstraction, and then applied to arrive at a trial design solution.

As depicted in Figure 1(b), in the solution-driven approach, on the other hand, designers began with a biological source of interest. They understood (or researched) this source to a sufficient depth to support extraction of deep principles from the source. This was followed by finding human problems to which the principle could be applied. Finally they applied the principle to find a design solution to the identified problem.

3.2 Compound Analogical Designs

We found that biologically inspired design often (in 66% of the observed projects) involved compound analogies in which a new design concept was generated by composing the results of multiple cross-domain analogies (Vattam *et al.*, 2008). This process of compound analogical design relies on an opportunistic interaction between two processes: *problem decomposition* and *analogy*. Of course, that designers decompose a large, complex design problem into smaller, simpler problems is not a new finding. Equally unsurprising is the fact that designers use analogies to generate new designs. However, an interesting aspect of biologically inspired design that we noted was how these two processes interacted and influenced each other, resulting in generation of a compound solution: the overall solution is obtained by combining solutions to different parts of the problem where the solution to each part is derived from a different (biological) source.

For example, in one of the projects the design goal was to conceptualize surfboard technology that prevented the formation of the surfboard silhouette to prevent hit-an-run shark attacks. The final solution was a combination of (1) the concept of ventral light glow (inspired by pony fish) that gives off light proportional to the ambient surface light for the purposes of counter-illumination and (2) the principle of photo-reception from surrounding light in the brittle star (echinoderms that are closely related to starfishes) for providing the counter-illumination rather than having to use energy to self-produce light.

Insert Figure 2 here

Figure 2 illustrates the design trajectory in a different project as yet another example of compound analogical design. The goal of this project was to design an 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?" The initial research for the underwater microbot focused on the copepod, small shrimp-like crustaceans, 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. Copepod locomotion provided a source for generating a solution to the former function (slow and stealthy motion). To address the latter (stealthy fast motion), they used squid locomotion as a source of inspiration, which uses jet propulsion to move forward and achieves stealth by wake matching.

3.3. Analogy Using Multi-modal Representations

We observed that designers consistently used a combination of textual descriptions, pictures, graphs, and mathematical representations throughout the design process. These representations span not only multiple modalities (textual, diagrammatic, and pictorial) but also multiple levels of abstraction (pictures and diagrams of specific structures or parts of a biological system, to graphs and mathematical equations representing more abstract processes). Further, the use of multi-modal representations extended across disciplinary and level-of-experience boundaries.

Insert Figure 3 here

This suggests that the mental representations that designers use are rich and multimodal in nature and are organized at different levels of abstraction. One instance of this can be seen in the examples from the BioFilter project. Figures 3(a) and 3(b) represent the filtering mechanism found in oysters and clams and a conceptual model inspired by that mechanism respectively. Figure 3(c) is a conceptual model of a bio-filter that was inspired by how human lungs work. As another example, Figure 3(d) represents a conceptual design of a fabric inspired by Beeswax.

These figures, reproduced from the designers' journal, give us insight into some of the knowledge requirements for successful biologically inspired designing. The biological sources (on the left) and the design solutions (on the right) are both represented using a combination of textual and pictorial representations, and thus are multimodal. Additionally, the representations are explicitly capturing: (1) the relationship between the biological function and the biological mechanisms that achieves that functions on the one hand, and the engineered function and the engineered mechanisms for achieving that function on the other hand, and (2) the affordances and constraints posed by the physical structures for enabling the mechanisms in both biological and engineering designs. Designer's extensive use of multimodal representations also suggests that information represented in different modalities have their own unique advantages for analogy-making during biologically inspired design. A cognitive model of biologically inspired design should account for how knowledge represented in different modalities affords and constrains analogical reasoning in the context of design.

4. THE CURRENT STUDY

Our second study was conducted in Fall 2008 in the similar context of the ME/ISyE/MSE/PTFe/BIOL 4803 course mentioned in a previous section. But this study 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 part of the data for this study. Various other documents produced by the team at different stages of the design process like the problem definition documents, 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 (2001) 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.

4.1 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 highly 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 4(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 4(b), which was reported in the team's problem definition document.

Insert Figure 4 here

4.2 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 nose 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 5(a) (seen from the perspective of what is happening to the water) to a pattern shown in Figure 5(b) (seen from perspective from what is happening to the air surrounding the water) and by comparing the camel's case to transformed pattern.

Insert Figure 5 here

4.3 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.

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 6(a) and 6(b) shows a side-by-side comparison of the biological source and the initial solution developed.

Insert Figure 6 here

4.4 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 maintaining 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 an 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 problems.

4.5 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 6(c), reproduced from the team's design report. The use of analogy in redesign process is not evident from the data collected and remains an open question.

4.6 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 required equations had to be derived from first principles. None of the designers understood the deep physics underlying their design and had to rely on the expert to do so. But the expert was traveling and hence was not available for consultation. 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. (1968) 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 (1) its structures were different and did not utilize a three chamber method, (2) it was prone to reaching a steady state resulting in the stoppage of flow, and (3) 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 and adapted the flow equations from Popper's situation to their current design situation. Using the adapted flow equations they estimated that their technique would produce a peak flow performance within the acceptable range. Thus, designers improvised using analogy to derive the flow equations and perform a quantitative analysis of their design.

5. 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 in the context of biologically inspired design.

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

The *Why* and *What* questions refer to the uses and the contents of analogical transfer. 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 7 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.

Insert Figure 7 here

Figure 7 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.

The *How* question relates to the methods of analogical transfer. 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 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, 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., Goel *et al.*, 1997; Goel & Chandrasekaran, 1992; Goel & Craw 2005; Maher & Pu, 1997). 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 (Gick & Holyoak, 1983), 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 (Bhatta & Goel, 1997; Goel & Bhatta, 2004). 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. Clement, 2008; Griffith *et al.*, 2008a; Griffith *et al.*, 2008b]), when an attempt to solve the target problem fails, the target problem is transformed using a variety of limiting case strategies (Nersessian, 2008). 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 (Wills & Kolodner, 1994) 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., Yaner & Goel, 2007; Yaner & Goel, 2008), 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).

Insert Figure 8 here

Figure 8 summarizes our analysis of the different models of analogies that occurred in our study of biologically inspired design. Results in Figure 8 indicate that the large frequency of analogies that occur during the first two stages of the design (problem definition and biological search) 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.

Insert Figure 9 here

Finally, when one looks at the distribution of models of analogies to purpose of analogies summarized in Figure 9, 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.

6. CONCLUDING REMARKS

This paper presents a study into one team's effort to produce a biologically-inspired, novel water desalination technology, followed by an analysis of the nature and purposes of analogies used in their design process. To summarize, our major findings include the following. First, 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. Second, 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.). Third, 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).

In concluding we return to our "big picture" goal and discuss the significance of the studies presented here with respect to that goal. Our long-term goal is to construct within the context of biologically inspired design, a grounded cognitive theory of non-routine design. Contextually grounded cognitive theories provide both "kinematic" and "dynamic" accounts of the phenomena being studied (Nersessian, 1992). Analogous to kinematics in physics (which describes motion without examining the causal forces which produce the motion), kinematics of design would be descriptive accounts of designing without regard to the underlying causal cognitive processes. On the other hand, dynamics of design would be explanatory accounts of designing that take into consideration the cognitive processes or 'mechanisms' that are causal to how the design unfolds. We can view the two studies presented here as addressing the kinematic and dynamic aspects of biologically inspired design respectively. Our initial study (briefly discussed in this paper) provides a descriptive account of biologically inspired designing and the sort of external representations that facilitate and constrain that process. Our current study, on the other hand, tries to understand the causal role that analogy plays in biologically inspired design. Combining these two aspects we hope to achieve a more comprehensive understanding of the cognitive basis of biologically inspired design.

ACKNOWLEDGEMENTS

We thank Jeannette Yen and Marc Weissburg, Director and Associate Director of Georgia Tech's Center for Biologically Inspired Design, respectively, for providing us access to classroom laboratories. This research has benefited from many discussions with them. We also thank the instructors of ME/ISyE/MSE/PTFe/BIOL 4803 in fall 2006: Jeannette Yen, Bert Bras, Nils Kroger, Mohan Srinivasarao, Craig Tovey, and Marc Weissburg. This research has been supported by an NSF IIS Grant (#0534622) on Multimodal Case-Based Reasoning in Modeling and Design as well as an NSF Creative IT Grant (#0632519) entitled Towards a Computational Model of Biological Analogies in Innovative Engineering Design.

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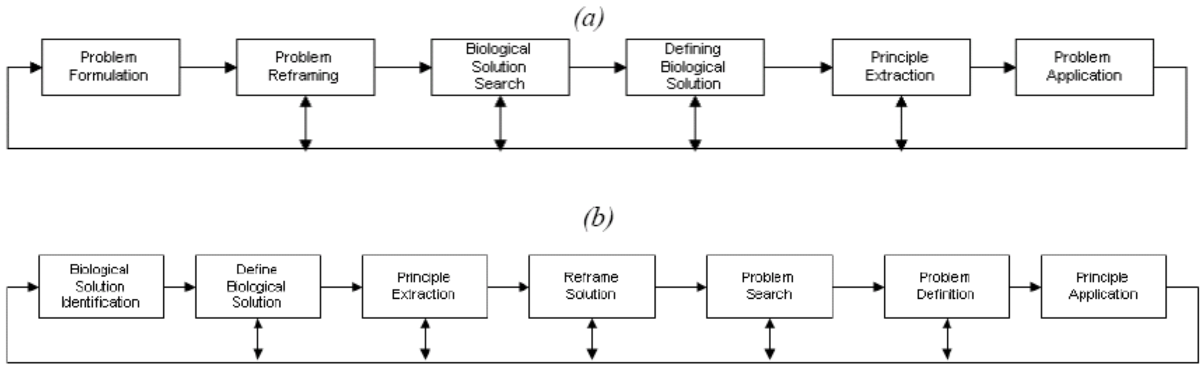


Figure 1: Observed biologically inspired design processes. (a) Problem-driven process, (b) Solution-driven process (adapted from Helms *et al.* 2009).

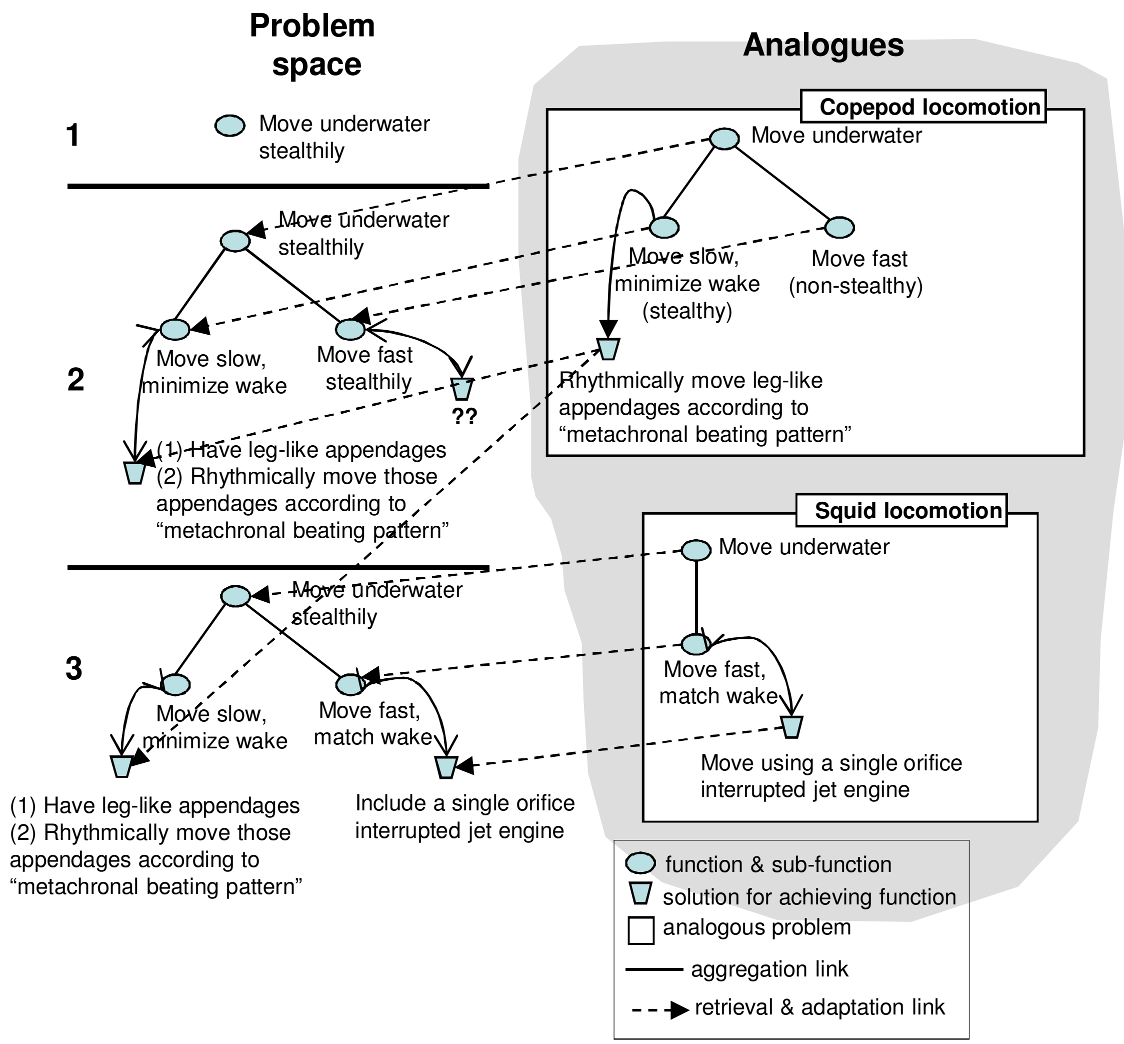
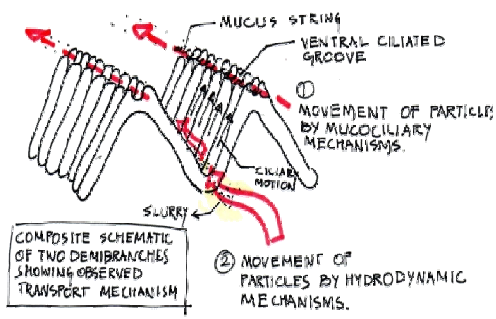
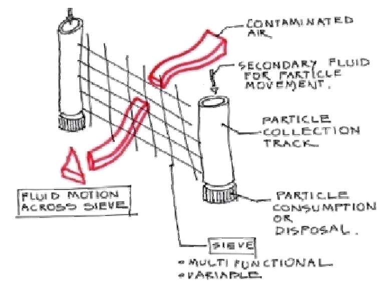


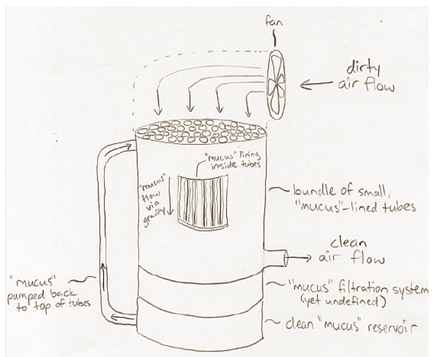
Figure 2: Design trajectory of one of the projects that exemplify compound analogical design (adapted from Vattam, Helms & Goel, 2008).



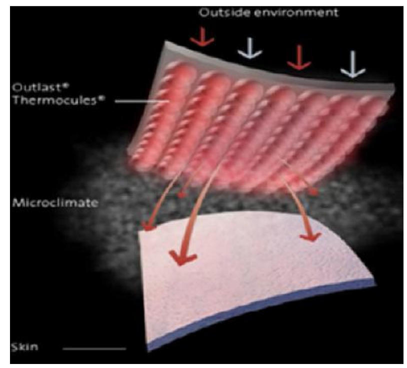
(a)



(b)



(c)



(d)

Figure3: Examples of the use of multi-modal representations obtained from design journals. (a) Filtering mechanism in oysters and clams. (b) Conceptual model of a filtering mechanism inspired by oysters and clams. (c) Model of a filter inspired by lungs. (d) Conceptual model of a fabric inspired by Beeswax.

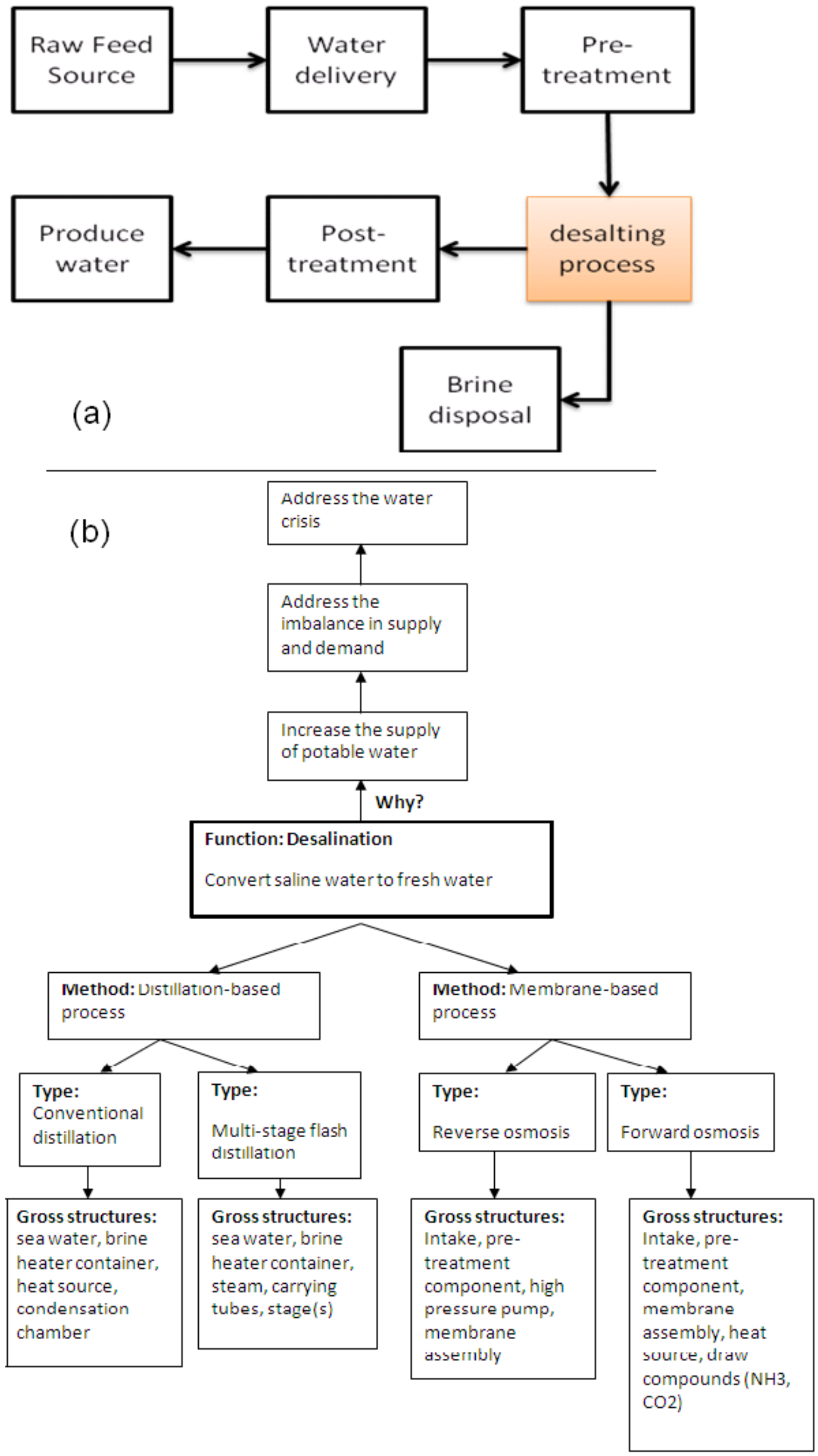


Figure 4: (a) Design pattern for membrane-based processes, (b) problem elaboration schema

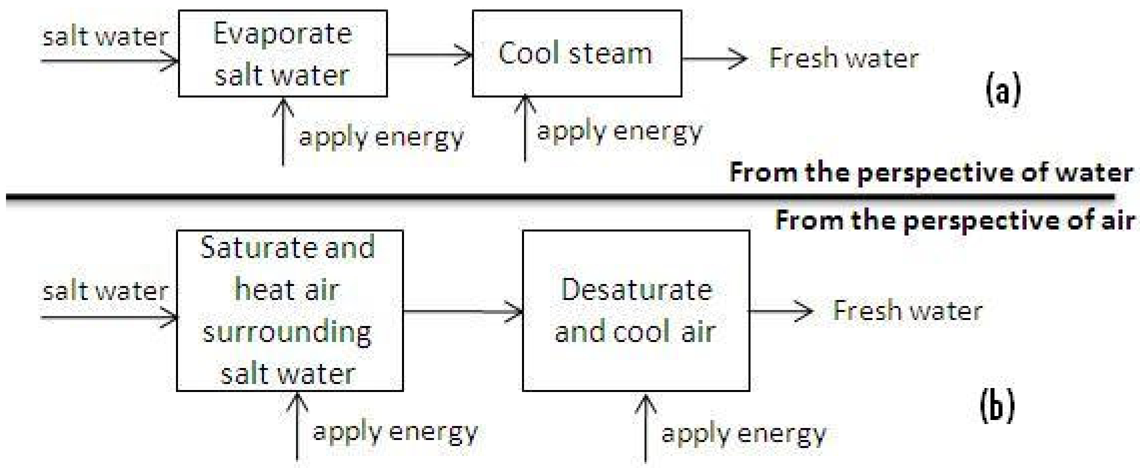


Figure 5: Pattern transformation to aid analogical retrieval

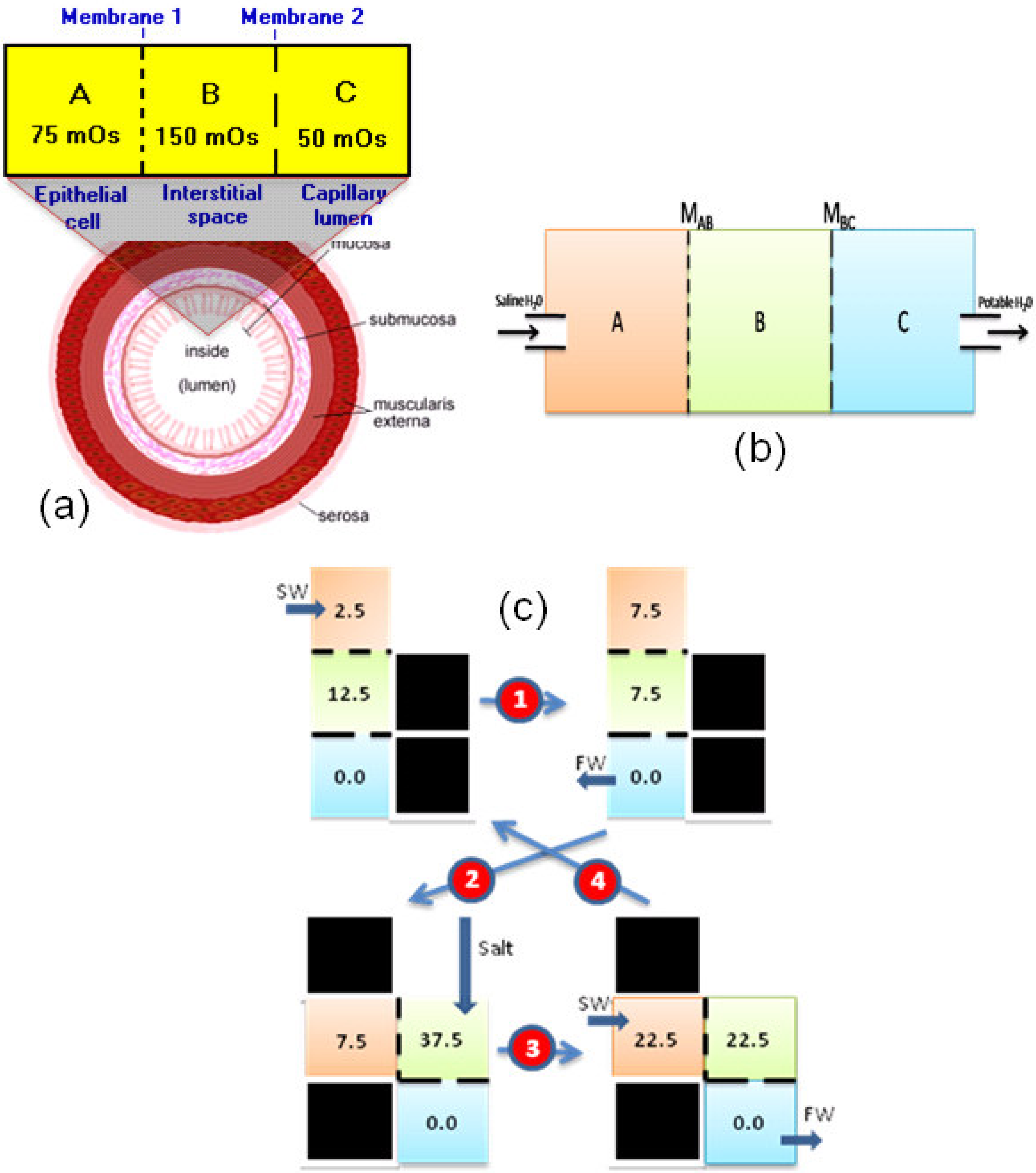
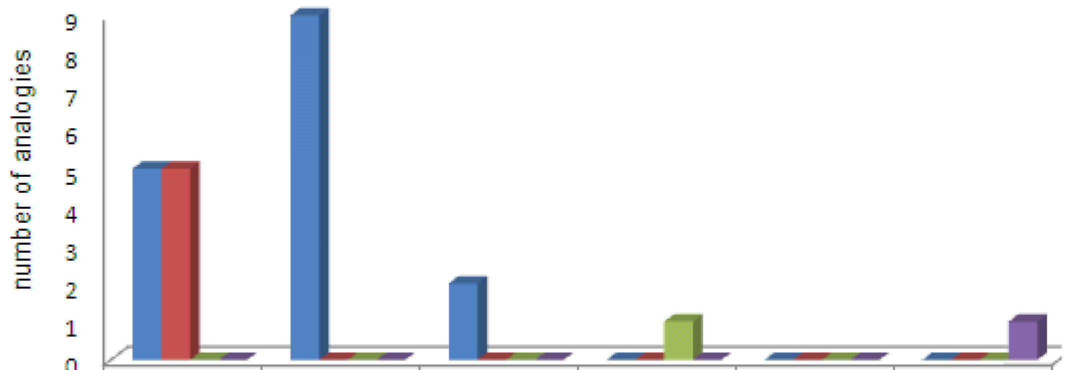


Figure 6: (a) Biological source (intestine), (b) the initial design solution, (c) redesigned solution.

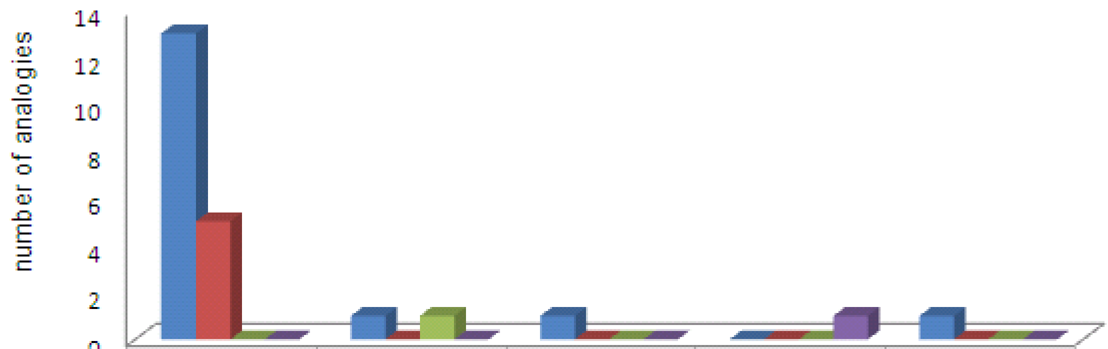


Purpose / Activity	Problem definition	Biological search	Initial design	Evaluation	Redesign	Design analysis
Mechanism	5	9	2	0	0	0
Problem decomposition	5	0	0	0	0	0
Evaluative	0	0	0	1	0	0
Explanatory	0	0	0	0	0	1

Figure 7: Uses of analogies distributed across different design phases.

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 8: Models of analogies distributed across different design activities.



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 9: Distribution of models of analogies to purpose of analogies.