Supporting Creative Concept Generation by Engineering Students with Biomimetic Design

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Abstract

Biomimetic design uses ideas from biology as inspiration for design, and is widely recognized as a promising approach to innovation. However, the biomimetic design process can stand to be made more accessible and systematic for engineers. In particular, we identified a number of obstacles that occur when novice designers attempt to retrieve and apply biological analogies to solve design problems. Two main obstacles are: 1) extracting analogical strategies from biology and 2) applying analogical strategies to develop solutions. This paper summarizes our efforts in addressing these two obstacles through a pilot study and subsequent experiments involving engineering students. We found that to facilitate effective analogical transfer in biomimetic design, students require support to recognize relevant causal relations in biology and to explore multiple solutions when generating analogical designs.

1 Introduction

Biomimetic design borrows ideas from nature to solve engineering problems. There are numerous successful applications where creative and innovative solutions were achieved through biomimetic design, from the invention of Velcro to the development of space robotics [1].

Biomimetic design is recognized for its potential to enhance creativity and innovation. Using biological analogies is a subset of design by analogy, which has been shown to inspire creative ideas [2]. In addition, biomimetic design involves inter-domain analogies, as ideas from biology are applied to the conceptually different domain of engineering. Such inter-domain analogies have been found to provoke more novel ideas than intra-domain analogies [3][4].

However, there are challenges in executing effective biomimetic design. Because of the enormous amount of biological knowledge, locating relevant biological analogies can be challenging. One approach is to develop keywords to retrieve relevant information from biological knowledge in natural-language format, much of which is already available. The authors' past work involved identifying biologically meaningful keywords that are more useful for searching biological text than their corresponding engineering keywords [5][6].

Another challenge arises in the recognition and transfer of relevant analogies from biology to engineering. Inter-domain analogies require designers to identify and match relational patterns between source and target domains without obvious superficial similarities [3][7]. While there are many well-known examples of biomimetic design that were first inspired from superficial similarities [8][9], fewer designs were inspired purely from deeper, structural similarities [10].

The challenge of using inter-domain analogies is even more prevalent in novice designers, e.g., engineering students, who often lack the ability to recognize and apply abstract principles from distantly related domains [7]. In our experience, many engineering students have difficulty identifying and applying possible analogies from biology, but instead fixate on irrelevant features in the descriptions of biological phenomena [11].

In this paper, we discuss our efforts to facilitate biomimetic design for novice designers. We explain how a specific semantic relation in biology may play a key role in a designer's recognition of analogical strategies and development of appropriate solutions. We then discuss how the analogical transfer tools we developed affected engineering students in generating creative concepts. We conclude with future research possibilities.

2 Pilot study: Students' use of biologically meaningful keywords

As mentioned, the authors identified biologically meaningful keywords corresponding to engineering keywords to retrieve relevant analogies in biological text. To examine their usefulness, some of these keywords were provided to undergraduate engineering students in a fourth-year mechanical design course at the University of Toronto [6]. Students worked in groups to design innovative products that provide protection in sports or hobbies. Table 1 shows the biologically meaningful keywords that correspond to the desired functions of "protect" and "secure" given to the students.

Table 1. Biologically meaningful keywords for the engineering keywords "protect" and "secure".

Eng. keyword	Biologically meaningful keyword
Protect	Cover, Surround, Inhibit, Destroy
Secure	Connect, Wrap, Anchor

Students used the above keywords to search for relevant information in a machine-readable copy of *Life, the Science of Biology* [12], the reference text for a first-year university level biology course. In this section, we provide examples of correct and incorrect student use of retrieved information to develop solution concepts.

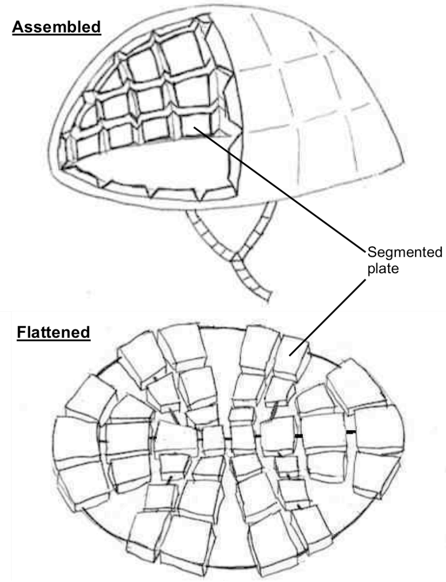
2.1 Student concept example – "protect"

One student group wanted to design a bicycle helmet that can be conveniently stored while not in use. The students used the four biologically meaningful keywords for "protect" to search for strategies in biology that provide protection while being flexible in size. Using the keyword "cover", the group was able to find the following biological phenomenon:

"An exoskeleton covers all the outer surfaces of the arthropod's body and all its appendages…The cuticle contains stiffening materials everywhere except at the joints, where flexibility must be retained." [12]

The students developed the idea of a segmented body into a helmet that consists of multiple plates that are connected by flexible straps (Figure 1). During use, the straps would hold the helmet in its conventional shape. When not in use, the tension in the straps would be released and the helmet can be flattened to more easily fit into a bag.

Figure 1. Helmet with segmented internal plates [6]



The specific phenomenon retrieved with they keyword "cover" describes how protection in biology is achieved, i.e., an exoskeleton "covering" an animal's body enables "protection" of the body. The resulting helmet concept was a good example of how students found a relevant strategy in biology and correctly applied it to develop a novel solution.

2.2 Student concept example – "secure"

Another student group wanted to redesign a hockey helmet that can more securely stay on a player's head and not fall off upon impact. The group used the three biologically meaningful keywords for "secure" shown in Table 1, and located the following biological phenomenon.

"Groups of segments at each end of a leech are modified to form suckers, which serve as temporary anchors that aid in movement. With its posterior sucker attached to a substrate, the leech extends its body by contracting its ***circular*** *muscles." [12]*

From this description, the group developed a concept of a circular strap inside a helmet that would wrap around a user's head. For this concept, the students were inspired by the specific terms in the biological description, "contracting its circular muscles". This part of the description is actually irrelevant to how a leech achieves secure movements, but the students nonetheless used it to incorrectly draw an analogy.

2.3 Discussion

The second example demonstrates how students could fixate on particular terms in biological descriptions that are irrelevant to the analogous strategy. Previous research found similar fixation when students were asked to map relevant strategies from biological descriptions to design solutions [11].

Therefore, we wanted to further investigate how to facilitate correct analogical transfer. In the process of identifying biologically meaningful keywords, we observed that there often exists a specific semantic relation, called a causal relation, that is formed between a biologically meaningful keyword and a corresponding engineering keyword in descriptions of biological phenomena [6]. We hypothesized that students would transfer analogies more correctly from descriptions that contain such causal relations. The next section discusses investigation of this hypothesis.

3 Experiment 1: Causal relations in biomimetic design

In a causal relation, one action causes another action. For example, in the phrase "A chases B, and B flees", the actions "chase" and "flee" are said to be in a causal relation. Causal relations are prevalent in biology and explain how particular behaviours achieve certain functions. In the example below, the "destroy" action causes or enables the action of "protect".

> *"Lysozyme is an enzyme that protects the animals that produce it by destroying invading bacteria." [12].*

In analogical reasoning, finding structural similarities between a source and a target is essential, especially when distantly related domains are involved in analogical transfer [3][7]. In biomimetic design then, identifying relational structures that are defined by causal relations would be a key process in performing analogical transfer correctly. Therefore, we provided students with various descriptions of biological phenomena as stimuli for solving design problems, and examined in which cases students are more successful in making correct analogies [13].

3.1 Experimental method

Forty-one engineering students in a fourth-year mechanical design course at the University of Toronto participated in this study. Each student was asked to individually solve three design problems. Participants were given a set of descriptions of biological phenomena retrieved from the corpus *Life* [12] to use as design stimuli for solving the problems.

Participants were randomly divided into three groups, each solving the same three design problems but receiving a different set of biological descriptions.

- Group A was given a pair of biological descriptions retrieved using only engineering keywords related to the design problem.
- Group B was given a pair of biological descriptions retrieved using both engineering and corresponding biologically meaningful keywords. These descriptions would therefore contain both types of keywords.
- Group C was given a pair of biological descriptions retrieved using only biologically meaningful keywords.

Because the descriptions given to Group B would likely contain a causal relation between a biologically meaningful keyword and a corresponding engineering keyword, we hypothesized that Group B would be more likely to perform correct analogical transfer for their concepts.

One independent rater examined whether participants' resulting concepts used the expected analogy from the given biological descriptions for each problem. The rater was a senior Ph.D. student researching design theory and methodology. The rater was given instructions and examples of correct and incorrect analogies, which were determined by the authors, for each problem prior to concept rating.

3.2 Experimental results

Based on the results, we could not conclude that Group B participants applied analogies more correctly than the other groups. In fact, we observed that it was less the presence of biologically meaningful or engineering keywords in descriptions that had an effect on participants forming correct analogies, but more the presence of causal relations which could be easily recognized that had a greater effect. We noticed after the experiment that causal relations could be found in the descriptions given to all the groups.

In general, we observed relationships between the complexity of biological descriptions and the rate of successful analogical solutions formed by participants. For one, we found a significant, negative correlation between the number of action words present in biological descriptions and the % of resulting concepts using correct analogies $r=-.52$, $p(\text{one-tailed})<.05$ (Figure 2). In addition, biological descriptions that contained keywords in the active form led to participants forming a higher % of concepts using correct analogies than descriptions with keywords in the passive form, $\chi^2(1) = 7.46$, $p < .01$ (Figure 3).

Figure 2. Percent concepts with correct analogies vs. number of action words present in stimulus [13].

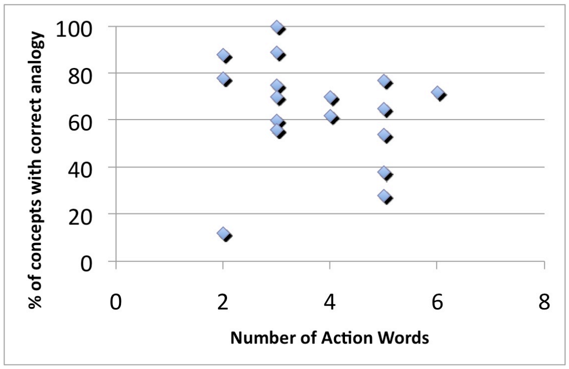
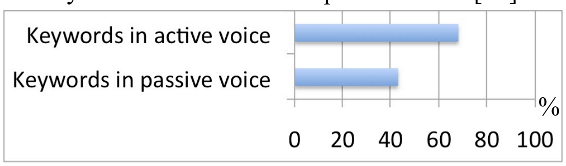


Figure 3. Percent concepts with correct analogies developed by participants from descriptions with keywords in active versus passive voice [13].



3.3 Discussion

We believe that the number and grammatical voice of action words, which characterize the complexity of the descriptions, affected participants' ability to recognize relevant causal relations. Examples of biological descriptions with different levels of complexity are given below [12]. Both examples contain a strategy based on "destroying". However, the first example contains fewer action words than the second example. Also, all of the first example's action words are in the active voice while the second example has the key action words in the passive voice. We found that participants who were given the first example (n=9, 78% correct) had a higher percent of their concepts using the expected strategy of "destroying" than those who were given the second example (n=10, 50% correct).

"Lysozyme is an enzyme that protects the animals that produce it by destroying invading bacteria."

"At high temperatures, enzyme molecules vibrate and twist so rapidly that their structure is eventually ***destroyed****, causing enzymes to become* ***inactivated****."*

The observations from this experiment suggest that the more difficult it is for participants to recognize a causal relation, the less successful the participants would be in forming a correct analogical solution.

4 Experiment 2: Analogical transfer tools for biomimetic design

Hence, we decided to design analogical transfer tools to help participants to 1) extract relevant causal relations from biological descriptions and 2) perform analogical mapping correctly. A subsequent experiment was conducted to investigate the effectiveness of these analogical transfer tools.

4.1 Experimental methods

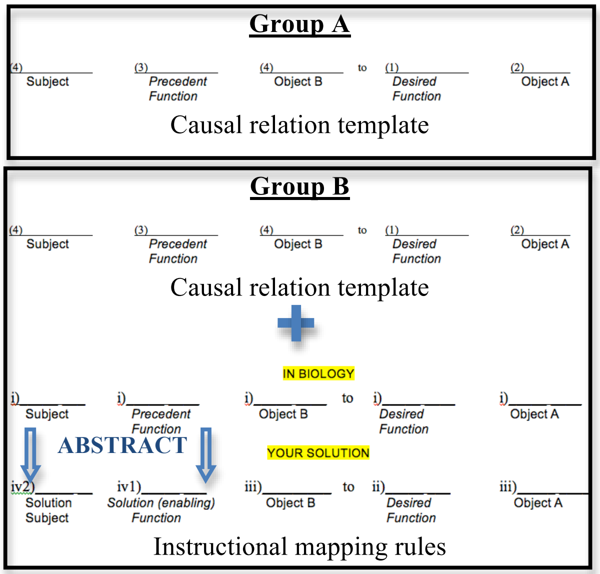
Sixty-one engineering students in a fourth-year mechanical design course at the University of Toronto were randomly divided into two groups, Group A (N=31) and Group B (N=27). Participants in both groups received the same design problems and one corresponding biological description as design stimulus.

Participants in each group were given a different set of aids for concept generation. Group A was given a *causal relation template* that the participants could use to systematically recognize the relevant causal relations as analogical strategies in biological descriptions. They were also given an example problem with a solution that was developed by using the template.

Group B was also given the *causal relation templates*. In addition, they were given *instructional mapping rules* of how to map each of the subject, two functions, and two objects associated with the retrieved causal relation to possible solutions. They were also encouraged to abstract the enabling object and function of the causal relation for a variety of solutions. Similar to Group A, they were given an example problem with a solution that was developed by completing the *causal relation template* and following the *instructional mapping rules.* Figure 4 shows the different aids given to the two groups.

Two independent raters were recruited to assess the participants' concepts with respect to correct analogical transfer and creativity. One rater was a senior Ph.D. student researching design theory and methodology. Another rater was an undergraduate student taking senior level design courses and completing a design-based undergraduate thesis. For the concept creativity measurement, we used Chiu's criteria [14] that measure novelty, usefulness and cohesiveness of the resulting concepts. In other words, a creative solution must: be original, solve the problem, and be wholly developed. For both correct analogical transfer and creativity ratings, the raters were provided example anchor concepts that would be given high or low scores. The average inter-rater agreement between the raters was calculated (Cohen's κ = 0.38) and indicated fair agreement [15].

Figure 4. Difference between the two experimental groups: Group B received *instructional mapping rules* in addition to the *causal relation template*.



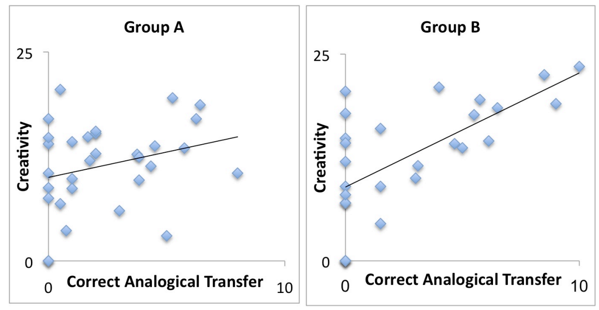
We predicted that Group B would score higher in correct analogical transfer, because the *instructional mapping rules* would improve participants' chance of performing correct structural mapping. We also predicted that increasing the likelihood of making correct analogical transfer would improve the creativity of the concepts generated by Group B.

4.2 Experimental results

The results show that there were no statistically significant differences in correct analogical transfer or creativity of concepts developed by the two groups. While our first hypothesis was not supported, we did find that concepts that are based on correct analogical transfer were more likely to be creative. Furthermore, we found this correlation between correct analogical transfer and creativity stronger for Group B than Group A, as shown in Figure 5.

For Group B, the ratings of correct analogical transfer had medium or large, statistically significant correlations with all the component measures of creativity: novelty (Problem 1: $r=.52$, $p<.01$; Problem 2: $r=.77$, $p<.001$), usefulness (Problem 1: $r=.54$, $p<.01$; Problem 2: $r=.52$, $p<.01$), and cohesiveness (Problem 1: $r=.42$, $p<.05$; Problem 2: $r=.53$, $p<.01$). For Group A, statistically significant and medium correlations were found only for usefulness in Problem 1 ($r=.45$, $p<.05$) and novelty in Problem 2 ($r=.44$, $p<.05$). These results suggest that the additional *instructional mapping rules* given to Group B had an effect on the strength of correlations between correct analogical transfer and creativity.

Figure 5. Stronger correlations between correct analogical transfer and creativity for Group B.



4.3 Discussion

In order to investigate why such an effect was present, we looked at Group A participants' concepts that did not have a strong correlation between correct analogical transfer and creativity. In general, we found that these concepts were vague and the level of detail was lacking. For example, while Group A participants applied the expected strategy of "destroying" entities to solve the problem, they did not explain how that "destroying" could be specifically achieved. Group B participants, on the other hand, were able to apply the same expected strategy and also include ideas of how "destroying" could be achieved.

We suspect that while the use of the *causal relation template* helped Group A participants to retrieve the expected strategy and correctly apply it to solutions, it did not necessarily lead to creative concepts because the solution means were not well specified. Group B participants, on the other hand, were specifically asked by the *instructional mapping rules* to generate ideas that are analogous to the enabling function in the expected strategy. This encouraged the participants to not only focus on applying the strategy to solution concepts, but also think further about how that particular strategy could be enabled. In other words, using the *instructional mapping rules* caused the participants to shift their frame of reference while solving the problems.

5 Conclusions and future work

This paper described our research efforts in facilitating effective biomimetic design for engineering students, focusing especially on recognizing and transferring relevant analogical strategies. Based on the pilot study and two subsequent experiments, we make the following conclusions:

- Novice designers were found to fixate on irrelevant features of biological phenomena. By helping them relate similar conceptual structures between biological phenomena and possible engineering solutions, we can increase their chance of performing correct analogical transfer.
- In biology, useful conceptual structures are often found in the form of causal relations. Novice designers may require aids to identify relevant causal relations in biology and correctly map them to engineering solutions.
- When analogous solutions are generated, novice designers may also require aids to shift their frame of reference and explore more solutions.

The observations above should be considered when designing analogical transfer tools for biomimetic design. Of particular importance is the last bullet for encouraging creative concepts. Defining the structure of analogical reasoning for novice designers can help them to perform analogical transfer correctly. However, because they may be so focused on finding solutions that are most structurally similar to biological analogies, structural mapping could also constrict their ideas. Others made similar observations while investigating design fixation, and they observed that designers tend to follow the "path of least resistance" during analogical reasoning and not look for more creative ideas [16]. Our future efforts should therefore focus not just on the convergent aspect of analogical reasoning, i.e., finding the most "correct" solution, but also on the divergent aspect, i.e., generating a variety of solutions.

Acknowledgements

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