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EFFECTIVE ANALOGICAL TRANSFER USING BIOLOGICAL DESCRIPTIONS RETRIEVED WITH FUNCTIONAL AND BIOLOGICALLY MEANINGFUL KEYWORDS

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ABSTRACT

While biology is well recognized as a good source of analogies for engineering design, the steps of 1) retrieving relevant analogies and 2) applying these analogies are not trivial. Our recent work translated the functional terms of the Functional Basis into biologically meaningful keywords that can help engineers search for and retrieve relevant biological phenomena for design, addressing step 1 above. This paper reports progress towards step 2: identifying and overcoming obstacles to effective analogical transfer and application of biological descriptions retrieved with functional and biologically meaningful keywords.

This work revealed that the presence of, and ease of recognizing, causal relations (relationships between two actions where one causes another) in biological descriptions plays a key role in the quality of analogical transfers. We observed that novice designers found it difficult to correctly transfer analogies when they could not easily recognize the causal relations present in biological descriptions. Two major factors that rendered this recognition difficult were: 1) a large number of action words appearing in the descriptions, and 2) key action words being used in the passive voice. To overcome these factors, we propose a template that guides designers to 1) recognize the relevant causal relations in biological descriptions and 2) focus on the functional elements of the causal relations.

1. INTRODUCTION

Many researchers in both cognitive science and design engineering have recognized analogy as a significant tool in making creative leaps during problem solving and design (Gentner 1989, Goel 1997, Holyoak and Thagard 1996). Our past and current research focuses on design using biological analogies, i.e., biomimetics. Gordon (1961) recognized biology as a promising source of analogies and humans have mimicked biological entities throughout history to serve their needs. While many successful applications have already been achieved, there lies an almost infinite amount of potential analogies in biology yet to be explored, as biological knowledge sources are quickly expanding (Rebholz-Schuhmann et al. 2005).

In general, the use of analogy involves two steps. First, the source analogy is retrieved and selected, and second, the source analogy is mapped to the target, or problem of interest, whereby inferences are generated about the target (Holyoak and Thagard 1996). At the Biomimetics for Innovation and Design Laboratory at the University of Toronto (BIDLab), we have studied in detail both the retrieval and mapping processes involved in biomimetic design.

Chiu and Shu (2007a) developed a systematic retrieval method for biologically meaningful keywords, which are words that are well suited to search natural-language text for biological information relevant to design problems. This method was then adapted and refined to translate the function sets of the Functional Basis into a set of biologically meaningful keywords (Cheong et al. 2008).

We have also studied challenges in using analogies from biological knowledge in natural-language format, particularly the extraction of strategies used in biological phenomena and applying these strategies to design problems (Mak and Shu 2004a, Mak and Shu 2004b). We will present in more detail our previous work in the Background section.

In the research reported in this paper, we aim to observe the effectiveness of source analogies retrieved and identify challenges in using the given analogies. We approached this by studying how novice designers use biological descriptions that are retrieved with engineering functional keywords versus biologically meaningful keywords to solve design problems.

2. NOMENCLATURE

Action word: verb that conveys action vs. forms of to be/have.

Active voice: when a sentence is written in the active voice, the subject performs the action expressed by the verb.

Analogical reasoning: a cognitive process in which information from one subject or domain (source) is transferred to another subject or domain (target).

Biologically meaningful keyword: a keyword that is well suited for searching biological text to retrieve relevant information. Biologically meaningful keywords encompass what were defined in previous work as biologically significant, i.e., terms defined in biological dictionaries, and biologically connotative, i.e., terms not defined, but used the definition of other terms in biological dictionaries (Chiu and Shu 2007a).

Causal relation: when one action is related to another action by being caused by it; e.g., in a phrase "A chases B, and B flees," the verbs "chase" and "flee" are said to be in a causal relation.

Design fixation: refers to a blind, and sometimes counterproductive, adherence to a limited set of ideas in the design process (Jansson and Smith 1991).

Engineering functional keyword: a keyword that is directly derived from the engineering problem and represents a specific function to be achieved by the solution.

Keywords: character strings used to search for text documents or passages that contain instances of these strings.

Mapping: making an analogical connection between two similar characteristics of the source and the target.

Passive voice: when a sentence is written in the passive voice, the subject receives the action expressed by the verb.

Relational mapping: a mapping based on similarity between a pair of objects in each domain; e.g., if A is larger than B and Y is also larger than Z, there is similarity of relationships of one object being larger than another in both cases.

Similarity: a degree of symmetry in analogy between two or more concepts or objects.

3. BACKGROUND

In this section, we first discuss in general how analogy works and how it can be used most effectively in design. We then turn our attention to biomimetic design, including BIDLab's findings in past work and case study applications.

3.1 Analogical Reasoning and Creativity

Analogy is a central component of human cognition in which information from a subject in the source domain is mapped, or transferred to another subject in the target domain (Gentner et al. 2001). More easily recognizable relationships between corresponding subjects in two domains lead to easier identification of analogies. While more obviously recognizable relationships may lead to the choice of one potential analogy over another, it can also prevent new inferences from being made, thereby hindering creativity (Holyoak & Thagard 1996).

Many researchers agree that in analogical reasoning, cross-domain or interdomain sources inspire designers more than same-domain or intradomain sources (Hon & Zeiner 2004, Benami & Jin 2002, Tseng et al. 2008). Holyoak and Thagard (1996) note that analogical reasoning between interdomain sources involves "relational mapping", which in engineering design is related to finding functional similarities between the source and target domains. When drawing analogies from interdomain sources, designers may not find any similarities at the perceptual level, e.g., surface similarities, but may be forced to compare deeper, functional similarities, possibly leading to more creative solutions.

In creative design, a designer may initially know neither the structure of the design space nor the design plans to explore that space (Brown 1996). This characterization suggests that knowledge required for creative solution is typically not easily recognized by designers; therefore, introduction of design stimuli, or new knowledge sources, can inspire creativity.

We believe that biological analogies in particular can help engineers greatly since it requires cross-domain analogical transfer. Also, biological phenomena may represent new knowledge to engineers.

3.2 Related Work in Biomimetic Design

Efforts have been made to develop systematic methods to achieve creative design using biological analogies. Vattam et al. (2008) developed a conceptual framework of compound analogical design to support bio-inspired design. Wilson and Rosen (2007) performed reverse engineering of biological systems in order to help designers systematically extract biological strategies. Tinsley et al. (2007) conducted functional modeling of several natural systems towards creating a biomimetic function-based repository. The repository aims to help engineers transfer the principles of a relevant natural system to an engineering system. This approach is however limited by the number of natural systems that is modeled and entered into the repository.

3.3 Previous Work at University of Toronto BIDLab

Our past work focused on both retrieving appropriate biological analogies and using these analogies effectively.

3.3.1 Biological Analogy Retrieval

We took the approach of providing engineers with search keywords that will enable them to explore the enormous amount of biological knowledge already available in natural-language format. Vakili and Shu (2001) generalized the method of using engineering functional keywords to locate relevant biological phenomena. One obstacle identified was that differences in lexicons between the biological and engineering domains hinder information retrieval.

Chiu and Shu (2007a) hence developed a systematic method that uses natural-language analysis to facilitate cross-domain information retrieval. Essentially, the method can generate biologically meaningful keywords corresponding to engineering functional keywords that are relevant to design problems. We found these biologically meaningful keywords more suitable for searching biological sources, as they are able to retrieve biological analogies that cannot be found by searching for engineering keywords alone.

Cheong et al. (2008) generated a set of biologically meaningful keywords for the terms of the Functional Basis, which is widely accepted as a standardized representation of the functionality of engineering products (Stone and Wood 2000). Hence, once engineers model a design problem using the terms of the Functional Basis, the corresponding biologically meaningful keywords can be used to identify relevant biological phenomena specific to the problem. In general, many of these biologically meaningful keywords are entailed with engineering functional keywords such that biologically meaningful keywords allow or enable the action of engineering functional keywords. An example of this from Purves et al. (2001) is as follows:

"Humans obtain amino acids by <u>**breaking down**</u> proteins from food and <u>*absorbing*</u> the resulting amino acids."

In this excerpt, the function of "breaking down" (biologically meaningful keyword in bold underline) proteins enables "absorbing" (engineering functional keyword in italic underline) amino acids.

3.3.2 Analogical Reasoning with Biological Information

Mak and Shu (2004a) identified four different types of similarity relationships between biological source and engineering target domains: literal implementation, biological transfer, analogy, and anomaly. When biological descriptions contain behaviors (e.g., descriptions of what is happening, who is carrying out the actions, and how they are being carried out) and principles (e.g., the reasons behind why a particular phenomenon works in nature), the resulting concepts would more likely be created using analogy rather than the other three, less desirable, similarity relationships.

Mak and Shu (2004b) also studied challenges in recognition and extraction of relevant strategies in biological phenomena and the application of these strategies to the target problem. They identified two types of fixation that frequently occurred in drawing analogies from biological descriptions. Participants tended to fixate on certain words instead of the overall strategy presented in descriptions. Participants also fixate on certain solutions regardless of the different stimuli presented. These types of fixations could be reduced by asking participants to explicitly identify the subject, verb, and object in both the biological description and the problem space. Such activity guides participants to create correct one-to-one mappings between source and target domains.

3.3.3 Past Case Studies

Successful applications include the development of a snap fit feature with predetermined break points for easy refurbishment (Hacco and Shu 2002) and using a sacrificial part for better manipulation of micro objects (Shu et al. 2006).

4. METHODS

The focus of the current work is to study the effectiveness of biologically meaningful keywords versus functional keywords in retrieving biological descriptions that can lead designers to form analogical solutions. Specifically, we aim to compare how successful participants were in drawing correct analogies from different biological descriptions retrieved using engineering functional keywords alone, biologically meaningful keywords alone, and the combination of the two.

4.1 Participants and Rater

Forty-one fourth year engineering students in a mechanical design course at the University of Toronto were asked to solve three design problems using a set of biological phenomena in a single one-hour session. Results from four students were discarded due to incomplete/improper solutions, reducing the number of samples to thirty-seven. Participants were given twenty minutes for each problem.

We instructed participants in advance on how to properly form analogies using correct mapping techniques between the source and target domains. Only written data were collected, which include any notes or sketches participants made during the experiment.

One independent rater was recruited to examine whether the resulting concepts followed the expected analogy for each problem. The rater was in the last year of an engineering Ph.D. research program involving design theory and methodology. The rater was given instructions and examples of correct and incorrect analogies for each problem prior to concept rating. The rater was not paid.

4.2 Experimental Setup

Participants were randomly divided into three groups, each group receiving the same three design problems but a different set of biological descriptions. For each problem, a pair of biological descriptions was given. The order of descriptions was randomized for each participant to reduce priming effects.

Group A was given a pair of biological descriptions retrieved using only the engineering functional keywords related to the design problem.

Group B was given a pair of biological descriptions retrieved using both engineering functional 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 the biologically meaningful keywords.

Our initial hypothesis was that Group B would be more likely to generate concepts using the expected analogy presented in the descriptions. As mentioned earlier, descriptions containing both the biologically meaningful keyword and engineering functional keyword would likely include certain causal relations, in which the former action enables or allows the latter action. We believe that such descriptions would increase participants' forming correct analogies, as they are more likely to recognize similar causal relationships between the source and target domains (Read 1983).

4.3 Experiment Material

The design problems along with different sets of biological descriptions are presented in Table 1. All the descriptions were retrieved using our biomimetic search tool from the corpus, *Life*, the Science of Biology, by Purves et al. (2001), a text for an introductory university-level biology course. None of the keywords were highlighted in the descriptions that participants received, nor were the participants told in which experimental group they belonged.

5. OBSERVATIONS

In general, it was difficult to conclude that one group generated better concepts than another. Table 1 shows the percentage of correct analogies formed by participants for each stimulus for all three problems. We observed that a causal relation could still be present in a biological description even if it did not contain both the biologically meaningful keyword and engineering functional keyword.

5.1 Recognition of Causal Relations in Stimuli

Overall, we observed that it was less the presence of biologically meaningful or engineering functional keywords in descriptions that played a factor in participants drawing correct analogies, but more the presence of causal relations which could be easily recognized that had a greater effect. Although some descriptions for Group A (retrieved with functional keywords alone) did not include biologically meaningful keywords that entailed functional keywords, they might still have other action verbs that enabled the functional keywords. Similarly for descriptions for Group C (retrieved with biologically meaningful keywords alone), there could be another action verb that created a causal relation pair with the biologically meaningful keyword. Figure 1 shows the causal relations typically found in the different stimulus types.

Group A: Phenomena retrieved with functional keywords alone

Group B: Phenomena retrieved with both functional and biologically meaningful keywords

Group C: Phenomena retrieved with biologically meaningful keywords alone

Fig. 1: Typical causal relations found in descriptions of biological phenomena for each participant group.

One can also observe from Table 1 a potential relationship between the complexity of descriptions of biological phenomena and the resulting rate of successful analogical solutions formed. In general, the more complex the descriptions were, i.e., the more difficult it was for participants to recognize a causal relation, the less successful the participants were in forming a correct analogical solution. Figure 2 shows the percentage of correct analogical solutions formed as a function of the number of action words present in the description stimulus, and suggests this inverse relationship.

We initially found the correlation coefficient for this relationship to be insignificant, $r = -.20$, p (one-tailed) $= .21 > .05$. However, the scatter plot of Figure 2 indicates there is a single case that could be considered an outlier. When we removed this case, we found that the correlation to be significant, $r = -.52$, p (one-tailed) $< .05$. Residual statistics for this case revealed a standardized residual of -2.59 and Cook's distance of .77. Although these values do not exceed the conventional guidelines (standardized residual > 3 or Cook's distance > 1) to ignore the associated case, they are close (Field 2005). We believe in hindsight that this case, the second description given to Group A for Problem 2, was not a good source to begin with in providing analogical concepts that are relevant to the design problem.

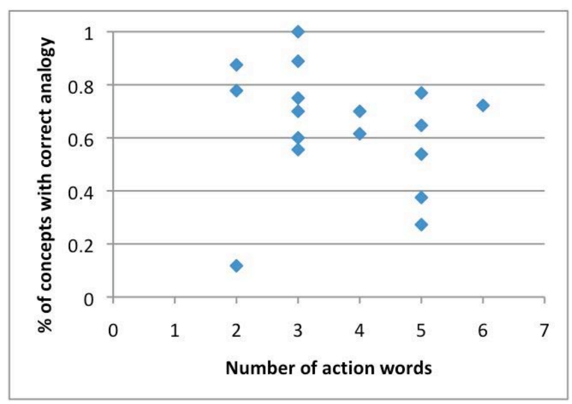

Figure 2: Percent of concepts w/correct analogy used vs. number of action words present in the stimulus.

Table 1: Problems and Associated Stimuli: Retrieval, Usage, Expression Characteristics

Group A: Phenomena retrieved with functional keywords alone

Group B: Phenomena retrieved with both functional and biologically meaningful keywords

Group C: Phenomena retrieved with biologically meaningful keywords alone

Problem 1	One system used for curbside recycling is "mixed wasted collection," where recyclates are collected mixed and the different materials are then separated at a sorting facility. Metals can be separated by exploiting its different density and/or reaction to magnetic fields. This is not the case with separating paper and plastic, which is usually done by hand. Develop concepts that will enable separation of paper and plastic from mixed recyclates.			
Stimulus Given:		**% of correct analogy used**	**# of action words**	**Grammatical voice of keywords**
Group A	"Bivalves (shellfish) feed by <u>bringing</u> water in through an opening and <u>removing</u> food from the water using their large gills, which are also the main sites of gas exchange. Water exits through another opening."	**65%**	**5**	**Active**
Group A	"Pathogens that reach the digestive tract (stomach, small intestine, and large intestine) are met by other defenses. The large intestine harbors many bacteria, which multiply freely; however, these are usually <u>removed</u> quickly with the feces."	**54%**	**5**	**Passive**
Group B	"Some halophytes (a type of plant) have other adaptations to life in saline environments. For example, some have salt glands in their leaves. These glands excrete salt, which <u>collects</u> on the leaf surface until it is <u>removed</u> by rain or wind."	**60%**	**3**	**Passive**
Group B	"Mucus in the nose and respiratory tract <u>traps</u> airborne microorganisms. Mucus and trapped pathogens are <u>removed</u> 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."	**38%**	**5**	**Passive**
Group C	"Bacteria <u>trap</u> nitrogen from the atmosphere by a chemical process called nitrification. They then <u>convert</u> it to amino acids and consequently to proteins through a series of biochemical reactions."	**78%**	**2**	**Active**
Group C	"A pitcher plant (a type of carnivorous plant) produces pitcher-shaped leaves that can attract and <u>trap</u> insects that fall into its pitchers. Insects eventually die and are <u>digested</u> by enzymes."	**28%**	**5**	**Passive**

Problem 2	As presented by the Canadian Space Agency, lunar regolith poses significant problems for space equipment such as a lydar (laser plus a telescope that serves as a radar). Regolith particles are very abrasive and tend to stick to each other. Protection is required for the joint that articulates the cover of the lens (e.g., hinge) and lens during and after opening, and closing of the lens cover. Develop concepts that effectively achieve the protection from lunar regolith.			
Stimulus Given:		**% of correct analogy used**	**# of action words**	**Grammatical voice of keywords**
Group A	"Plants have defense mechanisms that <u>protect</u> them against herbivores. One approach is to tolerate herbivores, by <u>diverting</u> the herbivore to eat non-essential parts of the plant."	**75%**	**3**	**Active**
Group A	"Parental care of eggs is widespread among amphibians. The female Indian python <u>protects</u> her eggs by <u>coiling</u> her body around them."	**12%**	**2**	**Active**
Group B	"Lysozyme is an enzyme that <u>protects</u> the animals that produce it by <u>destroying</u> invading bacteria."	**56%**	**3**	**Active**
Group B	"Clams have shells composed of protein strengthened by crystals of calcium carbonate. Shells <u>cover</u> their entire body and provide significant <u>protection</u> against predators."	**62%**	**4**	**Active**
Group C	"In the majority of plant cells, the plasma membrane is <u>covered</u> with a thick cell wall containing adhesion proteins that allow cells to <u>bind</u> to one another."	**56%**	**3**	**Passive**
Group C	"At high temperatures, enzyme molecules vibrate and twist so rapidly that their structure is eventually <u>destroyed,</u> causing enzymes to become <u>inactivated.</u>"	**70%**	**4**	**Passive**

Problem 3	In fall, cleaning fallen leaves can be a repetitive chore especially for large yards. Portable leaf collection systems (which function like vacuums) have been designed to make jobs faster and easier. However, replacing disposable collection bags can be non-economical, while the small size of permanent collection bag leads to frequent emptying. Also, grass clippings, flowers, and other material can clog the collection system. Develop new or improved concepts for leaf collection systems.			
Stimulus Given:		% of correct analogy used	# of action words	Grammatical voice of keywords
Group A	"In some cell types, microfilaments form a meshwork just inside the plasma membrane. For example, microfilaments support the tiny microvilli (protrusions) that line the intestine, giving it a larger surface area through which to absorb nutrients."	77%	5	Active
	"The liver interconverts fuel molecules and plays a central role in directing their traffic. When food is being absorbed from the gut, the liver takes up and converts carbohydrates to glycogen or fat."	72%	6	Active
Group B	"Fungi absorb food substances from their surroundings and break them down (digest them) within their cells. They are important as decomposers of the dead bodies of other organisms."	89%	3	Active
	"Humans obtain amino acids by breaking down proteins from food and absorbing the resulting amino acids. Another source of amino acids is the breakdown of existing body proteins."	70%	3	Active
Group C	"Breakdown of the ingested food exposes more food surface area to the action of pepsin (digestive enzyme) in the stomach and eventually other digestive enzymes in the small intestine."	88%	2	Active
	"Enzymes catalyze the chemical transformations in living systems as they break down simple sugars and other molecules in order to liberate energy."	100%	3	Active

% of correct analogy used \ # of action words	2 or 3	4, 5 or 6
0~40		
41~70		
71~100		

% of correct analogy used \ grammatical voice	Active	Passive
0~40		
41~70		
71~100		

Legends: Colored cells indicate the strength of expected relationship between % of concepts with correct analogy used versus 1) # of action words present and 2) grammatical voice of keywords.

Below are two examples of descriptions from Purves et al. (2001), which led to mid and high success rates of participants developing correct analogical solutions:

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

"**Breakdown** of the ingested food exposes more food surface area to the action of pepsin (digestive enzyme) in the stomach and eventually other digestive enzymes in the small intestine."

The first description, retrieved using both functional keyword (underlined italic) "protect" and biologically meaningful keyword (underlined bold) "destroy", contains the causal relation, lysozyme "destroying" invading bacteria in order to "protect." The second description, retrieved using only the biologically meaningful keyword (underlined bold) "breakdown" contains the causal relation of "breaking down" ingested food in order to "expose" more food surface area. Here, "expose" is neither an original functional nor biologically meaningful keyword used to locate the phenomenon. Since the above descriptions contained only three ("protect", "produce," and "destroy") and two ("breakdown" and "expose") action words respectively, participants should be able to recognize the causal relations.

On the other hand, when a stimulus description contains several action words, participants may have difficulty forming the correct causal relation. In addition, several action words could indicate the presence of multiple causal relations in the description, which could also hinder participants' ability to recognize causal relations relevant to the problem.

For Problem 1, participants were asked to develop new concepts for separating paper and plastic in mixed-waste recycling. One description stimulus given to participants, retrieved using only the biologically meaningful keyword, “trap” is as follows (Purves et al. 2001):

“A pitcher plant (a type of carnivorous plant) produces pitcher-shaped leaves that can attract and trap insects that fall into its pitchers. Insects eventually die and are digested by enzymes.”

We expected participants to form analogical solutions based on the causal relation of the plant “trapping” insects in order to “digest” them by enzymes. However, participants may focus on another causal relation present in the description, e.g., the pitcher plant “producing” pitcher-shaped leaves in order to “trap” insects. While the first relation could lead to our expected solution of disintegrating one of paper or plastic based on the function “digest” to separate paper from plastic, the second relation would lead to solutions using a particular sorting device as the focus is “producing” a certain object that can trap one material, separating it from the other.

We should address one important issue regarding our statistical analysis. We are treating data from each description, rather than data from each participant, as a single case. For each case then, the percentage value is therefore determined based on different sample sizes. For more accurate analysis in the future, we could rate each participant’s concept in numerical scales, rather than the categorical rating of “correct” or “incorrect.” This will allow us to conduct more rigorous statistical analysis, such as ANOVA. Here, our main objective was to demonstrate that there is a suspected trend of inverse relationship between the percentage of correct analogical solutions and the number of action words present in the description stimulus.

5.1.1 Transfer of Direction of Causal Relation

To confirm that participants are transferring causal relations when making analogies, we observed whether the same direction of causal relations are found in both the source phenomena and analogical solutions.

For Problem 3, the design challenge was to make an improved leaf collection system that does not require frequent emptying and prevents itself from clogging. All three sets of stimuli given to participant groups suggested converting or breaking down objects being absorbed. However, the sequence of two actions, e.g., “break down” and “absorb,” was different between Group A and Group B. The following are the different descriptions from Purves et al. (2001) given to the two groups and the corresponding sequence of actions for each description.

Group A: “When food is being <u>*absorb*</u>*ed* from the gut, the liver takes up and <u>convert</u>s carbohydrates to glycogen or fat.”

<u>Absorb -> Convert</u>

Group B: “Humans obtain amino acids by **<u>break</u>ing <u>down</u>** proteins from food and <u>*absorb*</u>ing the resulting amino acids.”

<u>Break down -> Absorb</u>

Our results suggest that the concepts generated reflect the specific sequence of actions given as stimulus for each group (Figure 3). All the concepts generated by Group A (9 concepts in total), which involved disintegrating leaves, involved collecting (or absorbing) fallen leaves first and then converting them into smaller pieces by various means. On the other hand, for Group B, 55% of the concepts (5 out of 9 total) involving disintegrating leaves converted or broke down the leaves into smaller pieces before absorbing or collecting them.

Figure 3: Group A – all 9 concepts involving disintegrating leaves had collection occur first; Group B – 5 out of 9 concepts disintegrating leaves had collection occur later.

The results suggest that the biological descriptions (source) and the solutions (target) in general followed a sequential similarity. In other words, participants were mostly able to recognize the specific causal relation between two actions present in the stimulus and correctly transferred the relation to the solution. Therefore, the direction of causal relation, i.e., the sequence of two actions, was the same in both the source and target domains in most cases.

5.2 Passive versus Active Use of Action Words

We found another possible factor that led to greater success of forming analogical solutions. Table 1 shows that biological descriptions that contained keywords in the active voice had participants develop analogical solutions more than the descriptions containing the keywords in the passive voice.

In Problem 2, the participants were asked to design a solution that can protect a space device from lunar dust that is both abrasive and adhesive. The following descriptions from Purves et al. (2001) were presented to Groups B (phenomena retrieved with both functional keyword indicated by italic underline, and biologically meaningful keyword indicated by bold underline) and C (phenomena retrieved using biologically meaningful keyword only):

“Lysozyme is an enzyme that <u>*protect*</u>s the animals that produce it by **<u>destroy</u>ing** invading bacteria.”

“At high temperatures, enzyme molecules vibrate and twist so rapidly that their structure is eventually **<u>destroy</u>ed**, causing enzymes to become <u>inactivat</u>ed.”

For both descriptions, we expected participants to develop concepts based on "destroying" lunar dust, i.e., by altering its structure so that its abrasive property is lost. We found that participants in Group B (7 out of 9, 78%) had a somewhat higher percentage of their concepts using this analogy compared to Group C (5 out of 10, 50%), as shown in Figure 4.

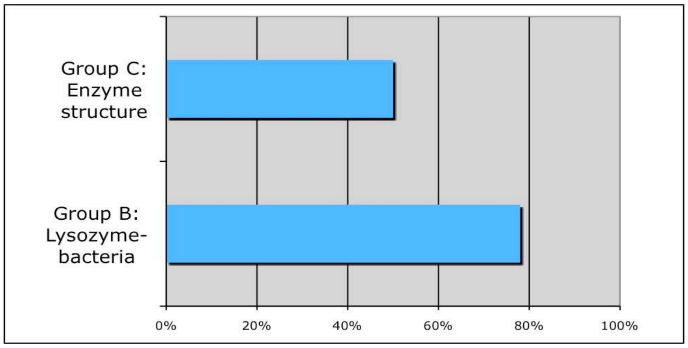

Figure 4: Percent of analogical concepts developed using "Enzyme structure" and "Lysozyme bacteria" descriptions for Problem 2.

In the description given for Group B, the keyword "destroy" is in the active form, i.e., "destroying", while in the description given for Group C, the same keyword "destroy" was in the passive form, i.e., "is destroyed."

Overall, for the three problems combined, participants were able to form correct analogies using descriptions with the key function verb in the active form 67% of the time, while for those in the passive form, the success rate was 46%. In fact, we found that there is a significant association between the grammatical form of keywords and whether or not analogical concepts were correct, $\chi^2(1) = 7.46$, $p < .01$.

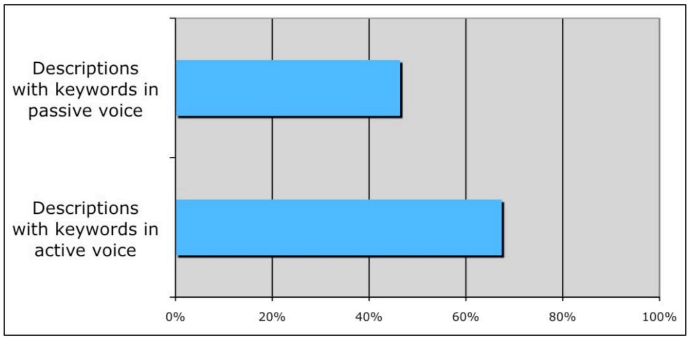

Figure 5: Percent concepts with correct analogies developed by participants from descriptions with keywords in active versus passive voice.

5.3 Fixation on Particular Words in Stimuli

Mak and Shu (2004b) had observed that participants tend to fixate on particular words in description stimuli, where such fixation shifted participants away from the expected analogies corresponding to the stimuli. Similar fixation occurred in our study again; however, this time we could observe this effect even when participants were able to draw the expected analogy.

For Problem 1, participants were asked to develop new concepts of separating paper and plastic in mixed-waste recycling. Some portions of stimuli given to each group are presented below. In all three groups, participants developed concepts of disintegrating one of paper or plastic first and then separating one from another, which was our expected solution.

Group A:
"Bivalves feed by bringing water…"
"Pathogens that reach the digestive tract…"

Group B:
"…until it is removed by rain or wind."
"Mucus in the nose and respiratory tract…"

Group C:
"Bacteria trap…by a chemical process called nitrification."
"Insects…are digested by enzymes."

We noted that although many participants used the idea of disintegrating one of the two materials, the variety of substances that was used for disintegration in their concepts differed for each group. Specifically, the majority of concepts in both Groups A and B, in fact all concepts in Group B, involved using water to disintegrate paper. However, this was not the case for Group C, where different substances such as water, chemical solution, heat and organisms were used. Figure 6 depicts these results.

We can speculate what led to these results by observing the stimulus provided for each group. In Group A's stimulus, the first biological description contained the word "water" and the second description contained the words "pathogens" and "bacteria". Figure 6 shows that in fact most concepts were based on water, with some incorporating living organisms. In Group B, words such as "rain" and "mucus" in the two biological descriptions caused participants to choose water as a means of disintegrating paper, perhaps because both materials are associated with water or water content. In Group C, the descriptions did not specify any aqueous solution, but included words such as "bacteria", "chemical process", and "digest." More varied means of disintegration were discussed in Group C concepts, including using heat and chemical solution.

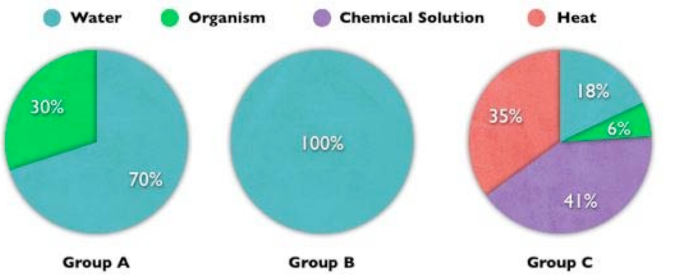

Figure 6: Percent of various substances used in concepts of disintegrating paper or plastic. Number of such concepts for each group: A = 10, B = 7, C =17.

Cognitive scientists have generalized that people tend to draw analogies by constructing mental models of source and target information, where the source information is retrieved from memory or by chance (Holyoak and Thagard 1996). In our experiment, participants noted specific words in descriptions, e.g., “water,” perhaps recalled instances of how paper deform upon absorbing water, and mapped such attributes to the solution space.

For participants in Group C, the words “chemical process” likely led them to recall the ideas of paper being burned, plastic being melted by heat, or using chemical solutions to deform paper or plastic. The Group C concepts involving water may have been evoked from the words “chemical process” as well.

We believe that such variety of concepts found in Group C agrees with other researchers’ results supporting that functional representations expressed in domain-general language tend to allow more creative solutions (Bonnardel 2000, Linsey et al. 2006). From the cognitive science perspective, if specific elements of analogy were represented in more general and abstract terms, a person would be better able to create analogical mapping of patterns of events rather than similarity of objects (Holyoak and Thagard 1996, Gentner et al. 2001).

6. RECOMMENDATIONS

Our results suggest that designers are more likely to apply correct analogies if they can recognize the causal relation present in the source analog. To guide this recognition process, we present a template that designers can use to rephrase various biological descriptions in a format that can aid in forming correct analogies. While this template would only work for descriptions that contain a causal relation, we believe such descriptions provide a better, i.e., function-based, analogy in the first place.

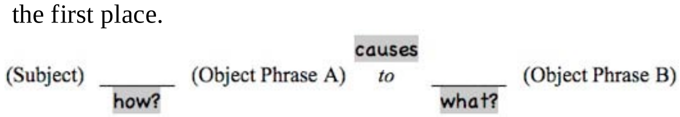

Figure 7: Template to rephrase causal relations found in biological descriptions. Verbs representing functions would be used to fill in underlined blanks.

This template can help designers identify which causal relation to transfer from the source analog to the solution space, forcing one to carefully consider which functions should be mapped and how functions are related. Designers must then express the action words, i.e., functions, in the active voice, which addresses the difficulty experienced with action words in the passive voice. The template also emphasizes recognition of the functional elements of the source analog, and therefore could limit participants’ tendency to fixate on certain objects.

One of the descriptions from Purves et al. (2001) that caused difficulties for some participants will be rephrased to illustrate use of the template:

“Bivalves (shellfish) feed by bringing water in through an opening and removing food from the water using their large gills, which are also the main sites of gas exchange. Water exits through another opening.”

There are a number of verbs or action words present in this description, along with numerous objects. Our template would help designers identify the most relevant functions and objects involved in a causal relation that would lead to the best analogy. Two causal relations could be retrieved from the description:

(Bivalves) **bring in** (water) to **remove** (food)

or

(Bivalves) **bring in** (water) to **exchange** (gas)

The above phrases isolate the two most significant functions and then only the relevant objects. Working now with this rephrased description based on the template, designers can focus on the most relevant functional elements and not on less relevant functions or objects, such as “opening”, “gills”, or “exits,” thus reducing the generation of non-analogous ideas.

We believe that the use of our template facilitates the analogical reasoning process because it systematically breaks up the process into two parts, identifying the casual relation in the source domain and later, applying the analogy in the target domain. While rephrasing biological information into this format may be more difficult for more complex descriptions, applying the correct analogy may be much easier once designers have recognized the significant causal relation using this template. In addition to facilitating designers’ extraction of strategies from natural-language descriptions themselves, such a template could also guide how such descriptions of biological phenomena can be stored and retrieved in a design repository. Appendix A includes all the descriptions used in this experiment rephrased using our template.

7. CONCLUSIONS AND FUTURE WORK

In this work, we were able to observe some interesting effects that occur when designers attempt to draw analogies from biological descriptions. First, the presence of causal relations in stimuli, i.e., one action enabling or causing another action, plays a dominating factor in designers using the correct analogy. In addition, designers may have trouble retrieving the correct analogy if descriptions are complex or written in the passive voice, such that a causal relation cannot be as easily recognized.

The significance of causal relations gives us another motivation for using our biologically meaningful keywords. If a biological source was searched with simply the functional keyword or words that are synonymous in engineering, it is likely that the matches found would only restate similar functionality found in biology. Our biologically meaningful keywords have the relationship with engineering functional keywords such that the former enables or causes the latter. Therefore, searching with biologically meaningful keywords may retrieve phenomena that serve as the preliminary action that causes the target functionality. Designers may not know in advance that the preliminary action is relevant to the desired functionality. The usefulness of identifying another function dissimilar, but related, to the original problem function was discussed in our previous research (Chiu & Shu 2007b, 2008).

To guide designers in recognizing causal relations present in biological descriptions, we constructed a template that encourages designers to focus on the relevant functional elements of the descriptions. In the future, we will examine how difficult it is for designers to use our template and whether designers can correctly transfer analogies from our template into solutions. Future experiments will also study whether designers who used our template could more easily form correct analogies compared to those who did not. In addition to facilitating designers' extraction of strategies from natural-language descriptions themselves, such a template could also guide how such descriptions of biological phenomena can be stored and retrieved in a design repository.

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ANNEX A: BIOLOGICAL DESCRIPTIONS (Purves et al. 2001) REPHRASED USING OUR TEMPLATE

"Bivalves (shellfish) feed by bringing water in through an opening and removing food from the water using their large gills, which are also the main sites of gas exchange. Water exits through another opening."

(Bivalves) <u>bring in</u> (water) to <u>remove</u> (food)
or
(Bivalves) <u>bring in</u> (water) to <u>exchange</u> (gas)

"Pathogens that reach the digestive tract (stomach, small intestine, and large intestine) are met by other defenses. The large intestine harbors many bacteria, which multiply freely; however, these are usually removed quickly with the feces."

(Large intestine) <u>removes</u> (feces) to <u>remove</u> (bacteria)

"Some halophytes (a type of plant) have other adaptations to life in saline environments. For example, some have salt glands in their leaves. These glands excrete salt, which collects on the leaf surface until it is removed by rain or wind."

(Halophytes) <u>collect</u> (salt on leaf surface) to <u>remove</u> (salt by rain)

"Mucus in the nose and respiratory tract traps airborne microorganisms. 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."

(Mucus) <u>trap</u> (airborne microorganisms) to <u>remove</u> (pathogens)
or
(Cilia) <u>beat</u> (themselves) to <u>remove</u> (mucus and trapped pathogens)

"Bacteria trap nitrogen from the atmosphere by a chemical process called nitrification. They then convert it to amino acids and consequently to proteins through a series of biochemical reactions."

(Bacteria) <u>trap</u> (nitrogen) to <u>convert</u> (it to amino acids)

"A pitcher plant (a type of carnivorous plant) produces pitcher-shaped leaves that can attract and trap insects that fall into its pitchers. Insects eventually die and are digested by enzymes.

(Pitcher plant) <u>traps</u> (insects) to <u>digest</u> (them by enzymes)
or
(Pitcher plant) <u>produces</u> (pitcher-shaped leaves) to <u>trap</u> (insects)

"Plants have defense mechanisms that protect them against herbivores. One approach is to tolerate herbivores, by diverting the herbivore to eat non-essential parts of the plant."

(Plants) <u>divert</u> (herbivores) to <u>protect</u> (plants themselves)

"Parental care of eggs is widespread among amphibians. The female Indian python protects her eggs by coiling her body around them."

(Python) <u>coils</u> (her body around eggs) to <u>protect</u> (eggs)

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

(Lysozyme) <u>destroys</u> (bacteria) to <u>protect</u> (animals)

"Clams have shells composed of protein strengthened by crystals of calcium carbonate. Shells cover their entire body and provide significant protection against predators."

(Clam shells) <u>cover</u> (clam's body) to <u>protect</u> (clams)
or
(Crystals of calcium carbonate) <u>strengthen</u> (protein) to <u>compose</u> (clam shells)

"In the majority of plant cells, the plasma membrane is covered with a thick cell wall containing adhesion proteins that allow cells to bind to one another."

(Thick cell wall containing adhesion proteins) <u>covers</u> (plasma membrane) to <u>allow binding</u> (to other cells)

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

(High temperatures/rapid vibration and twisting) <u>destroy</u> (enzyme structure) to <u>inactivate</u> (enzyme)

"In some cell types, microfilaments form a meshwork just inside the plasma membrane. For example, microfilaments support the tiny microvilli (protrusions) that line the intestine, giving it a larger surface area through which to absorb nutrients."

(Microfilaments) <u>give</u> (a large surface area) to <u>absorb</u> (nutrients)
or
(Microfilaments) <u>support</u> (protrusions) to <u>line</u> (the intestine)

"The liver interconverts fuel molecules and plays a central role in directing their traffic. When food is being absorbed from the gut, the liver takes up and converts carbohydrates to glycogen or fat."

(Liver) <u>takes up</u> (carbohydrates) to <u>convert to</u> (glycogen or fat)

"Fungi absorb food substances from their surroundings and break them down (digest them) within their cells. They are important as decomposers of the dead bodies of other organisms."

(Fungi) <u>absorb</u> (food substances) to <u>break down</u> (food)

"Humans obtain amino acids by breaking down proteins from food and absorbing the resulting amino acids. Another source of amino acids is the breakdown of existing body proteins."

(Humans) <u>break down</u> (proteins) to <u>absorb/obtain</u> (amino acids)

"Breakdown of the ingested food exposes more food surface area to the action of pepsin (digestive enzyme) in the stomach and eventually other digestive enzymes in the small intestine."

(??) <u>break down</u> (ingested food) to <u>expose</u> (more food surface area)

"Enzymes catalyze the chemical transformations in living systems as they break down simple sugars and other molecules in order to liberate energy."

(Enzymes) <u>break down</u> (simple sugars) to <u>liberate</u> (energy)