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Using descriptions of biological phenomena for idea generation

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Abstract Biomimetic design uses biological phenomena to inspire solutions to engineering problems. While many examples of biomimetic design involved detailed understanding of a particular biological phenomenon, the level of understanding required for idea generation is unclear. This paper reports on a study of how descriptions of biological phenomena are used to develop concepts for a simple problem. This study is a continuation of past work on the use of biological analogies for concept generation. Since previous studies had revealed difficulties with fixation and mapping, participants in this study were provided with support for analogical mapping. While participants were observed to extract strategies consistent with the biological phenomena presented, they persisted in applying strategies to specific attributes of the example problem. Since concepts generated varied with attributes chosen, applying the strategy to each possible attribute of the example problem may result in a larger variety of solutions.

Keywords Biomimetic design · Bioanalogous design · Design-by-analogy · Idea generation · Analogical reasoning

1 Introduction

Biomimetic design draws from nature for design ideas. However, the use of natural phenomena as design inspiration has often been the result of chance encounters with interesting phenomena. The frequently cited example, Velcro was inspired when a Swiss scientist noticed cockleburs entangled in his dog's fur (Velcro 1955). More recent examples of biomimetic design involve applications of biological phenomena recognized to be of practical use to engineering problems (Clark et al. 2001; Dalsin et al. 2003; Iwase et al. 2004; Kikuchi et al. 2004). We believe that the use of biological analogies in design would increase if engineers were able to better determine which natural phenomena would be relevant, and how to apply these phenomena to their design problems.

1.1 Related concept generation techniques

To support engineers in biomimetic design, our previous work outlined a concept generation process that included the identification of relevant biological phenomena from biology texts (Vakili and Shu 2001; Hacco and Shu 2002). Our objective was to develop a formalized process that was comparable to other concept generation techniques, such as Synectics, or theory of inventive problem solving (TRIZ).

Synectics is a technique that guides creative thinking through four types of analogies: direct, personal, symbolic, and fantasy (Gordon 1961). Biological analogies are classified as direct analogies, and are considered by Gordon to be the most abundant source of direct analogy for creative concept generation. Although Synectics is a structured approach for creative thinking and recommends the use of biological analogies, it does not specify how relevant biological phenomena can be identified.

Theory of inventive problem solving presents inventive principles that resulted from studying over 1.5 million patents (Altshuller 1984). Recurring engineering conflicts

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and their solutions were identified and categorized into the TRIZ database. Concepts are generated by identifying contradictions of the problem and applying inventive principles observed to overcome the contradictions. Relevant to supporting biomimetic design, Vincent and Mann (2002) proposed an extension of the TRIZ database to include biological information and principles. While this approach could be useful for biomimetic design, the cataloguing and maintenance of biological knowledge would require a substantial undertaking.

1.2 Related research in design-by-analogy

Our approach to biomimetic design involves identifying relevant biological phenomena by locating occurrences of engineering functional keywords in biological knowledge in natural-language format (e.g., academic texts, journal articles, etc.), thus using the significant amount of biological material already available. Inherent to this process is the creation of biological analogies that can be applied to the problem of interest.

The premise of our biomimetic design process is not unfounded. The use of functional keywords for problem description is well documented in design (Hirtz et al. 2002; Kirschman and Fadel 1998; McAdams et al. 1999; McAdams and Wood 2000; Pahl and Beitz 1996), and the use of biological analogies for concept generation is commonly recommended in engineering design texts (Dieter 2000; Dym and Little 2004; Hyman 2003; Otto and Wood 2001; Ulrich and Eppinger 2000). French (1994) illustrates how biology can describe and inform various engineering problems.

Design-by-analogy is also studied by design researchers. McAdams and Wood (2000) develop a quantitative metric for design-by-analogy, which is based on the functional similarity of commonly found products. The metric identifies analogies between the functional requirements of the product to be designed and products that are similar. Functions of existing products can be adapted to develop new products. Benami and Jin (2002) comment on the use of analogies for design stimulation, whereby analogies created from conceptually different domains result in more creative, and original ideas. In architecture, Casakin and Goldschmitt (1999) found that the use of visual analogy improved the quality of architectural design problem solving, and was particularly significant for novice designers.

1.3 Analogical reasoning

Analogies are created when knowledge is mapped from a source domain to a target domain (Gentner 1989). Biological analogies used in engineering are *cross-domain* analogies, since the domains of biology and engineering are conceptually different. Another category of analogies, *within-domain*, refers to the transfer of knowledge between two similar domains. McAdams and Wood's (2000) quantitative metric for functional similarity between electro-mechanical products is an example of such.

The defining element of an analogy is the perceived similarity found between two domains, allowing us to recognize the source domain's application to the target. The perceived similarity often begins with *surface similarity*, in which we notice similarity in object attributes, e.g., cockleburs that *adhere* to dog fur. However, to further develop the analogy, strategies and interactions are found at a deeper level, e.g., cockleburs adhere to dog fur because their surfaces are overlaid with stiff, hooked spines. The combination of surface and deep similarities results in a *knowledge structure* of similarity relationships between the source and target domain. The knowledge structure of the source domain is *mapped* onto the target, so that elements of the target knowledge structure can be inferred and explained (Holyoak and Thagard 1994).

1.4 Biomimetic concept generation

Our previous work in biomimetic design uses biological knowledge in natural-language format as a basis for problem solving. First, functional keywords are formulated to describe the problem of interest. Next, these keywords and their synonyms are entered into our biomimetic search tool, which uses an introductory biology text (Purves et al. 2001) as an initial source of biological knowledge. The search tool finds occurrences of the keywords in the biology text, and returns a list of text descriptions containing the keywords. With this list of text descriptions, the engineer begins to determine which biological concepts may be applicable to the design problem.

1.4.1 In context with comprehension

Many recent biomimetic designs closely reflect the biological system from which they borrow (Clark et al. 2001; Dalsin et al. 2003; French 1994; Iwase et al. 2004; Kikuchi et al. 2004), illustrating the elegant nature in which biology can inform engineering design. However, from an idea generation perspective, a question that arises is whether it is necessary to fully understand a biological phenomenon for design inspiration? Can practical ideas be generated from biology without full comprehension?

Researchers present opposing views. Biological systems can be classified as complex adaptive systems, which are "systems made up of many units, whose simple interactions give rise to higher-order emergent behavior" (Goldstone and Sakamoto 2003, pp. 417). Goldstone and Sakamoto (2003) also state that by understanding the underlying principles of complex adaptive systems, we can explain and infer knowledge of other scientific domains. However, ambiguity can also contribute to our ability to generate solutions. Vogel (1999) states that,

> Success depends inversely on how well we understand the underlying science. Where our science is strong, copying produces at best narrowly targeted items… But where our science is weak, copying can generate devices of broad utility. (pp. 270)

Benami and Jin (2002) indicate that ambiguous entities stimulate more ideas than non-ambiguous entities, whereas non-ambiguous entities tend to be fixating. This illustrates a paradox, whereby designs can be inspired by either very little detail of a biological phenomenon, or by full comprehension of a biological system.

In the context of our approach to biomimetic concept generation, the question of comprehension is of significance, because engineers may be unfamiliar with relevant biological concepts. The biomimetic search tool provides a list of short descriptions of biological phenomena. The engineer, who may have, at best, a superficial account of the biological phenomena, interprets the list. Due to the condensed nature of the descriptions, relevant biological phenomena may not be immediately obvious, and possibly overlooked. Thus, the presentation of the descriptions, and the approach for interpreting these descriptions is crucial to our studies.

1.5 Previous studies of biological analogies

To gain insight into the process and how it can be improved, studies were undertaken to observe people performing the following tasks:

1. Recognition of biological phenomena relevant to the design problem;
2. Extraction of strategies used in the biological phenomena; and
3. Application of strategies to the design problem.

A summary of these studies will be described in the following sections.

1.5.1 Types of similarities in biomimetic design

In our initial study, engineering students were asked to generate concepts for a simple problem using short text descriptions of biological phenomena as stimuli (Mak and Shu 2004a). No formal support was provided. Although many concepts were generated, few were analogous to the descriptions provided. Most analogous concepts were the product of descriptions containing biological forms, behaviors, as well as strategies. We identified four types of similarities achieved when using descriptions of biological phenomena in problem solving.

Literal implementation. The first type of similarity relationship is characterized by literal implementations of biological forms and behaviors. Biological forms carry out a strategy found in the biological phenomenon, but in an engineering context, e.g., use cockleburs directly for adhesion. Surface similarity is merged with deeper relational similarity.

Biological transfer. Biological transfers fixate on biological forms, but use strategies inconsistent with those found in the biological phenomenon, e.g., use cockleburs as button fasteners.

Analogy. Analogies implement strategies found in the biological phenomenon without transferring the biological forms, e.g., use the idea of many small hooks for adhesion. In this case, the concept is based on deep relational similarities. This category represents the type of similarity intended in biomimetic design.

Anomaly. An anomaly does not involve any apparent similarity between the concept and the biological phenomenon on which the concept is based. While the reasoning behind many such concepts is unclear, some responses of this category are due to misinterpretation of the phenomenon, and others are based on fixation on a few words of the description that does not represent the overall biological phenomenon.

1.5.2 Fixations in biomimetic concept generation

A second study engaged a different group of engineering students to again solve a simple problem using text descriptions of biological phenomena as stimuli. This time, all descriptions included biological forms, behaviors and strategies, and participants were informed of the above similarity types and the desired characteristics of analogies (Mak and Shu 2004b). The students were asked to identify the strategy in the description, and using this strategy, develop a concept to solve the given problem. This study also explored whether more suitable descriptions of biological phenomena and awareness of the four similarity types would increase the number of analogous concepts. A greater number of analogies were observed (82% of responses), in addition to a decrease in the occurrence of literal implementations (2%) and biological transfers (2%). However, various anomalies were still present (14%).

Two difficulties persisted that reduced the number of analogies. First, while many students were able to successfully identify strategies employed in the descriptions of biological phenomena, many were unable to map the strategies to the given problem. The students had a tendency to force fit their biological strategies to the problem in ways that were either inconsistent or impractical. Part of this problem may stem from students being fixated on applying their strategies to one aspect of the problem. Secondly, as observed in our initial study, the students also had a tendency to fixate on specific phrases found in the descriptions that were not representative of the overall biological phenomena, and use these phrases as a basis for their solutions.

A third study was conducted in which another group of students was asked to relate various attributes (i.e., forms, behaviors) found in five descriptions of biological phenomena to attributes found in the given problem. We hypothesized that this explicit requirement to relate attributes between domains would eliminate the fixation effects observed in the previous studies. However, similar results were observed.

Two of the five descriptions of biological phenomena resulted in the most difficulties described above. Therefore, these two descriptions are featured in the next study that is the focus of this paper.

2 Mappings study

In previous studies, we found that students were able to identify useful strategies from the descriptions of biological phenomena; however, mapping these strategies to the example problem proved to be difficult. The explicit requirement to relate attributes between domains did not appear to improve the consistency of mappings between biology and engineering domains.

In this study, we provided students with a skeleton strategy, and observed whether this strategy would be consistently applied to the engineering problem. The skeleton strategy also allowed us to observe the various mapped attributes and behaviors, while holding constant the strategies between the descriptions and the example problem.

2.1 Method

Thirty-two senior undergraduate mechanical engineering students were asked to solve a problem using biological phenomena in a single 2-h session. The students worked individually. The problem proposed to students was the following:

> Dry cleaning solvents dissolve grease and lift stains out of cloth that cannot be washed in water and detergent. Many of the solvent solutions yield wastes that are hazardous. Develop alternative ideas that will result in clean clothes.

This problem was selected since it did not require prior knowledge of the dry-cleaning process. Although the overall problem refers to alternative methods of clothes cleaning, we framed the problem in terms of dry cleaning to avoid fixation on washing machines, or other cleaning solutions already known to the students.

As stimuli, the students were given descriptions of two biological phenomena that were found to cause the most difficulty in consistent mapping between domains (Mak and Shu 2004b). These descriptions were identified from Purves et al. (2001) using our biomimetic search tool, with the functional keywords “defend”, “remove”, and “eliminate”. The descriptions included an account of biological forms, their corresponding behaviors, as well as the strategy used.

For each description, we extracted a biological strategy that was applied to the engineering problem. A corresponding engineering strategy was made, and a skeleton outline was created by comparing both strategies and removing the analogous items. This process will be further detailed in the next section.

Students were given the example problem, descriptions of the two biological phenomena, and their corresponding skeleton outlines. For each description, each student was required to complete the outline of the biological strategy on paper with the appropriate forms and behaviors extracted from the description. The outline of the engineering strategy was then completed with items analogous to those forms and behaviors found in biology. The engineering strategy was applied to the example problem, and each student generated one concept for each description. The concepts were described on paper, often with an illustration included.

The two descriptions are presented with our observations. Titles for the descriptions were added for reference within the paper, but were omitted during the study. For each description of biological phenomena, we obtained the students’ biological and engineering strategies, and corresponding concepts. The strategies identified will be summarized in the text, and a tree diagram will present the strategies and concepts developed by the students for each biological phenomenon.

2.1.1 *Cell surface area/volume*

The first example describes how the surface area to volume ratio (SA/V) governs the size of cells because of its effect on the rate of waste removal (Purves et al. 2001):

> As a cell increases in volume, its surface area will also increase, but not to the same extent. As a cell grows larger, its rate of production of wastes and its need for resources increase faster than the surface area through which it must obtain resources and eliminate wastes. The more limited increase in surface area restricts the increase in volume as the cell grows.

To create the skeleton outline, we extracted the following biological strategy from the description: "maximize the surface area to volume ratio by minimizing the volume of cells to maximize the removal of wastes from the cell." After mapping the biological strategy to the problem in question, we obtained the following engineering strategy: "maximize the surface area to volume ratio by minimizing the volume of dirt to maximize the removal of stains from dirty clothing." We removed the analogous items from both strategies, and the remaining skeleton outline consisted of, "maximize *** by minimizing *** to maximize the removal of *** from ***," where *** represents the removed analogous items. The students were given the skeleton outline to complete for both biological and engineering domains. An emphasis was placed on preserving similarity between the analogous items, and maintaining consistency between strategies. Five strategies were found in total, where three were consistent with the biological phenomenon:

1. Maximize *SA/V ratio* by minimizing *the size or volume of cells* to maximize removal of *wastes* from *cells*.
2. Maximize *surface area* by minimizing *the volume of cells* to maximize removal of *wastes* from *the body*.
3. Maximize *surface area* by minimizing *the volume of cells* to maximize removal of *resources* from *the environment*.

The remaining two strategies were not entirely consistent with the description of the biological phenomenon:

1. Maximize surface area by minimizing volume of cells to maximize removal of wastes from restricted cell growth (or death).
2. Maximize SA/V ratio by minimizing the volume of the cell to maximize the removal of wastes from the surface area where wastes are removed.

In total, 30 students developed analogous concepts, and 2 students developed anomalous concepts. All of the analogous concepts were associated with the three consistent biological strategies, whereas the two anomalous concepts were associated with the two inconsistent biological strategies. This result supports that a basic understanding of the biological phenomenon may affect the success of creating a coherent analogy. Figure 1 details the distribution of student concepts, where values within the parentheses indicate the number of students with concepts under each category.

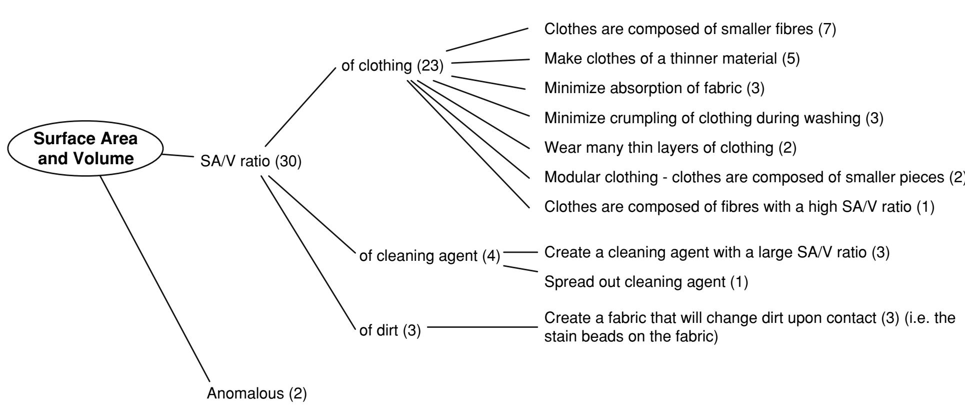
Although we anticipated that our version of the engineering strategy—to apply the SA/V ratio to *dirt*—would be most prevalent among the student responses, the majority of students in fact, applied the strategy to *clothing*. The remaining students applied the strategy to cleaning agents or dirt.

Of the 23 students that applied the strategy to clothing, we observed seven different interpretations (Fig. 1). The most common concepts included "creating clothes out of smaller fibers," and "making clothes out of a thinner material."

Concepts that applied the SA/V strategy to cleaning agents did so by proposing smaller particles of cleaning agent, or by spreading the cleaning agent over a larger area. All three of the students who applied the SA/V strategy to dirt sought to create a fabric that would alter the shape of dirt upon contact for ease of removal. An example provided was the beading of dirt once in contact with fabric, thus enabling the dirt to be wiped off.

All of the analogous concepts were based on a variation of the following strategy: "maximize the SA/V ratio (or

Fig. 1 Concepts for cell surface area/volume description



surface) by minimizing the volume of *** to maximize the removal of dirt from clothing," where *** represents items that are analogous to the biological form, "cells." For concepts that made improvements to clothing, as expected, the analog for "cell" was usually a variation of "clothing." Furthermore, these analogs were appropriate to the concepts elicited. For example, the "small fiber" concept listed "fibers" as the corresponding analog for "cell." Likewise for "no crumpling," students responded with "clothing" as the analog.

For concepts that suggested improvements to cleaning agents, three of the four students indicated a specific form of cleaning agent (e.g., soap) as the analog to "cells." Likewise, the same was observed for concepts that suggested modifications to dirt. Of those that developed concepts relevant to dirt removal, two of the three students chose "stain molecules" as the analog to "cells."

2.1.2 Fish extract oxygen

The following description explains how fish extract oxygen from their aquatic environment:

> Fish can extract an adequate supply of oxygen from meager environmental sources by maximizing the surface area for diffusion, minimizing the path length for diffusion, and maximizing oxygen extraction efficiency by means of constant, unidirectional, countercurrent flow of blood and water over opposite sides of their gas exchange surfaces.

The following biological strategy was extracted from the phenomenon: "maximize the surface area of the gas exchange surfaces to maximize the removal of oxygen from the environment." By mapping the biological strategy to the problem of interest, we obtained the engineering strategy: "maximize the surface area of clothing to maximize the removal of dirt from clothing." We removed the analogous items from both strategies, and the following skeleton outline results: "maximize *** of *** to maximize removal of *** from ***," where *** represents the removed items.

We found ten biological strategies in total, where four were consistent with the provided description:

1. Maximize *surface area* of *gas exchange surfaces* to maximize removal of *oxygen* from *the environment*.
2. Maximize *surface area* of *gas exchange surfaces* to maximize removal of *carbon dioxide* from *blood*.
3. Maximize *flow* of *blood and water* to maximize removal of *oxygen* from *water*.
4. Maximize *the efficiency* of *gas exchange surfaces* to maximize removal of *oxygen* from *meager environmental sources*.

The remaining strategies were either inconsistent with the biological phenomenon (e.g., maximize *the surface area* of *fish* to maximize removal of *oxygen* from *the environment*), or were not entirely correct (e.g., maximize *extraction* of *oxygen* to maximize removal of *waste products* from *the fish's body*). However, it should be noted that English proficiency might have been a factor for one student, as inconsistent strategies were observed for both descriptions.

In total, we found 30 analogous concepts and 2 anomalous concepts. Unlike the "Cell surface area/volume" example, the analogous concepts corresponded to both consistent and inconsistent biological strategies. The same was observed with the anomalous concepts. While we continue to believe that having a basic understanding of the biological phenomenon increases the success of creating a coherent analogy, this example suggests that other factors also contribute.

Figure 2 details the distribution of student concepts, where the values shown in parentheses indicate the number of students with concepts of a similar type.

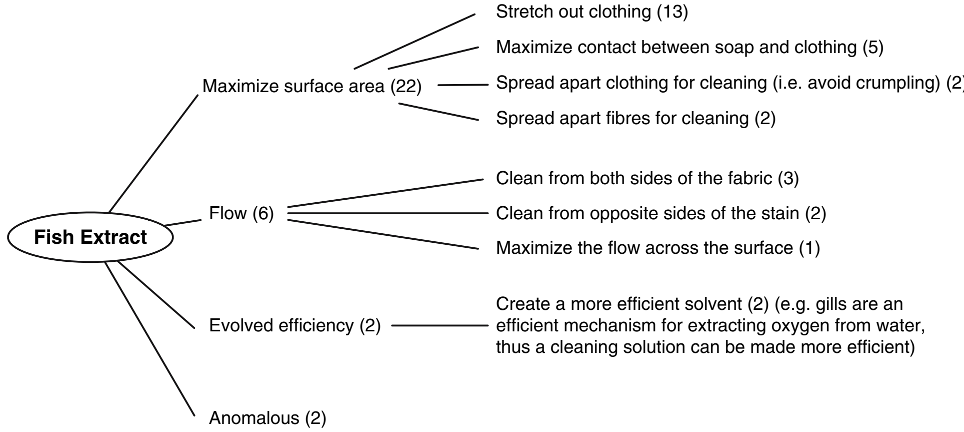
While we anticipated that the aforementioned engineering strategy (i.e., "maximize surface area of clothing to maximize removal of dirt from clothing") would be fairly representative of the resulting concepts, we in fact, observed three categories of concepts. Similar to our findings in our previous study (Mak and Shu 2004b), each concept focuses on a single aspect of the overall biological phenomenon. The categories are:

1. Maximize surface area.
2. Maximize flow.
3. Maximize efficiency.

Each category will be further discussed in the following sections.

Maximize surface area. The majority of responses (22/32) had the engineering strategy, "maximize surface area of *** to maximize removal of dirt from clothing," where *** represents items that are analogs to the biological entity, "gas exchange surfaces" (Fig. 2). Four different interpretations of this strategy focused on increasing the contact area between cleaning agents and clothing. Most concepts sought to stretch the clothing during the cleaning process, enabling better access to stains. A similar concept, found in the "Cell surface area/volume" example, e.g., "avoiding the crumpling of clothing during the wash cycle," was also observed. Appropriately, the corresponding analogs to "gas exchange surfaces" for these examples were either variants of "clothing surfaces," or "cleaning agents."

Fig. 2 Concepts for fish extract oxygen description



Maximize flow. Out of the 32 concepts, 6 referred to "maximized flow" on clothing surfaces (Fig. 2). For concepts that involved cleaning from both sides, or for concepts that involved cleaning from opposite sides, the corresponding engineering strategy referred to "maximizing the surface area of clothing/cleaning agent to maximize removal of dirt from clothes." A third concept, which involves maximizing flow across a clothing surface, directly referred to the strategy of "maximizing flow of a cleaning agent to maximize removal of dirt from clothes."

Maximize efficiency. Out of the 32 concepts, 2 referred to increasing the efficiency of cleaning agents used in the washing process (Fig. 2), with the corresponding biological strategy of "maximizing the efficiency of gas exchange surfaces to maximize removal of oxygen from meager environmental sources." While consistency was maintained between biological and engineering strategies, we felt that the engineering strategy was too general, and the resulting concept was not particularly informative.

2.2 Discussion

For both descriptions of biological phenomena, 30 of the 32 students developed analogous concepts (94% of concepts). We observed neither biological transfers nor literal implementations. Two anomalies were observed for each description. These results are a significant improvement over our earlier studies.

As expected, when provided with a skeleton outline, the majority of responses were consistent with the biological phenomenon presented in the description. However, most of the responses did not reflect the concept we had anticipated the students to develop. This is best illustrated in the "Cell surface area/volume"example, where we had anticipated that most concepts would involve applications of the strategy to dirt. Instead, most concepts involved applications of the strategy to clothing. This tendency to apply the strategy to a single attribute, e.g., clothing, of the problem domain resulted in corresponding concepts that were not always feasible (e.g., "make clothing out of tiny pieces that can be removed and washed"). On the other hand, students who applied the strategy to other attributes of the problem domain obtained other concepts, some of which were more practical.

3 Conclusion

This paper reports on a study of how descriptions of biological phenomena were used to develop concepts to solve a simple problem. This study is a continuation of previous work on the use of analogy within our biomimetic concept generation process. Compared to our initial studies, the results of this study indicate improvement in the quality of concepts generated. Two persisting difficulties were observed in past studies: students' inability to transfer information from biology to engineering; and fixation on specific phrases of the description.

This study presented students with an outline of a strategy to be applied to both biological and engineering domains. As expected, we found greater consistency in the biological strategies obtained by the students, though the students had a tendency to fixate on applying their strategies to specific attributes of the given problem. For example, students were compelled to apply strategies to "clothing", even though the resulting concepts were not necessarily feasible. A possible way of mitigating fixation is to encourage one to list out various attributes of the problem, and then generate ways in which the strategies can be applied to the list of attributes.

While the concepts generated in our studies may not match the elegance (or detail) for which other biomimetic designs are known, the "general" nature of the examples did result in a large variety of concepts. In selecting a general, introductory text as a corpus for our biomimetic search tool, we trade-off detailed information with a greater variety of general information that is easier to understand. Further studies could investigate the use of more specific material as corpus for our biomimetic search tool.

Finally, these findings suggest that while precise comprehension of biological systems can be ideal for detailed designs, for the purpose of concept generation, ambiguity and "generalness" can also be useful.

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