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USE OF BIOLOGICAL PHENOMENA IN DESIGN BY ANALOGY

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ABSTRACT

Biomimetic design involves the use of biological phenomena as analogies to solve engineering problems. The use of biological knowledge in natural-language format to support biomimetic design removes the need to create and maintain a database of biological phenomena for engineering purposes. However, challenges arise in recognition and extraction of relevant strategies in biological phenomena and the application of these strategies to the target problem.

This paper describes two studies of how descriptions of biological phenomena are used to develop solutions to an example problem. Participants were informed of the types of similarities to avoid that were observed in a previous study. The occurrence of such non-analogous similarities declined.

Two types of fixation were observed during the first study: fixation on certain words instead of the overall strategy presented in descriptions and fixation on certain solutions regardless of the description used as stimuli. The second study aimed to reduce these types of fixation. While fixation was observed to decrease in the second study, the need for support of analogical mapping persisted.

1. INTRODUCTION

Biomimetic design uses biological phenomena as analogies to help solve design problems. First presented will be terminology and related work in analogical reasoning, followed by existing work in design by analogy. Next described is how biomimetic design fits into the technique of Synectics and how TRIZ is relevant to biomimetic design.

1.1. Analogical Reasoning

Analogical reasoning involves the transfer of information from a source to a target domain. The source domain contains the analogous phenomenon, and the target domain contains the problem to be solved by analogy (Vosniadou & Ortony 1989).

Similarity links analogically related items between the source and target domains. Surface similarity is grounded in easily retrievable aspects of representations, and is based on shared object attributes, e.g., color of two tiles. Deep similarity is based on relational structures between two domains, e.g., flow of heat vs. flow of water (Gentner 1989).

The analogies abstracted from similarity relationships can be further divided into two types. Within-domain analogies are used between the same or at least conceptually close, source and target domains, e.g., from one type of electromechanical product to another. Between-domain analogies are used between different source and target domains, e.g., from biological phenomena to electro-mechanical products.

Benami and Jin (2002) developed a Cognitive Model of Creative Conceptual Design that captures the relationship between the properties that stimulate cognitive processes and the design operations that facilitate cognitive processes. The underlying conclusion of the study was that ambiguous entities stimulated more ideas than non-ambiguous entities, which tend to be fixating. Alternatively, between-domain analogies resulted in more creative, original ideas than within-domain analogies, which resulted in a greater quantity of ideas.

1.2. Related Work in Design by Analogy

A number of design frameworks exist for facilitating the abstraction of within-domain analogies. Of these, there are knowledge based systems that rely on surface similarity, such as Syn, where topological patterns of air circulation systems are matched with the requirements of the given architectural design problem (Goel 1997). More complex is the Ideal system developed by Bhatta and Goel (1994) that evaluates functional and causal patterns with no topological information such that deep functional similarities are explored.

McAdams and Wood (2000) developed a quantitative metric for design-by-analogy, which is based on the deep functional similarity of products within the domain of engineering. One goal of the metric is to reveal analogies between the functional requirements of the product to be designed and products that are similar, at a level that is useful for concept generation. Relationships between product functions and customer needs result in a procedure where critical functions of existing products can be adapted to solve the design problem of interest.

1.3. Synectics and biological analogies

Synectics is a technique for creative thinking that uses four types of analogies: direct, personal, symbolic, and fantasy (Gordon 1961). Biological analogies fall under direct analogies, and many design textbooks specify biological systems as a source of analogies (Dieter 2000, Ulrich & Eppinger 2000, Otto & Wood 2001, Hyman 2003, Dym & Little 2004). However, what remains unavailable to engineering students and practicing engineers are tools to formally support the identification and use of biological analogies for design. Many engineers do not have sufficient knowledge of biological phenomena to recall the most relevant biological analogies for a given design problem. When pressed, the biological analogies that come to mind are typically the most obvious, e.g., modeling flying machines after birds, underwater machines after fish, etc., and thus less likely to lead to creative solutions.

1.4. TRIZ and biomimetic design

The Theory of Inventive Problem Solving (TRIZ) is a method used to trigger creativity in problem solving (Altshuller 1984). The foundation of TRIZ is the compilation and organization of technical knowledge through the analysis of patents. Recurring engineering conflicts and their solutions were identified and categorized into the TRIZ database. To use TRIZ, challenges of the design problem are matched with a list of engineering conflicts. Possible design principles are then suggested to overcome contradictions.

Relevant to supporting biomimetic design, Vincent and Mann (2002) propose the extension of the TRIZ database to include biological information and principles.

2. PREVIOUS WORK IN BIOMIMETIC DESIGN

To avoid the significant and possibly subjective task of creating and maintaining a database of biological information for design, a method was developed to search for instances of keywords and synonyms that describe engineering problems through biological knowledge in natural-language format. Although there is an immense amount of such knowledge, the initial source, or corpus, used is an introductory biology text, *Life the Science of Biology,* by Purves et al. (2001). Previous applications using this method to support biomimetic design are problems in design for remanufacture and microassembly (Vakili & Shu 2001, Hacco & Shu 2002, Shu et al. 2003).

Challenges in using analogies from biological knowledge in natural-language format include:

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

To gain insight on the process and how it can be improved, studies were undertaken to observe people performing the above tasks. A previous study identified four types of similarities achieved when using biological phenomena in problem solving. This paper describes follow-up studies that use the information learned from the previous study, with the goal of improving the process and identifying other challenges.

2.1. Types of similarities in biomimetic design

Four types of similarities between the biological phenomena presented and the concepts developed using them as stimuli, observed previously (Mak and Shu 2004), will be illustrated using an example problem from Dieter (2000):

> Develop ways to eliminate puddles from pedestrian walkways after a rainstorm.

Solutions for this problem will be generated using the following description of a biological phenomenon from Purves et al. (2001) as stimulus:

> A parasitic leech makes an incision in its host to expose its blood. It can ingest so much blood in a single feeding that its body may enlarge several times. A substance secreted by the leech into the wound keeps the host's blood flowing. Leeches are used to reduce fluid pressure and prevent blood clotting in damaged tissues and to eliminate pools of coagulated blood.

a. Literal Implementation

The first type of similarity relationship is characterized by literal implementations of biological forms and behaviors, e.g., using leeches (source domain) to ingest puddles on walkways (target domain). Surface similarity is merged with deep similarity in literal implementations. The strategy implemented is the same as that presented, but the same biological forms, leeches, carry out the strategy.

b. Biological Transfer

Biological transfer does not implement the strategy presented, but remains fixated on the domain of biology by transferring the biological forms of the phenomenon to another strategy. “Use leeches to fill up depressions in sidewalks so that puddles don’t form” is a possible response of this category. In this case, the response is based entirely on surface similarities. The leeches (source domain) are used to solve the problem of walkway puddles (target domain) by physically filling in the areas where they tend to form.

c. Analogy

Analogies implement strategies derived from the biological phenomena without transferring the biological forms. A response obtained from this category incorporates the strategy used by leeches, but replaces the actual leeches (source domain) with suction- and/or absorption-based solutions (target domain). In this case, the concept is based entirely on deep relational similarities. This category represents the type of similarity intended in biomimetic design.

d. Anomaly

An anomaly does not involve any apparent similarity between the concept and the biological phenomenon on which the concept is based. An anomalous concept could be “develop material that reacts with air to clot puddles on sidewalks.” While the reasoning behind many such concepts is unclear, some responses of this category are due to misinterpretation of the phenomenon leading to extraction of incorrect strategies.

Anomalous concepts can also be based on association with certain words or phrases, e.g., 'clotting,' that is not representative of the overall strategy presented.

3. STUDY 1

After identifying the above types of similarities, we wanted to explore whether simple awareness of the types of similarities that could occur, but should be avoided, would increase the number of analogous solutions. Therefore, the study was repeated, with a different group of participants, but the same problem, and five descriptions of biological phenomena, three of which will be discussed. The different types of similarities observed to arise from attempts at biomimetic design were explained to the participants, such that they knew what to avoid while developing the desired analogous solutions.

3.1. Methods

Fifteen third/fourth year mechanical engineering students were asked to solve a problem using biological phenomena in a single two-hour session. The same problem that was created for the previous study was provided to the students:

> 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 ways that will result in clean clothes.

This problem was selected since it did not require prior knowledge of the dry-cleaning process. Although the problem requires improvements made to clothes cleaning, we framed the problem in terms of dry cleaning to avoid fixation on improvements made to washing machines, or cleaning solutions already known to the person.

Five descriptions of biological phenomena were presented with the problem. The fifteen people were divided into three blocks of five. For each block, the order of the descriptions was randomized. After reading each description of biological phenomena, the task was to underline the information most relevant to the problem, and determine strategies used in the biological phenomenon. Emphasis was placed on extracting an appropriate strategy used in each phenomenon. The strategies were then developed into concepts, for which analogies were preferred over other types of similarity.

Our previously developed biomimetic search tool was used to identify possible phenomena through functional keyword searches of 'defend', 'remove', and 'eliminate' in Purves et al. (2001). A functional keyword is a verb that describes the desired effect or action of the solution. The words 'remove' and 'eliminate' can be roughly described as synonyms of clean, i.e., removing and eliminating dirt. The search word 'defend' was suggested as a biological purpose of cleaning. Details on generating keywords are described by Chiu and Shu (2004).

The results of the searches were filtered using natural-language processing rules, whereby instances of words used in a different sense or otherwise deemed irrelevant were removed. Segments of text output by the search tool were selected to make the task more manageable for the participants. All descriptions of biological phenomena contained a strategy, along with text containing biological forms and behaviors.

Due to space limitations, three of the five descriptions of biological phenomena used will be shown along with observed reactions to the descriptions. Titles for descriptions have been added for future reference within the paper, but were not presented with the biological phenomena during the study.

3.2. Observations

For each description of biological phenomena below from Purves et al. (2001), a table summarizes the corresponding strategies identified and concepts developed from the description. The strategies were compared with a representative strategy for each phenomenon, and categorized as correct, incomplete and incorrect. The authors formed a representative strategy for each phenomenon before the study. Future efforts will be made to develop a metric for which strategies can be validated objectively. In this study, correct strategies contain similar elements to the representative strategy. Incomplete strategies contained partial elements of the representative strategy, and incorrect strategies did not embody any elements of the representative strategy.

The participants' actions and thought processes were not recorded during the study. Only the responses were analyzed.

a. Plant Defenses

A segment on plant defenses follows (Purves et al. 2001):

> When pathogens pass these barriers, plant defenses are activated. Plants seal off and sacrifice the damaged tissue so that the rest of the plant does not become infected. This approach works because most plants can replace damaged parts by growing new stems, leaves, and roots.

Table 1 lists the strategies and concepts developed from the plant defenses example, where quantities are indicated in parentheses. The strategy we found representative of this description is to "sacrifice and replace damaged/dirty area to save the whole." Six of fifteen responses expressed a similar strategy, and three each had strategies "seal and sacrifice" and "sacrifice." Incomplete responses containing a portion of the entire strategy, focused on "sealing" and "defense system."

Twelve of fifteen people developed analogy-based concepts, which were developed from the three strategies that included the idea of "sacrifice." Solutions common to the twelve were: "flaky clothes," "replaceable sections of clothes," and "altering clothing to remove damage."

Three concepts were anomalous: two were based on the sealing strategy (specifically, use a spray on clothing to repel stains), and one was derived from "defense system," which did not elaborate beyond "stain resistance."

Table 1: Plant Defenses Strategies and Concepts

<table>
<tr><th></th><th>Analogy</th><th>LI</th><th>BT</th><th>Anomaly</th></tr>
<tr><td>Correct Strategies</td><td colspan="4"></td></tr>
<tr><td>Sacrifice / replace damaged area to save whole (6)</td><td rowspan="3">Flaky clothes (6)
Replaceable sections of clothes (3)
Altering clothing to remove damage (3)</td><td rowspan="3"></td><td rowspan="3"></td><td rowspan="3"></td></tr>
<tr><td>Seal and sacrifice (3)</td></tr>
<tr><td>Sacrifice (3)</td></tr>
<tr><td>Incomplete Strategies</td><td colspan="4"></td></tr>
<tr><td>Seal (2)</td><td></td><td></td><td></td><td>Repel stains (2)</td></tr>
<tr><td>Defense system (1)</td><td></td><td></td><td></td><td>Stain resistance (1)</td></tr>
</table>

Quantities are indicated in parentheses ( ).

b. Barriers

The text on barriers from Purves et al. (2001) follows:

> 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.

Table 2 lists strategies and concepts developed from the barriers example, with quantities indicated in parentheses. The strategy we found representative of this example is "space competition for defense against pathogens/dirt." Eight of fifteen responses identified a similar strategy. Five identified the strategies of "innate defense" or "natural defense." Two incorrect strategies were found.

For the eight strategies indicating "space competition for defense," six concepts were of the analogy type. Four of these six concepts detailed the use of a coating to fill up areas of clothing that are prone to getting dirty. The remaining two of the six concepts were less descriptive, indicating a surface stain repellent. One concept corresponding to a correct strategy was a literal implementation, and the other one was anomalous.

For five strategies indicating "innate defense" or "natural defense," one concept detailed the same coating/displacement of dirt method mentioned above, two concepts described a surface stain repellent, and two concepts were anomalous.

For the two incorrect strategies, one led to the coating/displacement of dirt method mentioned above, and the other strategy was not used to produce a concept.

The coating/displacement of dirt concept corresponds to the "competition for defense" strategy. Likewise, the surface stain repellent solution could correspond to the "innate defense" strategy. Examining which part of the description was underlined, nine of fifteen selected "innate defense," which may explain the prevalence of the "stain repellent" solution.

Table 2: Barriers Strategies and Concepts

	Analogy	Literal Implement.	BT	Anomaly
Correct Strategies				
Space competition for defense against pathogens/dirt (8)	Coating/ displace dirt (4) Surface stain repellent (2)	Introduce normal flora into clothing to compete against odor-causing bacteria (1)		Ultra clean detergent targeting only dirty area (1)
Incomplete Strategies				
Innate/natural defense (5)	Coating/ displace dirt (1) Surface stain repellent (2)			Have pockets where dirt can be stored away (1) Active treatment component to attack dirt and oils (1)
Incorrect Strategies				
Mass production (1)				(none given)
Eat up nutrients (1)	Coating/ displace dirt (1)			

Quantities are indicated in parentheses ( ).

c. Surface Area and Volume

The text on cell size from Purves et al. (2001) follows:

> 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.

Table 3 lists strategies and concepts developed from the surface area and volume example. The strategy from this example we found relevant to the problem is "increased surface area is required for increased waste elimination."

Two of fifteen responses mirrored the above strategy of increasing surface area, but both corresponding concepts had difficulty implementing the strategy. One proposed an unclear cleaning method that uses "larger surface area to clean entire volume where dirt is trapped." The other proposed using clothing material with increased surface area/volume ratio to reduce dirt absorption, which is both incorrect and inconsistent.

Another two identified the strategy of containing the growth, spreading and absorption of stains, which is followed with concepts to prevent dirt absorption.

Table 3: Surface Area/Volume Strategies & Concepts

	Analogy - A	Analogy - B	Bio. Transfer	AM
Correct Strategies				
Increase SA/volume ratio; SA/volume ratio needed for waste removal (2)	Use large-area cleaning method (1)	Increase SA/volume of clothing to reduce dirt absorption (1)		
Contain growth/spread/ absorption of stain (2)	Apply detergent to new stains/stop dirt from being absorbed (2)			
Limited increase in surface area restricts increase in volume (6)	Reduce spreading of dirt (1)	Reduce material used in clothing (3)		
	Reduce cloth surface area and absorption (1)	Set maximum dirt density on cloth (1)		
Limit production rate by decreasing production means (1)	Reduce cloth surface area and absorption (1)			
As cell gets larger, waste generation is limited (1)	Expand clothing fiber to increase SA of dirt exposed (1)			
Incomplete Strategies				
Growing cells produce more waste and need more resources (1)		Reduce material used in clothing (1)		
Need for resources (1)	Powder to absorb dirt from clothes (1)			
Incorrect Strategies				
Eat up stains (1)			Create cells to eat stains (1)	

Quantities are indicated in parentheses ( ).

Six responses used the text from the final sentence of the description as the strategy: "limited increase in surface area restricts increase in volume." Corresponding analogous concepts included reducing dirt absorption/spreading as above. However concepts that propose "using less material in clothing so there is less material that can become dirty" dominated.

For a similar complete strategy expressed with biological terms, the resulting concept interestingly suggested that clothing fiber could be expanded using a chemical so that the surface area of dirt is better exposed to cleaning agents.

Two strategies identified were incomplete, in that they expressed neither the relationship between surface area and volume, nor cell size being restricted by need for resources and waste elimination. One resulting concept suggests the same idea of reducing material used in clothing. The second incomplete strategy specified only the "need for resources," resulting in the concept of "use powder to absorb dirt from clothes." One incorrect strategy was also found, i.e., "eat up stains," which led to a biological transfer, "genetically engineer cells to eat up stains."

Overall, the most common concept was to reduce the surface area of clothing so there was less to become dirty. Somewhat similar to one of the concepts mentioned, the concept we had in mind for this example is to "break stain into smaller particles, so that the volume of individual stain particles is decreased, but total surface area is increased, maximizing the amount of cleaning solution that comes in contact with dirt." Instead of applying the strategy to clothing, we applied the strategy to the dirt itself. Even those who had identified our expected strategy of "increased surface area is required for increased waste elimination," seemed to have difficulty applying the strategy. One successful solution expressed the concept as an application to clothing. Another concept may have applied this strategy to the cleaning agent, "powder to absorb dirt from clothes," although this concept followed a strategy of "need for resources." It is possible that people were primed to limit application of strategies to clothing, since the concepts developed for other biological examples mostly treat clothing as opposed to dirt.

We had originally categorized many of the above concepts as anomalous. However, since the concepts were not entirely unrelated to the description, we used two categories of analogies. The first, Analogy –A, contains concepts originally categorized as analogous. Analogy –B contains concepts that were inaccurate, unclear, or subjectively less successful in applying a strategy.

3.3. DISCUSSION

Table 4 summarizes the types of similarities found for each biological phenomenon presented in Study 1.

For the descriptions of "plant defenses" and "barriers," people were successful at developing analogy-based concepts. The quality of concepts for "surface area and volume" may have been affected by priming, where people were fixated on applying the strategy to clothing as opposed to the dirt. In addition, the expected strategy was not as explicitly stated as it may have been in the other descriptions.

The numbers of literal implementations and biological transfers are quite low, i.e., one of each for the three phenomena combined. This supports the theory that awareness of the types of similarities to be avoided would reduce their occurrence. There are still a few anomalous solutions, but some of these may be inappropriately categorized due to our limited understanding of how these concepts relate to the biological phenomena. For the last example, we created a second category of analogies to reflect the presence of less clear or successful application of corresponding strategies.

However, two types of fixations contributed to anomalies and less successful analogies. Several people were observed to fixate on certain aspects of the descriptions of biological phenomena during the abstraction process. One person consistently produced anomalous results by placing incorrect emphasis on certain words or phrases in the description. For example, in the barriers description, "mass production" was identified as a strategy, referring to "reproduce in great numbers," which was underlined in the excerpt. This association with incorrect words and phrases was also observed in a previous study. Similarly, another person consistently used incomplete strategies to formulate concepts. For example, in plant defenses, the concept "make clothing that repels stains" was developed from the incomplete strategy of "sealing."

Fixation on a mode of solution was also observed. One person appeared to be fixated on a "spray" solution to the problem. For each phenomenon, a similar concept based on coating the clothing material was developed. This association with similarity among concepts was also observed previously.

Table 4: Summary of Concepts in Study 1

	Analogy	Literal Imple.	Bio. Trans.	Ano-maly
Plant Defenses	12 occurrences (3 concepts)			3
Barriers	10 occurrences (2 concepts)	1		3
Surface Area and Volume	A 8 occurrences (5 concepts) B 6 occurrences (3 concepts)		1	

4. STUDY 2

To determine whether fixation problems observed in Study 1 can be reduced, a follow-up study was conducted with the same people. The same cleaning problem was to be solved, but using two new descriptions of biological phenomena.

4.1. Methods

The first type of fixation involves concepts developed based on particular words or phrases instead of the overall phenomenon presented. The corresponding strategies demonstrated partial, if any, understanding of the biological phenomenon. To motivate the consideration of the entire phenomenon, participants were asked to identify for each phrase in the description, the subject, verb and object. The subject was described as a noun performing the action, the verb as the action, and the object, as the noun being acted upon. Identification of these parts of speech was expected to require more thought and yield more insight than simply underlining portions of the description deemed relevant. By having to process each phrase of the description, we hoped that fixation would not occur on limited aspects of the description.

A second fixation effect in Study 1 occurred when people fixated on a single solution. Resulting concepts did not relate to the strategy presented in each biological phenomenon, but reflected a general theme throughout their concepts (e.g., spray solution). In hopes of discouraging this behavior, nouns in the description analogous to 'clothing' and 'dirt', if any, were to be identified for each of the two descriptions. This emphasized mappings between analogous items in the biological phenomenon and the problem. Next identified were strategies used by the noun(s) analogous to clothing against the noun(s) analogous to dirt. Finally, concepts based on the strategies were to be developed to solve the problem.

An example demonstrating each step of the process was provided. An unintended effect of the example and the layout of the exercise is that specific aspects of the phenomena were considered individually. Strategies were processed as unrelated, as opposed to belonging to an interactive system as a whole.

Each description of biological phenomena used will be shown along with observed responses to the description. Titles for the descriptions have been added for future reference within the paper, but were not presented during the study.

4.2. Observations

Analysis of the responses revealed that the first section, which required identification of subjects, verbs, and objects, was troublesome for most people. However, poor performance in the first section was not a contributing factor to poor performance in the latter half of the task. The inability to process and classify parts of speech had little impact on the ability to reason by analogy. Therefore, the responses from the first section will be disregarded.

For each description of biological phenomena below from Purves et al. (2001), we will present the strategies and concepts developed. Most people developed two sets of strategies and concepts for each description. Since the sets tend be clustered around certain themes, the two sets will be discussed separately for each description. For each description, a table presents the objects analogous to dirt and clothing, the corresponding strategies identified and concepts developed. Subscripted quantities indicate multiple contributions by the same person.

a. Respiratory Tract

Text on respiratory tract from Purves et al. (2001) follows:

> Mucus and trapped pathogens are removed by the beating of cilia in the respiratory passageway, which moves a sheet of mucus and the debris it contains up toward the nose and mouth. Sneezing is another way to remove microorganisms from the respiratory tract.

The responses from the "Respiratory Tract" example can be divided into two categories: cilia and sneezing.

i. Cilia / Mucus

All fifteen people were able to extract strategies pertaining to this category. Eleven indicated 'respiratory passageway' as analogous to clothing and some combination of 'pathogens, debris and microorganisms' in addition to 'mucus' as analogous to dirt. An interesting factor in this example was whether mucus was identified as analogous to clothing or dirt. In the biological phenomenon, mucus is used as a complement to cilia to clean the respiratory passageway. Although the mucus is disposed of through sneezing, in the context of the excerpt, mucus is considered a part of the cleaning mechanism.

Eleven of fifteen people identified mucus as analogous to dirt and had strategies such as, "cilia beat to remove mucus and trapped pathogens," and "cilia collect dirt and transport it away." These strategies focus on cilia as the cleaning mechanism. Consequently, the corresponding solutions emulate cilia in terms of form and behavior. However, one person who identified mucus as analogous to dirt seemed to consider it as a cleaning mechanism while developing his strategy, "beating cilia removes trapped pathogens," into the concept "layers of plastic sheet film that can be pulled off clothes."

Four of the fifteen people did not identify mucus as analogous to dirt, one of who specified mucus as well as cilia as being analogous to clothing. Three of the four produced the same strategy as above, "cilia beat to remove mucus and trapped pathogens." However, one of these three continued to develop an additional concept for another strategy that reflected understanding of the role of mucus, i.e., "use stickers to remove dirt trapped in clothes". The final one of the four produced a strategy that more explicitly mimics the role of mucus, "produce a substance to trap debris, move substance to areas where debris can be disposed" and a corresponding concept.

Most people focused on the 'beating' and 'moving' actions of cilia to develop concepts. Brushing, an often-used term, can be considered analogous to the motion of cilia in the respiratory passageway. However, the concept "beat clothing to remove dirt" seems more associated with the sense of 'beat' corresponding to, "hit something with repeated heavy blows," where the intended sense with cilia and heart beating is to "make natural short rhythmic movements." Other solutions use terms such as 'shaking' and 'mechanical vibrations.'

ii. Sneezing

Thirteen of fifteen people indicated a second biological strategy as "sneezing removes objects in the respiratory tract." Sneezing removes mucus and debris from the respiratory passageway. If the concept of sneezing is considered on its own, 'mucus' can be treated as dirt, since it is removed with the debris. Thus, regardless of whether the person listed 'mucus' as analogous to dirt or clothing, they would extract similar strategies for sneezing.

Most of the analogous solutions developed from the 'sneezing' strategy were very similar: the use of sudden movement or blast of air to remove dirt. One unusual sneezing-based solution suggested "small airbags with layers of cloth that pressurize rapidly and shake off dirt."

The remaining two of fifteen people did not refer to 'sneezing' as a strategy. One student's second strategy came from the clause, "the respiratory passageway moves a sheet of mucus and the debris it contains up toward the nose and mouth," which resulted in the concept "use stickers to remove dirt trapped on clothes," already mentioned in the previous section. Since 'sticker' was likely derived from 'sheet of mucus', this strategy and concept were categorized under the 'cilia/mucus' columns. The second person made a generalized statement of what the respiratory passageway did: "the respiratory tract removes microorganisms and debris away from the lungs" to develop the concept, "clothes have specific passageways that channel dirt away from the surface."

Table 5: Respiratory Tract Analogous Objects, Strategies and Concepts

		CILIA / MUCUS		SNEEZING	
Clothing	**Dirt**	**Source (Biology) Strategy**	**Target (Engineering) Concept**	**Source (Biology) Strategy**	**Target (Engineering) Concept**
Respiratory Passageway	(Pathogens, debris, microorganisms) AND mucus	Cilia collect dirt and transport it away (1)	Brush to remove dirt (1)	Sneezing removes objects in respiratory tract (11)	Large blast of air (6) Substance that reacts in an explosive fashion with dirt (1) Shake/vibrate dirt (3)
		Respiratory tract is lined with cilia (1)	Mechanical vibrations directed at dirt (1)		
		Cilia beat to remove mucus and trapped pathogens (8)	Beat clothing to remove dirt (3) Use a tumbler with clean shoes to beat against clothing (1) Self cleaning clothing (2) Brush to remove dirt (2)		
		Beating cilia removes trapped pathogens (1)	Have layers of plastic sheet film that can be pulled off clothes as it gets dirty (1)		Have many small airbags with layers of cloth that pressurize rapidly and shake off dirt (1)
Respiratory Passageway	Pathogens, debris, microorganisms	Produce a substance to trap debris. Move substance to areas where debris can be disposed (1)	Have clothes create a substance that traps debris and moves using body movement towards cuff and bottom of clothes where they can be disposed (1)	Sneezing removes objects in respiratory tract (2)	Large blast of air (2)
		Cilia beat to remove mucus and trapped pathogens (1)	Brush to remove dirt (1)		
		Cilia beat to remove mucus and trapped pathogens (1)$_1$	Shake clothes to remove dirt (1)$_1$		
		Respiratory passageway moves sheet of mucus and the debris it contains up toward nose and mouth (1)$_1$	Use stickers to remove dirt trapped in clothes (1)$_1$		
Cilia and Mucus	Pathogens, debris, microorganisms	Cilia beat to remove mucus and trapped pathogens (1)	Self cleaning clothing (1)	Respiratory tract removes microorganisms and debris away from the lungs (1)	Clothes have specific passageways that channel dirt away from surface (1)

Subscripted quantities in parentheses refer to multiple contributions by the same person.

b. Fish Gas Exchange Surfaces

The second description from Purves et al. (2001) is:

> Fish can extract an adequate supply of O_2 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 the opposite sides of their gas exchange surfaces.

Responses to this description can be divided into two categories: surface area/thickness, and flow. For each category, there was a greater variety of responses than for the previous biological phenomenon.

i. Surface Area / Thickness

Table 6 presents responses for "surface area/thickness." Two people did not identify a strategy in this category, and three produced more than one strategy for this category.

Certain forms from the descriptions were commonly selected as objects that are analogous to clothing and dirt. The majority of people identified either fish or gas exchange surfaces as analogous to clothing. Exceptions include one who identified oxygen and three who identified "meager environmental sources" or "environment" as analogous to clothing. All but two people identified oxygen as analogous to dirt, and the two indicated that nothing was analogous to dirt.

Many also identified a common, analogous strategy: nine of sixteen strategies expressed "maximizing surface area for diffusion." One reversed the maximizing of surface area to "decreasing surface area to allow less oxygen to attract." Two strategies were to "minimize path length" and another cited the effect on oxygen due to changes in path length. One strategy was simply a statement of the biological phenomenon, "extraction of oxygen from meager environmental sources."

It is worthwhile to note that applying the most common strategy to the most commonly identified analogous objects is problematic. For example, the most common mappings are:

Fish/Gas exchange surfaces – Clothing

Oxygen – Dirt

The most common strategy, to "maximize gas exchange surfaces to maximize oxygen extraction (from environment)" would map to "maximize clothing (surfaces) to maximize dirt extraction (from environment)," which is contrary to what is desired. Indeed, this interpretation led to three people suggesting that clothing surface area be minimized to minimize dirt absorbed into clothing. The corresponding concepts range from those that explicitly call for reduced surface area in the form of skimpier clothing, to those that leave open the possibility of reducing surface area by e.g., changing the weave so that similar coverage is obtained with less effective surface area to absorb dirt.

An interesting, related concept is to "maximize surface area of cleaning particles." Although the object identified as being analogous to clothing is "gas exchange surfaces", the actual object analogous to gas exchange surfaces in the final concept are cleaning particles. Given this correction, the resulting object analogous to clothing would be "meager environmental sources," resulting in the following mappings:

Gas exchange surfaces – Cleaning particles

Oxygen – Dirt

Meager environmental sources – Clothing

With the above, the strategy of "Maximize surface area of <u>gas exchange surfaces</u> to maximize extraction of <u>oxygen</u> from <u>meager environmental resources</u>" can be consistently mapped to obtain "Maximize surface area of <u>cleaning particles</u> to maximize extraction of <u>dirt</u> from <u>clothing</u>."

However, none of the three people who actually identified "meager environmental sources" or "environment" as analogous to clothing were able to develop the above or another concept consistent with their mapping. Instead, two of the three suggested, "stretch out clothing" or "maximize contact between clothes and solvents", which are practical and valid concepts, although inconsistent with their analogous object mappings. The remaining one of the three did not develop a concept in the "Surface Area/Thickness" category.

One way in which a person attempted to resolve the contradiction resulting from the most common mapping was to add conditions for why such a solution would work. The concept was to "increase surface area of clothes to absorb more dirt, decreasing the appearance of dirt." Although the solution is somewhat practical, the person was unable to move away from the mapping.

Anomalous concepts include "amount of solvents is controlled by amount of dirty clothes" and "install small purifier on clothes to remove dirt from air before it contacts clothes."

ii. Flow

Table 6 contains responses related to the flow aspect of the phenomenon. Three people did not extract a strategy pertaining to 'flow.'

Nine of the twelve people expressed strategies based on the flow of water over gas exchange surfaces, with varying degrees of completeness. Some only refer to the flow of blood and water, while others focus on the unidirectional and countercurrent aspects of the flow. Yet others refer to 'meager environmental sources' and 'oxygen extraction efficiency.'

The strategies that directly refer to 'flow' resulted in the most analogous solutions. Seven resulting concepts involved the flow of fluid on clothing. Although the benefit of countercurrent flow in providing favorable concentration gradients for diffusion was not explicit in the description, many concepts seemed to have made use of the word 'countercurrent.' For example, one proposed a solution of "an air cleaner that applies air in different directions," derived from the strategy of "constant, unidirectional, countercurrent flow of blood and water." In other concepts, 'countercurrent' may have been interpreted as the flow of two fluid streams over the opposite sides of a surface, without appreciation for the opposite directions of the two fluid streams.

Another flow related concept was "make flow turbulent on either side of cloth to promote mechanical separation." This concept derived from a biological strategy expressed as "turbulence in fluids at gas exchange boundaries promotes travel across boundary." It is unclear what led to the focus on turbulence since 'turbulence' is not present in the description.

A difficulty in applying a strategy, similar to one in the "Surface Area/Thickness" category, is embodied in the solution, "avoid exposure to wind, which produces a flow of dirt and particles over clothing."

One generalized strategy, "gas exchange surface allows oxygen to be pulled through for use" resulted in a concept, "use removable inner surface of clothes to absorb dirt; inner surface can be replaced." Other solutions, with no obvious relationship to the description, were deemed anomalous.

4.3. Discussion

The purpose of the second study was to address two types of fixation found previously. The first type of fixation is on specific words rather then the overall strategy of the phenomenon. The second type refers to particular concepts repeated for different biological phenomena used as stimuli.

The first type of fixation on specific words was found to decrease. This may be attributed to the requirement that each description of biological phenomena be processed by clause, although the actual identification of parts of speech, subject verb and object was largely unsuccessful.

The second type of fixation where similar concepts are developed regardless of stimuli was not observed in the second study, and may be attributed to the specifications of the exercise, and the lack of superficial and conceptual similarity between the biological phenomena presented.

Although responses clustered around certain aspects of the biological phenomena, extracted strategies varied in completeness. This was also observed in the first study. Some responded with sparse, incomplete strategies, whereas others were more effusive. Those who oversimplified the phenomena tended to develop less practical concepts based on incorrect suppositions.

The "Respiratory Tract" description resulted in successful analogous concepts based on the biological functions carried out by cilia and sneezing. Although the concepts focused predominantly on specific aspects of cilia and sneezing, with less regard for biological system interactions, this behavior may have been a product of the design of the task.

The "Fish Gas Exchange Surface" description also resulted in successful analogous solutions. The concept of surface area/thickness resulted in a number of mapping difficulties, where people were unable to develop a practical solution from a correctly extracted strategy. As a result, a number of people resorted to reversing the strategy in order to develop a working solution. This behavior was also observed in the Surface Area/Volume phenomenon from the first study.

Table 6: Fish Gas Exchange Surface Analogous Objects, Strategies and Concepts

		SURFACE AREA/THICKNESS		FLOW	
Clothing	**Dirt**	**Source (Biology) Strategy**	**Target (Engineering) Concept**	**Source (Biology) Strategy**	**Target (Engineering) Concept**
Fish	N/A	Maximize surface area for diffusion (1)$_1$	Increase surface area of clothes to absorb more dirt, decreasing appearance of dirt (1)$_1$		
		Minimize path length (1)$_1$	Design clothing that is very thin, minimizing thickness for less dirt to accumulate (1)$_1$		
Fish	Oxygen	Path length changes to extract supply of oxygen (1)	Amount of solvents is controlled by amount of dirty clothes (1)	Constant, unidirectional countercurrent flow of blood and water (1)	Control water temperature and amount of water to achieve maximum dissolving efficiency of solvents (1)
		Extract oxygen from meager environmental sources (1)	Install a small purifier on the clothes to remove dirt from the air before contact with clothes (1)	Constant flow of blood and water (1)	Use constant flow of water to remove dirt on clothes (1)
		Maximize surface area for diffusion (1)	Decrease surface area to attract less dirt (1)		
Gas exchange surface	Oxygen	Maximize surface area for diffusion (2)	Stretch out clothing to increase contact with solvent (2)	Constant, unidirectional countercurrent flow of blood and water (1)	Spray both sides of the dirty area with a liquid, loosening dirt from both sides (1)
		Maximize surface area for diffusion (1)$_2$	Maximize contact between clothes and solvents (1)$_2$	Constant, unidirectional countercurrent flow of blood and water (1)$_2$	Apply an air cleaner that applies air in different directions (1)$_2$
		Maximize surface area for diffusion (1)	Maximize surface area of cleaning particles (1)	Efficient blood and water flow maximize oxygen uptake (1)	Develop a more efficient cleaning process that maximizes the uptake of dirt (1)
		Maximize surface area, minimize path length, maximize oxygen extraction efficiency by means of constant, unidirectional, countercurrent flow of blood and water (2)$_3$	Decrease surface area to attract less dirt (1)$_3$ Increase the thickness of clothing to make it harder for dirt to penetrate (1)$_3$	Maximize surface area, minimize path length, maximize oxygen extraction efficiency by means of constant, unidirectional, countercurrent flow of blood and water (1)	Avoid exposure to wind which produce a flow of dirt and particles over clothing (1)
		Minimize path length, only allowing certain areas to be exposed (1)$_2$	Only clean the minimum area required to make the clothes look clean (1)$_2$		
				Turbulence in fluids at gas exchange boundaries promote travel across boundary (1)	Make flow really turbulent on either side of cloth to promote mechanical separation (1)
Surface area, path length, gas exchange surface	Oxygen	Decreased surface area will allow less oxygen to attract (1)	Decrease surface area to attract less dirt (1)	Gas exchange surface allows oxygen to be pulled through for use (1)	Use removable inner surface of clothes to absorb dirt. Inner surface can be replaced (1)
Environ-ment	Oxygen	Maximize surface area for diffusion (1)	Stretch out clothing to increase contact with solvent (1)	Efficient blood and water flow maximize oxygen uptake (1)	High pressure flow directed on opposite sides of stained area (1)
Meager environ-mental sources	Oxygen	Maximize surface area for diffusion (1)	Maximize contact between clothes and solvents (1)	Maximize countercurrent flow of blood and water (1)	Maximize flow of solvent solutions through clothing to remove dirt (1)
				Meager environmental source is robbed of oxygen by fish that optimize oxygen extraction by controlling the flow of blood and water over their gas exchange surfaces (1)	Develop a clothing hanger that uses electric current to generate a magnetic force and remove all magnetic debris (1)
Oxygen	N/A	Maximize surface area for diffusion (1)	Expose surface area to a cleaning solution (1)	Maximize oxygen extraction efficiency (1)	Use OxyClean™, a naturally powerful, yet effective cleaning detergent (1)

Subscripted quantities in parentheses refer to multiple contributions by the same person.

Table 7: Summary of Concepts in Study 2

	Analogy	Lit. Implem.	Bio. Transfer	Anomaly
Respiratory Tract				
Cilia /Mucus (16)	12A, 4B			
Sneezing (14)	14			
Fish Gas Exchange				
SA/t (16)	7A, 6B			3
Flow (12)	6A, 3B			3

Table 7 summarizes the types of similarities for each biological phenomenon, where the 'B' designation under analogy indicated a less successful application of a strategy.

Both descriptions of biological phenomena in the second study were successfully developed into analogous concepts, although there were differences in the quality of concepts. Analogous concepts were more successfully developed for "Respiratory Tract" than for "Fish Gas Exchange Surfaces". Difficulties with the "Fish" phenomenon can be attributed to structural mapping problems. Although people were asked to provide analogous objects to clothing and dirt, subsequent strategies and concepts were not always consistent with those mappings. Some difficulties with mapping led to less practical concepts, but some inconsistent mappings led to viable and practical concepts. This poses the need to make more visible the structures between the source and target domains, such that similarity relationships can be better extracted.

While decreases in the amount of fixation observed may be attributed in part to learning, difficulties in mapping that contribute to anomalies and unsuccessful analogies persisted.

5. SUMMARY

This paper described two studies of how biological phenomena are used to develop concepts to solve engineering problems. Two types of fixation were observed in the first study. Fixation on specific words does not use the overall strategy of the phenomenon. Fixation on a particular concept, e.g., sprays, regardless of stimuli presented also occurred.

The second study aimed to identify methods that can reduce the fixation observed in the first study. Both types of fixation decreased, although this may be attributed in part to the learning that occurred over the course of the two studies.

In the first study, a description involving surface area/volume resulted in difficulties in structural mapping to develop viable solutions. This difficulty in structural mapping was again observed with a description used in the second study. The persistence of this problem suggests the need to support structural mapping between source and target domains so that more successful analogous concepts can be developed.

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REFERENCES

Altshuller, G.S., 1984, Creativity as an Exact Science, Gordon and Breach, Luxembourg.

Bhatta, S. and Goel, A., 1994, Innovation in Analogical Design: A Model-Based Approach, Proceedings of the Third International Conference on Artificial Intelligence in Design (AID-94), Aug. 15-18, Lausanne, Switzerland, pp.57-74.

Benami, O., Jin, Y., 2002, Creative Stimulation In Conceptual Design, Proceedings of ASME DETC/CIE, Montreal, QC, Canada, DETC2002/DTM-34023.

Chiu, I., Shu, L., 2004, Natural Language Analysis for Biomimetic Design, Proceedings of ASMEDETC/CIE, Salt Lake City, UT, DETC2004/DTM57250.

Dieter, G.E., 2000, Engineering Design: A Materials and processing Approach - 3rd edition, McGraw-Hill.

Dym, C., Little, P., 2004, Engineering Design: A Project-Based Introduction, 2nd Edition, John Wiley & Sons, NJ.

Gentner, D., 1989, The Mechanisms of Analogical Learning, Similarity and Analogical Reasoning, Cambridge University Press, Cambridge.

Goel, A.K., 1997, Design, Analogy and Creativity, IEEE Expert Intelligent Systems and Their Applications, 12: 62-70.

Gordon, W.J.J., 1961, Synectics, Harper & Row, NY.

Hacco, E., Shu, L.H., 2002, Biomimetic Concept Generation Applied to Design for Remanufacture, Proceedings of ASME DETC/CIE, Montreal, QC, Canada, DETC2002/DFM-34177.

Hyman, B., 2003, Fundamentals of Engineering Design, Second Edition, Prentice Hall, NJ.

Mak, T., Shu, L., 2004, Abstraction of Biological Analogies for Design, Annals of the CIRP, Vol. 53/1, in press.

McAdams, D., Wood, K., 2000, Quantitative Measures for Design by Analogy, Proceedings of ASME DETC/CIE, Baltimore, Maryland, DETC2000/DTM-14562.

Otto, K., Wood, K., 2001, Product Design, Techniques in Reverse Engineering and New Product Development, Prentice Hall, NJ.

Purves W.K., Sadava, D., Orians, G.H., Heller, H.C., 2001, Life, The Science of Biology, 6/e, Sinauer Associates, Sunderland, MA.

Shu, L., Lenau, T., Hansen, H., Alting, L., 2003, Biomimetics Applied to Centering in Microassembly, Annals of the CIRP, 52/1:101-104.

Ulrich, K.T., and Eppinger, S., 2000, Product Design and Development, 2nd Edition, McGraw-Hill, New York.

Vakili, V., Shu, L.H., 2001, Towards Biomimetic Concept Generation, Proceedings of ASME DETC/CIE, Pittsburg, PA. DETC2001/DTM-21715.

Vincent, J., Mann, D., 2002, Systematic Technology Transfer from Biology to Engineering, Philosophical Trans. of The Royal Society: Physical Sciences, 360: 159-173.

Vosniadou, S., and Ortony, A., 1989, Similarity and Analogical Reasoning: A Synthesis, Similarity and Analogical Reasoning, Cambridge University Press, Cambridge.