Abstraction of Biological Analogies for Design

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Abstract
Biomimetic design uses biological analogies to inspire design concepts. This paper describes a study on selecting and using relevant biological phenomena for design. A hierarchy of forms, behaviors and principles classifies how biological phenomena are presented as potential analogies. The type of similarity achieved between biological phenomena and resulting concepts is affected by the types of information presented in the descriptions of the phenomena. Results suggest that concepts based on strategically similar analogies occur more frequently in the presence of principles that explain the biological phenomena, rather than descriptions of phenomena that focus on forms and behaviors.

Keywords:
Conceptual design, information, biomimetic design

1 INTRODUCTION

Creativity and innovation are fundamental to the engineering design process. Although it is widely believed that creativity cannot be invoked on demand, presentation of appropriate stimuli greatly enhances the generation of concepts. Specifically, the presentation of analogies is one useful approach to enhancing creativity.

Biomimetic design examines biological analogies to solve engineering problems. Although biological phenomena have been used in the past to evoke design solutions, they have not been systematically evoked from a design need. To make biomimetic design more accessible to engineers, a generalized method is required to identify and use relevant biological phenomena for any given engineering problem in an objective and repeatable manner.

This paper describes efforts to determine factors that affect extraction of relevant analogies to apply to an engineering problem. The results of a study involving idea generation using biological phenomena are presented. The relationship between the description of biological phenomena and the type of similarities achieved between concepts and these phenomena will be described.

2 BACKGROUND ON BIOMIMETIC DESIGN

2.1 Related work

Numerous examples of biomimetic design have been documented and include those described in CIRP Annals. Ueda *et al.*, have developed the concept of Biological Manufacturing Systems (BMS) to deal with complexity in manufacturing based on biologically inspired ideas such as self-organization, learning and evolution [1-5]. Evolution-based and self-organization models of manufacturing systems were used more recently to design line-less production systems [4] and generate facility layout plans [5].

Alting *et al.* [6] and De Chiffre *et al.* [7] recognize the potential for biomimetics in micro and nano engineering.

Specific to generalizing the process of biomimetic design, Vincent and Mann [8] explore the extension of the TRIZ (theory of inventive problem solving) database to include biological information and principles. TRIZ is a creative problem-solving methodology, using inventive principles to overcome typical system conflicts that were identified by studying over a million patents.

2.2 Previous work

This study uses a biomimetic search tool previously developed that identifies relevant phenomena by locating in natural-language biological knowledge, occurrences of keywords describing engineering problems. While difficulties common to natural-language processing can occur, this approach does not require the tremendous task of categorizing all biological phenomena by engineering function. As such, this approach can readily take advantage of biological knowledge already available in natural-language format. The initial source of biological information is the text *Life, the Science of Biology*, by Purves *et al.* [9]. Previous application problems using this tool include those in design for remanufacture and microassembly [10-12].

3 PROBLEM DESCRIPTION

3.1 Background and purpose

Analogical reasoning maps information from a source domain to a target domain [13], where a similarity forms a relationship between the domains. For biomimetic design, the source domain is biology and the target domain, engineering. It is important to differentiate between analogical matching, which simply relates existing and known analogous phenomena between two domains, and analogical carryover [14], required for the development of novel concepts in engineering based on biological phenomena, which is the goal of biomimetic design.

A difficulty associated with the biomimetic design method described by Shu *et al*. [12] is the extraction of relevant analogies from the biological phenomena that can be practically applied to the design problem. Gick and Holyoak [15] have found that a major block to successful use of an analogy is failure to spontaneously recognize its pertinence to the target problem. Using the method developed in previous work, the selection and use of relevant biological phenomena falls on the designer, governed by certain aspects such as expertise and domain-related knowledge.

The purpose of this study is to assess the processes involved with the selection and use of relevant phenomena, and the quality of resulting analogies evoked.

3.2 Methods

Ninety-one first-year engineering students were asked to solve a design problem using biological analogies in a single two-hour session. One advantage of lower-year students is that they may have fewer preconceived notions of engineering solutions that would result in analogical matching of biological phenomena to solutions that are already known to them. Due to their level of engineering training, a simple problem was selected, and described as:

> 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 concepts that will result in clean clothes.

A list of ten descriptions of biological phenomena was presented with the problem. Of the ten phenomena, five deemed most relevant to the problem were to be selected. A concept was to be developed from each of the chosen phenomena.

The biomimetic search tool was used to identify possible phenomena through functional keyword searches of ‘clean’, ‘eliminate’, and ‘defend’ in the *Life* text. The keyword ‘defend’ was used since it was suggested as one biological purpose of cleaning.

The results of the searches were filtered using natural-language processing rules, and segments of text output by the search tool were shortened to make the task more manageable for the students. No attempt was made to change the content of, e.g., clarify, the phenomena presented. Due to space constraints, not all ten descriptions of the biological phenomena presented will be listed here, but some will be shown as examples to facilitate discussion. In the descriptions shown, the first phrase represents the title of the text section from which the excerpt was taken.

4 OBSERVATIONS

4.1 Nature of descriptions of biological phenomena

The descriptions of biological phenomena presented in this study can be classified into three categories that form an abstraction hierarchy shown in Figure 1.

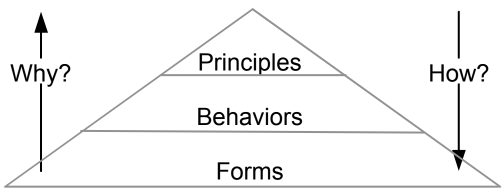

Figure 1: Abstraction hierarchy of descriptions.

Forms

The first category at the bottom of the hierarchy consists of descriptions that present only references to biological forms; the premise of why these forms exist or how they function is not specified in the descriptions. The excerpts identify what is happening, and the players carrying out the actions. **Dialysis** is a typical example of this first category:

> Cleansing the blood through dialysis – a dialysis unit, or ‘artificial kidney,’ eliminates metabolic waste products normally removed from the blood by the kidneys.

This excerpt makes reference to a dialysis unit and its relationship to the human kidney, but does not explain how a dialysis unit works, or why it is performing such an action. **Horsetails** is another example in this category:

> Horsetails grow at the bases of their segments – Like the club mosses, the horsetails (phylum Sphenophyta) are represented by only a few present-day species. They are sometimes called scouring rushes because silica deposits found in the cell walls made them useful for cleaning.

Behaviors

The second level of the hierarchy consists of descriptions that present biological forms and their corresponding processes. Such a description identifies what is happening, who is carrying out the actions, and how they are being carried out. Typical of this second category is the description, **Antibodies and Antigens***:*

> Antibodies share a common structure, but may be of different classes – IgG defends the body in several ways. For example, after some IgG molecules bind to antigens, they become attached by their heavy chains to macrophages. This attachment permits the macrophages to destroy the antigens by forming a pocket of membrane around the antigen, and pinching off the pocket.

Described above is how antibodies bind to antigens, and the process of phagocytosis. The phenomena in this category are behavior oriented, focused on biological processes, as opposed to biological forms in the first category. Most of the biological phenomena used in this study can be classified under this second category.

Principles

The third and top category consists of phenomena that present underlying principles. Often the description includes the reasons behind why a particular phenomenon works in nature. A typical example of this third category describes **Population Control***:*

> Life history information is used to control populations – A far more effective approach to reducing the population of a species is to remove its resources, thereby lowering the carrying capacity of its environment. We can rid our dumps and cities of rats more easily by making garbage unavailable (reducing the carrying capacity of the rats' environment) than by poisoning rats.

Described above is the principle of lowering an environment’s carrying capacity through the removal of resources. This particular phenomenon is the most abstract of those used in this study.

As illustrated in Figure 1, as one moves upwards in the hierarchy, the next level progressively answers ‘why’ the previous level exists. As one moves downwards through the levels, each level below explains ‘how’ the level above was achieved.

Other phenomena classified under the *Principles* category include *Skin Defense,* a description shown in the next section. Although the *Skin Defense* example presents the underlying principle that explains the phenomenon, it also includes the biological forms and behaviors involved.

4.2 Types of similarity relationships

Four types of similarity relationships were observed between the concepts generated and the biological phenomena presented. The categories will be explained in terms of the source domain (biology) and the target domain (engineering). To clearly differentiate the types of similarity relationships, a single biological phenomenon that was described with references to form, behavior, as well as principles will be used. As mentioned in the previous section, this is true of the description for the phenomenon **Skin Defense**:

> Barriers and local agents defend the body – skin is a primary innate defense against invasion. The bacteria and fungi that normally live and reproduce in great numbers on our body surfaces without causing disease are referred to as normal flora. These natural occupants of our bodies compete with pathogens for space and nutrients, so normal flora are a form of innate defense.

Gentner [14] mapped similarity types related to analogies along two axes, relations shared and attributes shared. The axes we identified to describe relationships between concepts developed by the students and the biological phenomena presented to them are, accuracy of the strategy applied and abstraction away from biological entities. Resulting types of similarities are shown in Figure 2.

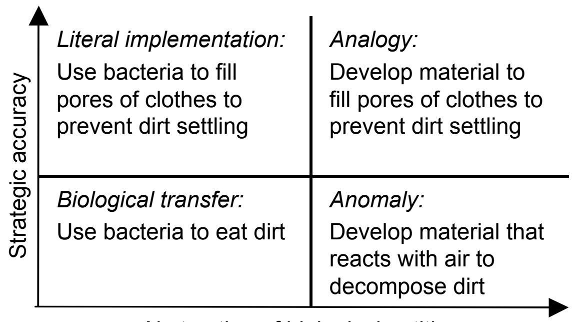

Figure 2: Types of similarity.

Literal Implementation

The first type of similarity relationship is characterized by literal implementations of biological phenomena, *e.g.,* using bacteria (source domain) to fill pores of clothing (target domain) such that dirt cannot settle. Here, the strategy implemented is the same as that presented, but the same biological actors, bacteria, carry out the strategy, *i.e.,* no abstraction of biological entities was performed.

Biological Transfer

The next type of similarity does not implement the strategy presented, but remains fixated on the domain of biology by transferring the biological actors of the phenomenon to another strategy. Responses of this category include 'immerse the garment in a pool of bacteria that will eat grease and stains.' The bacteria (source domain) are used to solve the problem of dirty clothes (target domain) by eating grease and stains.

Analogy

The third type of similarity relationship implements strategic principles derived from the biological phenomena without transferring the biological actors. A response obtained from this category incorporates the strategy of 'competition for space' and replaces bacteria and fungi (source domain) e.g., with a saturating solution (target domain), such that the settling of stains cannot occur. This category represents the type of similarity intended in biomimetic design.

Anomaly

The final type of similarity actually does not involve any apparent similarity between the concept and the biological phenomenon on which the concept is based. One concept based on *Skin Defense* is, 'develop material that reacts with air to decompose dirt.' While the reasoning that led to this particular concept is not obvious, some other responses of this category can be attributed to a number of reasons. Some students misinterpret the phenomenon presented and therefore apply an inaccurate strategy in their concept. Other students develop concepts based on association with a single or a few words presented, without using the strategy presented. For example, in the *Antibodies and Antigens* example, it is conjectured that many students associated the phrase "heavy chains" with larger molecules, and developed concepts based on making lumps of dirt larger, believing that increasing dirt volume would facilitate their removal. Another example, the *Dialysis* excerpt, which is lacking in useful information, resulted in many anomalous concepts.

4.3 Similarity types and abstraction hierarchy

The results suggest that the manner in which biological phenomenon is presented corresponds to the number of responses received within a similarity relationship category. For each category of biological phenomena, there was a tendency for the majority of responses to fall within a corresponding similarity relationship category.

Form-driven descriptions at the lowest hierarchical level result in more literal implementations of biological phenomena. In the *Horsetails* example, 68% (21/31) of responses suggested using silica deposits of horsetails, an object of the biological phenomenon, to clean clothing.

In contrast, principle-driven descriptions at the top of the hierarchy result in more strategic similarities, as indicated by 75% (36/48) of the *Population Control* responses.

Behavior-driven descriptions in the middle of the hierarchy can also result in strategic similarities, as was true for **Plant's Outer Surface***:*

> Plant's defensive responses – Tissues such as the epidermis or cork protect the outer surfaces of plants, and these tissues are generally covered by cutin, suberin, or waxes. This protection is comparable to passive non-specific defenses of animals. One of the plant's first defensive responses is the rapid deposition of additional polysaccharides to the cell walls, reinforcing a barrier to invasion by the pathogen.

In this example, 69% (41/59) of the responses incorporated similar strategies, *e.g.,* by suggesting development of a barrier for protection of clothing.

Thus far, we have only discussed the relationships pertaining to the majority of responses; not all responses for a biological phenomenon belonged to the same similarity category, which is discussed further next.

5 CONCLUSION

Although a general trend exists between the types of descriptions of phenomena and the similarity achieved using these descriptions, exceptions to the trend were present. Figure 3 relates the type of descriptions with the resulting similarity type, qualitatively representing likelihood of occurrence by the thickness of the connecting lines.

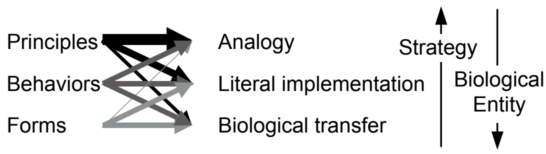

Figure 3: Abstraction hierarchy and similarity categories.

Concepts based on descriptions of biological phenomena that include principles tend to find similarities in strategies between the source and target domains. However, as shown in the *Skin Defenses* example, although the principle of competition for space was clearly presented, resulting responses may not apply the principle, but instead concentrate on the biological entities involved, *e.g*., bacteria. Therefore, it is always possible to focus on lower levels of phenomena presented, *i.e.,* forms, or to abstract downwards from the higher levels presented.

However, the ability to abstract a principle from a lower-level description of biological phenomena is more difficult since this information is not present in the description. Such abstractions rely on additional insights and knowledge of the source domain that had been attained outside of the problem solving exercise. The *Dialysis* example resides in the *forms* level of the hierarchy since it only presents biological forms. The majority of its non-anomalous responses remained fixated in the biology domain, indicating the need to 'use a kidney to remove dirt.' However, 20% (8/40) of responses proposed the strategy of filtering, not mentioned in the description. This suggests that a number of participants had prior knowledge of how the kidney functioned.

Instances of literal implementation of biological phenomena to solve engineering problems, *e.g.*, bioremediation of wastes, exist and are commendable. However, the potential of biomimetic design is fully realized when one can abstract a strategy used in biological phenomena and implement this strategy in a way that is not limited to a literal one using the same biological players.

For behavior-driven descriptions in the middle of the hierarchy, the majority of responses achieve similarity in the processes between the source and target domains. When a principle can be readily abstracted from the description given, strategically similar analogies occur.

The use of biological phenomena relies on the type of information presented. Information presented at higher levels of abstraction would be ideal. When confronted with information at lower levels of abstraction, an attempt to abstract progressively upwards in the hierarchy leads to more strategically based concepts.

6 SUMMARY

The nature of how biological phenomena are presented can be classified into a hierarchy of forms, behaviors and principles. The type of similarity achieved between biological phenomena and concepts based on these phenomena is affected by the type of information present in the descriptions of the phenomena. Concepts using strategically similar analogies occur more frequently in the presence of principles that explain the biological phenomena. It was rare that participants abstracted principles when one was not readily available, and the only instance of this was when participants had prior knowledge of the phenomenon. Analogies that also abstract the biological entities involved in the phenomena are preferred since resulting concepts are not constrained by direct use of biological forms.

7 ACKNOWLEDGEMENTS

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