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REPRESENTING ANALOGIES: INCREASING THE PROBABILITY OF INNOVATION

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ABSTRACT

Design-by-analogy is well-recognized for its power in innovation processes. This paper presents experimental results showing the representation of a product in a person's memory influences the person's ability to later use the product for a design analogy. Representation has the potential to facilitate the design-by-analogy process both in human reasoning and for automated tools. We show specific experimental results and insights for three analogy problems: an air mattress analogy to a water-filled travel weights product, a football analogy to a bullet raft product and a whisk analogy to a flour sifter product.

KEYWORDS

Design-by-analogy, analogy, representation, idea generation, semantic representation

1. INTRODUCTION

The ability to invent, create and innovate is at the very core of engineering and product development. While this core ability is well recognized and acknowledged, significant research questions exist regarding the understanding of invention and creation as part of the design and product development process. During the product development process, invention and creation are usually most strongly associated with "conceptual design." The initial phases of design, which include conceptual design, have been shown to have the most significant impact on the cost of a product [1]. Only relying on a design teams' personal experiences during

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concept generation can result in the exclusion of a vast array of feasible concepts, especially ideas inspired by concepts that lie outside the stated problem domain.

Design-by-analogy, analogies to nature, analogous products and design reuse are noted methods for conceptual design [2,3,4,5]. Visual or functional similarity is found based in these methods. Figures 1-3 illustrate three innovative designs based on analogies, a fuel cell bipolar plate, a set of goggles designed to remove mud from dirt bike racer's field of view and a beach chair capable of rotating and.

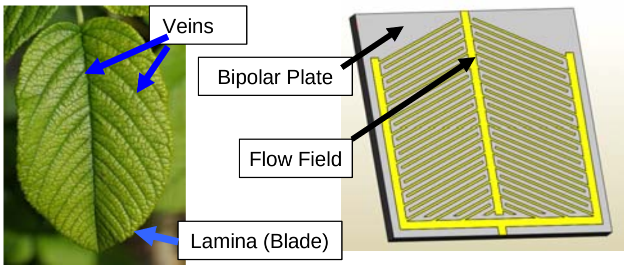

Figure 1: Fuel cell bipolar plate design generated from an analogy to a leaf.

The leaf provides a useful analogy for a bipolar plate of a fuel cell due to its similarity in functionality. The most significant functions affecting the current generation capability of a fuel cell bipolar plate is the 'distribute fluid: guide fluid: disperse fluid' function chain. One analogy that possesses a similar function chain is a plant leaf, where the veins and lamina perform the functions 'distribute fluid: guide fluid' and 'disperse fluid' respectively. In Figure 1, the bipolar plate flow field has been designed to mimic the structure of the leaf.

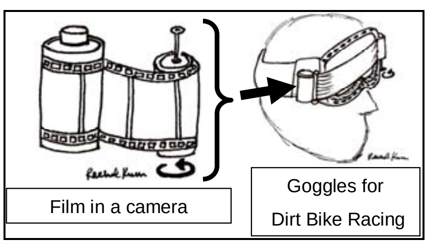

Figure 2: The spooling of film in camera provides a unique solution to removing mud from a dirt bike racer's goggles [6].

An innovate design of dirt bike racing goggles and a beach chair are also based on analogies. A problem for dirt bike racers is quickly and easily removing the mud from their racing goggles. One solution is to use a number of transparent layers on the outside of the goggles. These layers are torn off during the race to remove the mud and restore vision. A better solution is based on an analogy to the spooling of film (Figure 2). For a beach chair, an analogy to a computer monitor produces a unique easily rotating solution. The current method to turn most beach chairs requires the user to stand up and move the chair. The new solution allows the user to face various directions without requiring them to stand up (Figure 3) [6].

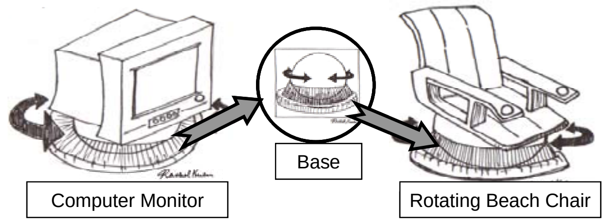

Figure 3: Solution allows a beach chair to rotate as the suns changes position, analogous to a monitor base [6].

As previously discussed, analogy is an important tool for conceptual design. A robust design-by-analogy method would enable designers to identify non-obvious analogous solutions even in cases where the mapping between concepts is tenuous and/or the concepts occupy different domains. This work takes a two prong approach to ultimately develop both new design-by-analogy methods that harness human abilities and an automated web-based analogy search tool to support the process (Figure 4).

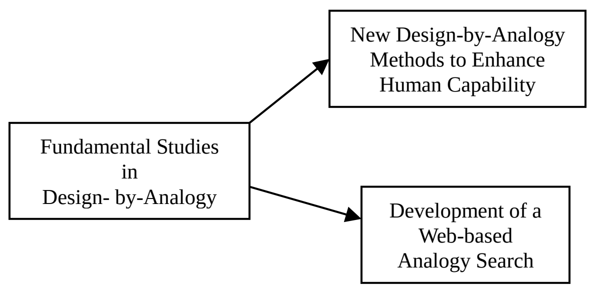

Figure 4: Two prong approach for increasing innovation through analogous design.

2. MOTIVATION AND PREVIOUS WORK

2.1 FORMAL DESIGN-BY-ANALOGY METHODS

A few formal methods have been developed to support design-by-analogy such as Synetics, Biomimetic concept generation and analogous design through the usage of the Function and Flow Basis. Synetics is a group idea generation method based on four types of analogy being used to solve problems: personal (be the problem), direct (functional or natural), symbolic and fantasy [7]. Synetics gives little guidance on finding successful analogies. Other methods also base analogies on the natural world. Biomimetic concept generation provides a systematic tool to index biological phenomena [8]. From the functional requirements of the problem, keywords are derived. The keywords are then referenced to an introductory college textbook and relevant entries can be further researched.

Analogous concepts can be identified by creating abstracted functional models of concepts and comparing the similarities between their functionality. Analogous and non-obvious products can be explored using the functional and flow bases [9]. A case study of a pick-up winder for a guitar is shown in Figure 5 [9]. A guitar pick-up is an electro-magnetic device with thousands of small-gauge wire windings used to transmit the sound from the strings. Obvious analogies for the pick-up winder include a fishing reel and a bobbin winder on a sewing machine. In addition to the obvious analogies, the abstracted functional model for the pickup winder identified the similarity to the vegetable peeler. The analogy to a vegetable peeler leads to an innovative design (prototype shown in Figure 5). Developing a systematic approach to search for and evaluating the utility of functionally similar concepts is critical to the successful implementation of design-by-analogy as is enhancing natural human capability.

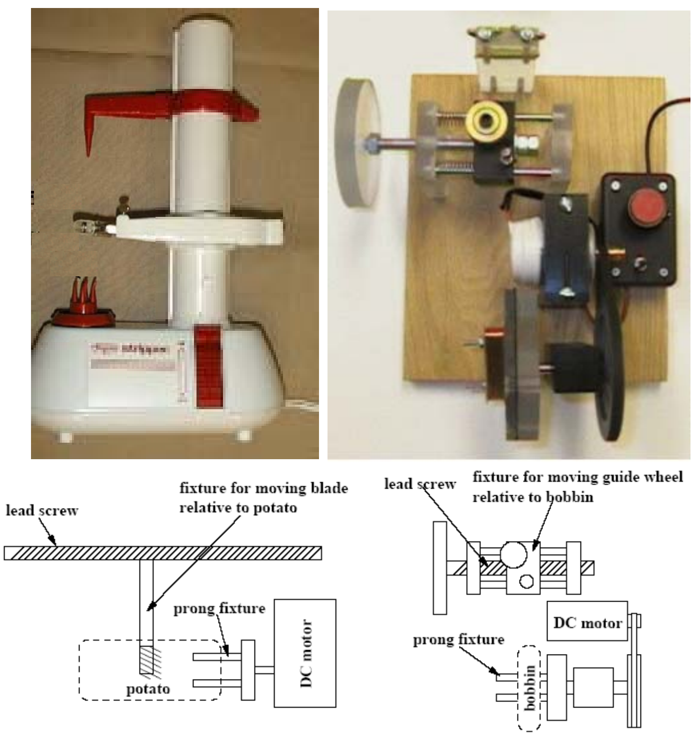

Figure 5: An innovative analogy discovered based on the function and flow basis.

2.2 COGNITIVE PROCESSES: DESIGN-BY-ANALOGY

Understanding the cognitive process involved in the formation of analogies is important for understanding the concept generation process. Analogy can be viewed as a mapping of knowledge from one situation to another enabled by a supporting system of relations or representations between situations [10,11,12]. This process of comparison fosters new inferences and promotes construing problems in new insightful ways. The potential for creative problem solving is most noticeable when the situation domains are very different [13].

A significant amount of work has been done in psychology to understand the cognitive processes people use for creating and understanding analogies [13,14,15,16,17]. Figure 6 shows the basic process steps involved in reasoning by analogy, the most cognitively challenging steps, and the design methods that are available to support each step.

The majority of prior work, with the notable exception of Dunbar [18], has not focused on the use of analogy in highly trained populations such as engineers. Little work has been carried out based on a strong psychological understanding of analogical reasoning combined with the design knowledge of analogies for good designs. This paper takes a distinctive interdisciplinary route to combine these threads of research to develop a more complete understanding of the use of analogy in engineering design and to provide the basis for formal method development.

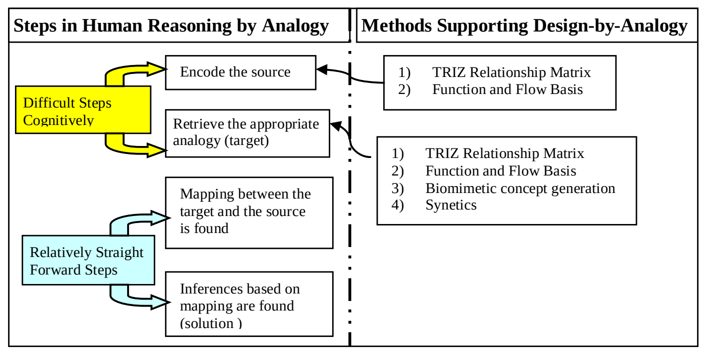

Figure 6: Steps in human reasoning by analogy and the current methods available to support those processes.

2.3 FUNCTIONAL REPRESENTATIONS

Designers use various external design representations for a wide range of functions, and it has been shown that specific representations are better suited for specific tasks e.g. sketching for solution development or complex models for verifying requirements [1]. For concept generation, design problems should be represented by a set of solution-neutral functions to minimize design fixation and enable the greatest number of concepts to be considered [3,5,19]. The process of developing a functional representation of a concept is called functional modeling and begins with an abstracted black box formulation of the overall product function. The black box model is then decomposed it into sub-functions connected by their associated input flows.

Decomposing the abstracted functional representation into aggregated function chains results in the creation of a repeatable function structure representing the internal functionality of a concept [20,21]. In addition to the development of a decompositional methodology, extensive efforts have produced a standard language for representing the function and flows associated with each sub-function called the Functional Basis [22,23]. The Functional Basis consists of a set of function and flow terms used as a verb-object couple to describe the action imparted on the input flows of each sub-function and is sufficiently abstracted to cover the entire function and flow space. This basis forms a standard vocabulary for describing a design concept and enables concepts or products to be directly compared.

An extended method for representing functional models is a hierarchical semantic functional representation [24]. This text-based representation would greatly increase the amount of accessible design information. Semantic representations enable direct searching of patent archives [25], websites and text-based databases. Several tools have been developed to perform data retrieval and information interpretation using semantic representation [26]. Previous work on enhancing information retrieval in large medical databases utilized a meta-thesaurus of medical terms to generate a large number of related search terms based on simple semantic phrases, ensuring a greater portion of the database information is queried [27,28,29].

2.4 SYSTEMATIC WEB-BASED ANALOGY SEARCH

As a motivation for fundamental studies in design-by-analogy, consider the following description of a search methodology. The systematic analogy search methodology under development is shown in Figure 7. The proposed methodology consists of generating a hierarchical semantic representation of the concept functional model. Then an engineering term thesaurus will be used to generate multiple related semantic queries over a broad range of problem domains. A web-based analogy search engine will then be used to identify similar concepts. The final step of the methodology is generating the concept similarity score for each analogous concept to determine the level of relevance.

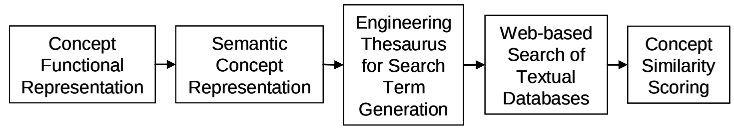

Figure 7: Schematic of web-based analogy search method using semantic functional representations.

2.5 SEMANTIC CONCEPTUAL REPRESENTATIONS

The hierarchical semantic representation consists of text-based descriptions of the concepts' functionality at three levels of abstraction: System level, Module level and Sub-function level. Using the Functional Basis, the semantic representations can be extracted from the function structure at each level of abstraction. The hierarchical function structures of a Black and Decker Firestorm jigsaw is given in Figure 8 where the modules were derived using the modularity heuristics of Stone and Wood are identified [30].

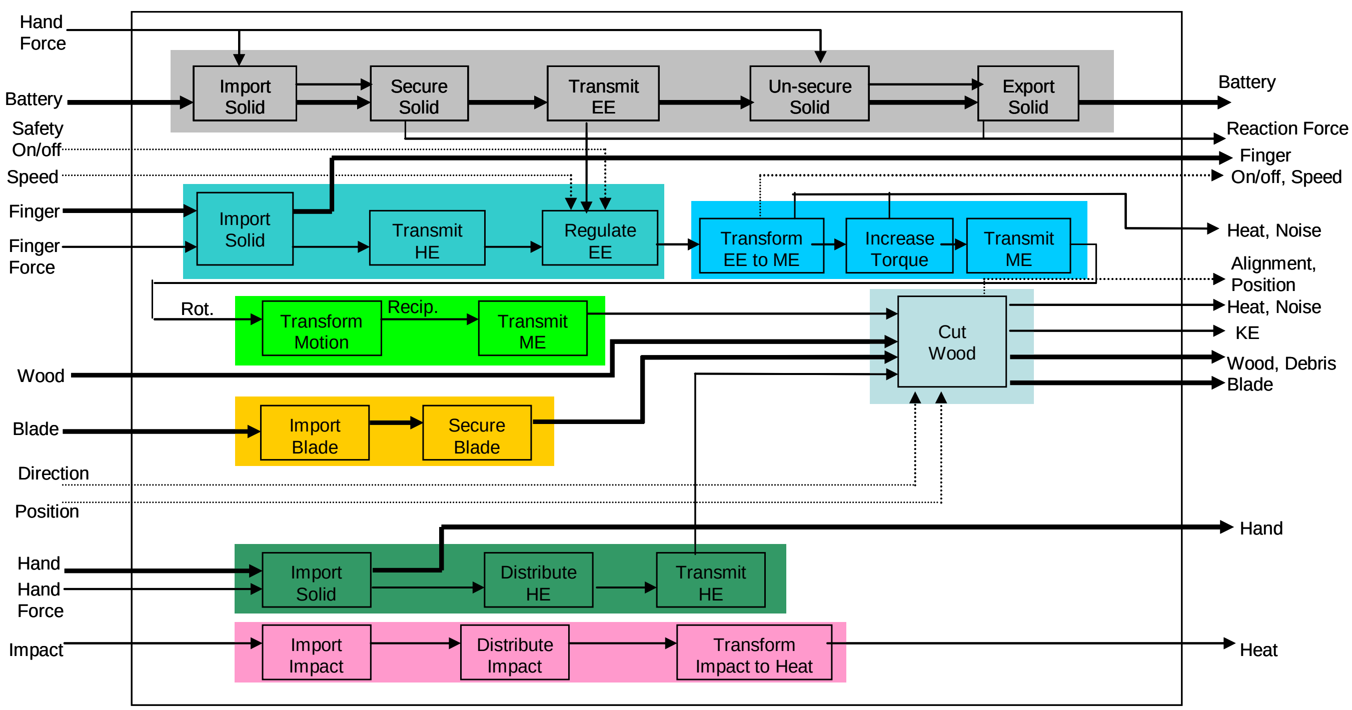

Figure 8: Hierarchical function structure of a Black and Decker Firestorm jigsaw.

Representing the function structures semantically results in the following semantic phrases:

- System Level Representation: '*Cut Wood*'
- Module Level Representation: '*Supply EE*: *Regulate EE*: *Transform EE*: *Transform ME*: *Secure Blade*: *Transmit HE*: *Distribute Impact*: *Cut Wood*'
- Sub-function Level Representation: '*Import Solid*: *Secure Solid*: *Transmit EE*: *Release Solid*: *Transmit HE*: *Regulate EE*: *Transform EE*: *Regulate ME*: *Transmit ME*: *Transform ME*: *Distribute HE*: *Transmit HE*: *Import Force*: *Distribute Force*: *Transform Force*'

During the transformation, redundant function-flow couples were eliminated to simplify the representation and because identical couples will result in identical analogies. The next phase in the method is to use an engineering thesaurus to generate multiple search queries.

2.6 ENGINEERING FUNCTION-FLOW CONTEXTUAL THESAURUS

The Engineering Function-Flow Contextual Thesaurus (EFFCT) is an extension of the functional basis and flow basis representations that includes less abstracted extensions of those basis representations. EFFCT generates contextually-related semantic phrases for the purpose of search query expansion. The process of query expansion using EFFCT is shown in Figure 9.

Beginning with the initial function-flow couple, the couple is first transformed into the primary functional basis level. Then permutations are generated at each of the less abstracted levels of the functional basis. Finally, a synonym generation algorithm is applied to the function-flow couple to generate semantic phrases compatible with web-based search engines.

2.7 WEB-BASED ANALOGY SEARCH TOOL

Once the search query terms have been generated using the EFFCT tool, a web search engine will be used to search for the resulting terms. Several algorithms have been developed for searching web-based information sources and the most well known is the commercial Google search engine [31,32]. The original web browsers used simple text search algorithms to generate search results, but the Google search engine uses a variety of factors such as the number of links to the page and source of the links to determine the relevance of a web page hit. Other web-based information retrieval algorithms such as F-logic take the structure of the web into consideration when searching for information [33]. In F-logic and WebSQL, hierarchical semantic searching is utilized to facilitate retrieval of relevant on formation from the semi-structured environment of the web.

Initially, lab-scale analogy search trials will be conducted using commercial search engines such as Google and the built-in USPTO patent search functions to evaluate the performance of the semantic representations and query generation. Full scale analogy searches may require more sophisticated software, such as F-logic or WebSQL discussed previously, that can track the number and frequency of matching function-flow descriptions. This information is necessary as a precursor to determining the level of analogy present between the concepts.

2.8 CONCEPT SIMILARITY SCORE (CSS)

A key to finding good results from a web-based search tool is in accurately measuring how similar two concepts are. Previous metrics for determining the level of similarity between a concept and the analogous product or structure on functionality have been developed [9]. This work seeks to expand on the previous metric to establish a normalized threshold for determining when two concepts are truly analogous. We propose that the CSS will be a function of the number of matched function-flow couples and inferential distance of the matched couples. The inferential distance is a measure of how closely two terms are related conceptually and methods for determining the inferential distance between semantic representations have been developed for other applications [34,35].

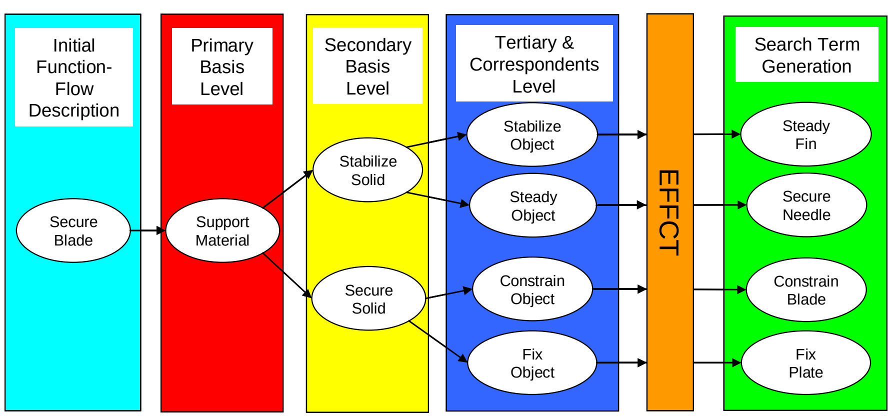

Figure 9: Example of search term generation using the Engineering Function-Flow Contextual Thesaurus.

2.9 PRIOR ANALOGY IN DESIGN EXPERIMENTS

The web-based analogy search tool and new human-based design methods require a deep understanding of the processes people use and the areas where guidance or assistance could improve the process. This knowledge is gained largely through experimental work. Even though design-by-analogy is a well-recognized method for design, not many human experiments exist focusing on analogy in design. Casakin and Goldschmidt found that visual analogies can improve design problem solving by both novice and expert architects [36]. Visual analogy had a greater impact for novices as compared to experts. Ball, Ormerod, and Morley investigated the spontaneous use of analogy with engineers [37]. They found experts use significantly more analogies than novices do. The type of analogies used by experts was significantly different from the type used by novices. Novices tended to use more case-driven analogies (analogies where a specific concrete example was used to develop a new solution) rather than schema-driven analogies (more general design solution derived from a number of examples). This difference can be explained because novices have more difficulty retrieving relevant information when needed and have more difficulty mapping concepts from different domains due to a lack of experience [38].

A structured design-by-analogy methodology and search tool would be useful for minimizing the effects of the experiential gap between novices and experts. The cognitive analogical process is based on the representation and processing of information, and therefore can be implemented systematically given appropriate conceptual representations and information processing tools [39,40].

Prior research in analogical reasoning found the encoded representation of a source analogy can ease retrieval if it is remembered such that the key relationships apply in both the source and target problem domains [41,42]. The analogies and problems used in these experiments were not specific to any domain of expertise and used fantasy problems relying on strictly verbal descriptions. The use of various representations, including visual and semantic, warrants further understanding for use in design. The following experiments will further investigate visual and semantic representation effects on design-by-analogy and lead to a deeper understanding of how to enhance the design-by-analogy process.

3. EXPERIMENTAL METHOD

To further explore the effects of representation on analogy use for real-world problems and to further understand where automated search tools will be of greatest use, two experiments were implemented. The first experiment provided initial evidence for the effect of different representations and the second experiment used a larger sample to further understand a representation's effects. Both experiments used a combination of visual and semantic information to represent the source design analogy.

3.1 PILOT EXPERIMENT

The first experiment served to provide evidence that the phenomena observed by Clement, et al. [41,42] occurs for real-world problems and further information about the effects of representation in the design process. The experiment consisted of three tasks: *Studying the Source Product Analogies, a Distracter Activity (Evaluate a Set of Concepts) and Solve the Design Problems*. Participants were told the experiment evaluated various skills used in the design process. Participants were graduate students in the area of mechanical design with previous instruction and experience in concept generation methods. This group was selected because they were likely to have more experience and higher success rates in design-by-analogy, thus the effects of representation were more likely to be observable. Two groups of participants were compared, a *"Domain Specific Description"* Group (n=5) and a *"General Description"* Group (n=6). A sample size of eleven (11) total participants provided a foundation for evaluating the experiment design and evaluation process.

3.2 PROCEDURE

In the first task, *Study the Source Product Analogies*, participants were given five short functional descriptions of products along with a picture (Figure 10) and asked to memorize the descriptions (see Appendix A). The General Description group also drew function structures for these devices (see reference 5 for details of function structure concepts). Participants were run individually and no time limit was given. Both groups were then required to write out the memorized descriptions and then evaluate their results. Three of the products acted as source analogies for the design problems in the last task, *Solve the Design Problems*, and two were distracter products that shared surface similarities with the design problems. The products were functionally described in a few short sentences either with a more general description that applied in both the source analogy and target problem domains, or with a domain-specific description. An example of the descriptions used for the air mattress is shown in Table 1 (see Appendix A for a complete list). The product descriptions and the design problems included a few pictures. The semantic descriptions of the devices were varied but the pictures were identical for both conditions. The focus of this experiment was on the verbal representations of the devices, but visual information was also present.

In the second task, the student participants were asked to evaluate a series of concepts from a prior activity. The purpose of this task was to require the participants to think about something else. Normally when faced with a design problem a useful analogous product has not been seen immediately beforehand, but the analogous product is stored in a person's long term memory. The decision was made to use a short break period rather than a more realistic time period, because this was a pilot experiment. The break task required about 15 minutes and was long enough for the students to not make a connection between the tasks.

In the last task, *Solve the Design Problems*, participants were given three design problems to solve in a series of the following five phases:

Phase 1: Open-ended design problems, few constraints
Phase 2: Highly constrained design problems
Phase 3: Identify analogies and try using analogies
Phase 4: Informed task 1 products are analogous
Phase 5: Correct source product is given

Phase 1 and 2 were completed for all three design problems followed by phases 3, 4 and 5. Throughout all phases participants were given the general idea generation guidelines to (1) generate as many solutions as possible with a high quality and large variety, and (2) to write down everything even if it did not meet the constraints of the problem including technically infeasible and radical ideas. Participants were also instructed to use words and, or sketches to describe their ideas. They were asked not to discuss the experiments with their classmates until after all the experiments were completed.

In phase 1, the problems were initially presented with few constraints. Participants were told to spend 10-15 minutes generating ideas and once finished were given the same problem with additional constraints. The additional constraints limited the design space thus increasing the chance the participants would try using the desired source analogy. The pilot study required only one solution to be found for the constrained problems and subsequent stages. One slight modification to the wording of problem 3, the flour duster, had to be made during the pilot study. Originally the problem was described as “spreading” flour over a surface but for one participant this description produced solutions that created a thick layer of flour rather than a thin sprinkle. The word was then changed to “dust” for three participants. This caused analogies to a feather duster to occur. Finally the problem was changed to “sprinkle”.

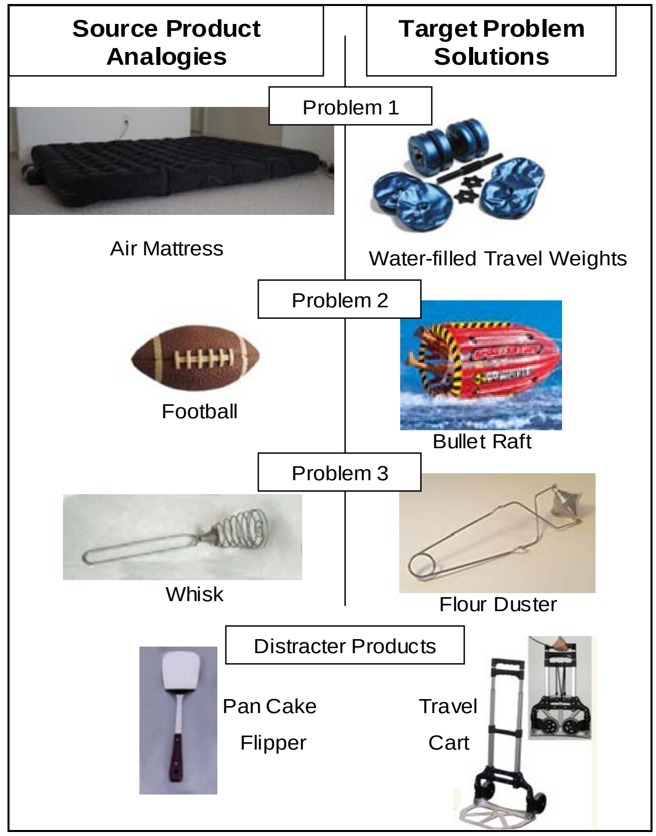

Figure 10: Source products analogies, corresponding target problem solution and the distracter products for the pilot and main experiments.

Table 1: General and domain specific descriptions for the functioning of an air mattress. The air mattress provided a source analogy for the design of travel exercise equipment.

Sentence / **General (G) or Domain (D) Specific**									
1	**G**	The	device	is filled with	a substance	at the location	where it will be	used.	
	D	The	air bed	is inflated with	air	in the home	where it will be	slept on.	
2	**G**	The	substance	required	to cause	the device	to function	is available	at the location
	D	The	air	required	to cause	the air bed	to inflate	is available	in the home
3	**G**	The primary purpose		of the device	is to	distribute the force	of the person	during	the task
	D	The primary purpose		air bed	is to	provide a comfortable	bed for the person	during	sleep.
4	**G**	The	device	accomplishes	this by	importing, storing	and	exporting the substance	
	D	This	allows	accomplishes	this by	using the air to inflate	and	to deflate	
5	**G**		This	allows	the device	to be easily	stored.		
	D		This	allows	the air bed	to be easily	put into a closet.		

In phase 3, participants were asked to list any analogies they had used and instructed to try to use analogies to find additional solutions. In phase 4, the participants were told products from the first task were analogous, to mark their solutions that used the analogy and to generate additional solutions using analogies. Finally, participants were given the correct analogy for each problem, asked to place a check where they had used it and to generate more ideas if they had not used the described analogy.

At each phase, participants used a different color of pen thus identifying the phase. A short survey at the end evaluated English language experience, work experience, if the participant had heard about the experiment ahead of time and prior exposure to the target problem solutions. The entire experiment required about two hours.

3.3 DESCRIPTION OF THE DESIGN PROBLEMS

The design problems (Figure 10) were developed by first finding innovative products that participants were unlikely to have seen and then developing analogies along with design problems likely to lead to those target problem solutions. A survey at the end of the experiment asked if the participants had been exposed to any of the design solutions prior to the experiment. Three problems and analogies were chosen with varying difficulties using a combination of visual and semantic information. The analogy between the whisk and the flour duster, problem 3, was expected to be the easiest since the design problem and the analogous product share the most similarities. Both devices are used in a kitchen, are made of the same material and are used to distribute forms of flour (batter or dry flour). Problem 1 was expected to be the most difficult since it asked for an exercise device capable of being easily carried in a suitcase. Initially an air mattress appears to have little in common with this problem. The key relationship that is used in both devices is they "import a fluid (or another substance) at the location where they are being used and export the fluid allowing for easy storage". The key relationship between the raft and the football was the exterior shape allows both devices to easily rotate as they move through a fluid. Clearly a bullet is a better analogy for the raft but a football was chosen to see which features participants would chose to map and which ones they would modify.

Two other products were chosen to act as distracter products, thus making it more difficult to find the correct analogy even when told the products from the initial task are analogous. Participants tend to try using the pan cake flipper to try and solve problem 3 since the problem domain is the same, devices used in a kitchen. The air mattress also acted as a distracter product for problem 2, because items pulled behind a boat are frequently inflatable.

3.4 METRICS

Each analogy produces a set of solutions not a single solution (Figure 11). The main metric used for this experiment was when did the participants produce a correct solution to the constrained design problem based on the analogy and then identify the correct analogy. Clearly it is possible to reach a correct solution without basing it on the analogy. Most solutions for design problem 3 that were labeled with the correct analogy were counted as correct solution since the lack of detail and poor sketch quality for design problem 3 made it extremely difficult to judge if a solution was correct or not. For the main experiment, two evaluators rated the data independently, one of whom was blind to the conditions of the experiment. The pilot evaluation was completed by one of the authors who was not blind to the conditions. Initial agreement was about 80% and disagreements were readily resolved through discussion. The most common reason for different scores was the participant referenced a solution on a previous page and one of the raters missed the reference.

3.5 RESULTS & DISCUSSION

The pilot results show that representation does influence the design-by-analogy process. The pilot results show a trend of the more general description group resulting in a greater probability of using the analogy for design problems 2 and 3 (Figure 12 and Figure 13). About 80% of the participants in both groups remembered seeing the solution to design problem 1. Therefore the two groups used the analogy at similar rates, and it was not a valid test since most participants had seen the solution prior to the experiment.

The pilot experiment was set up to test whether a change in an analogous product's representation could affect how easily it could be used for finding a new solution. Therefore the two conditions were created to maximize the expected difference in results to verify whether a larger sample size experiment was justified. The experimental group, "General Description Group", was given both a more general verbal description and also told to draw function structures. This creates a confounded factor since it is not clear if the results are primarily due to the verbal descriptions or the functional structures, but this will be investigated later.

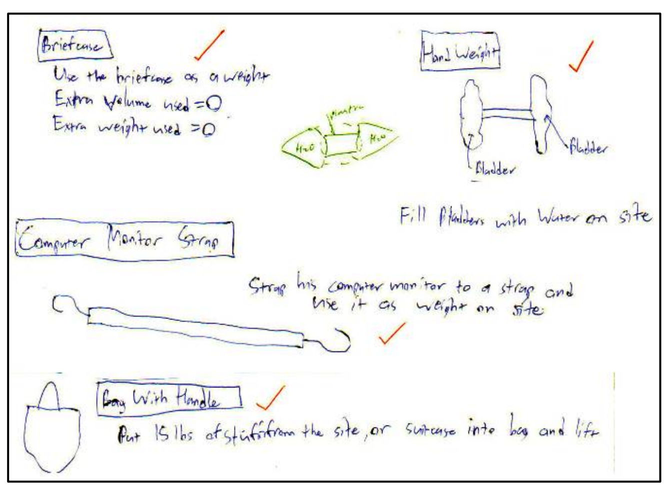

Figure 11: Example solutions for problem 1, based on the analogy to an air mattress.

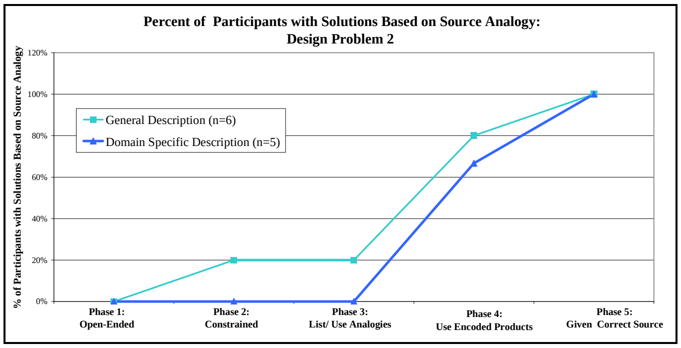

Figure 12: Pilot data shows a trend of the general product description increasing the probably of analogy.

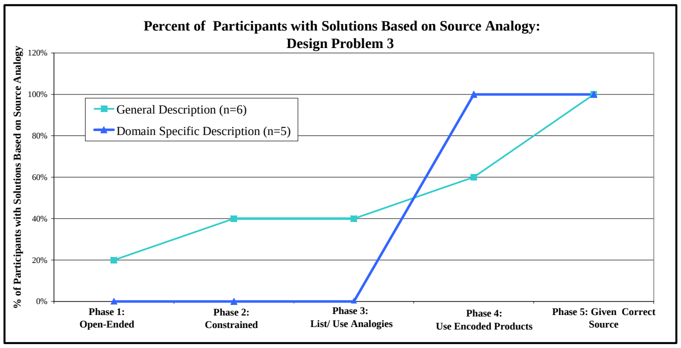

Figure 13: Pilot data shows a trend of the general product description increasing the probably of analogy.

4. MAIN EXPERIMENT METHOD

The pilot experiment showed initial evidence that the representation of a source product is likely to affect how easily the product can be used to find solutions to novel design problems. The sample size in the pilot experiment was too small to draw any definitive conclusions; therefore, a larger sample size was used in a follow-up experiment.

The main experiment used the same source analogies, target design problems and was identical to the pilot experiment with a few exceptions. The main experiment included two tasks: *Studying the Source Product Analogies and Solve the Design Problems* with a week in between for most participants. A week was chosen, because any analogies retrieved will clearly be taken from long-term memory. This time frame has been used in previous experiments [43]. Results from the first task were matched to the second task. Participants in the main experiment were senior mechanical engineers with instruction in design methodology including idea generation. Multiple solutions were encouraged for the constrained design problems and subsequent stages. The main experiment was also set-up so the students could be run in groups of up to 10 people, with each task and phase having set time periods. Time periods were chosen based on the pilot study to be longer than what was required for the average participate in the pilot study. In the first session, where participants were first exposed to the source analogies, participants were given 30 minutes to study the products, up to 15 minutes for the quiz and then about 10 minutes to check their answers. For the second task, where participants completed new design problems, participants were given 12 minutes for each of the six open-ended and constrained design problems. Next they had a 5 minute break followed by 15 minutes to write down any analogies they used and to generate more solutions based on analogy. Participants were then told the products they had seen in the previous week's task were analogous. They were given 10 minutes to write down any analogous products they had used from the previous week and generate more solutions. Finally, participants were told which products matched with each design problem and given up to 10 minutes to find a solution based on the analogy.

4.1 RESULTS AND DISCUSSION

Appropriate representations can improve the success rate in design-by-analogy. Representation of analogous problems stored in long-term memory affects the probability they will be used to solve an appropriate design problem in certain instances (Figures 14-16). Each figure shows the cumulative percentage of participants who found a valid solution to the constrained design problems and identified the appropriate analogy at each phase in the experiment. Results do not include participants who remembered seeing the expected solution prior to the experiment. The results for phase 4: Use products from task 1 to find analogies are statistically significant for design problems 1 and 2. Using a binomial probably distribution, the probability that the domain specific description group is from the same distribution as the general description group is almost zero [44].

For design problem 1 (Figure 14), a more general semantic representation of the source analogy allowed significantly more participants to find an analogous solution to a difficult design problem. This trend is less prominent for design problem 2 (Figure 15) and does not exist for the third design problem (Figure 16). Example results and artistic renditions of the results are shown in Figure 17.

A few hypotheses exist for the influence of semantic representation in design problem 1 but not in the other two. All three design analogies included the coexistence of visual information. The key features to be mapped in problems 2 and 3 were visual information, the shape of the football and the varying spacing of the wires in the whisk. The semantic representation may only influence the analogical reasoning process when the information that must be accessed and mapped is stored verbally instead of visually. This proposal is consistent with our observation that nearly all prior studies of analogical reasoning involve verbal materials (typically written stories) [41,42]. Visual and verbal information are two distinct types of knowledge stored in long-term memory [45]. In design problems 2 and 3, it was also much more difficult to evaluate the correctness of the solution and isolate the features that had been mapped. This would lead to more incorrect solutions being counted and erroneous results.

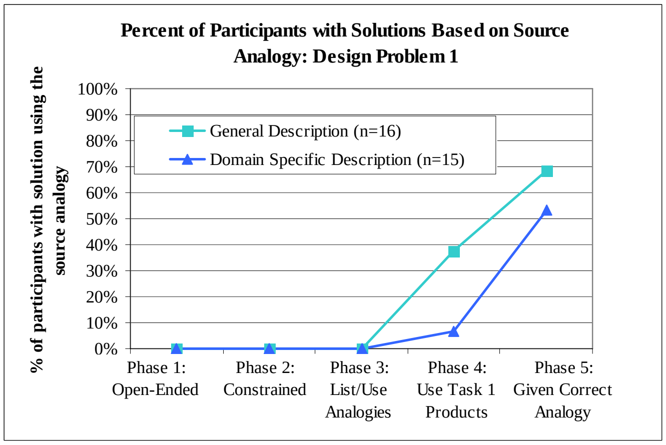

Figure 14: A more general description of the analogous product results in an analogous solution being found more often.

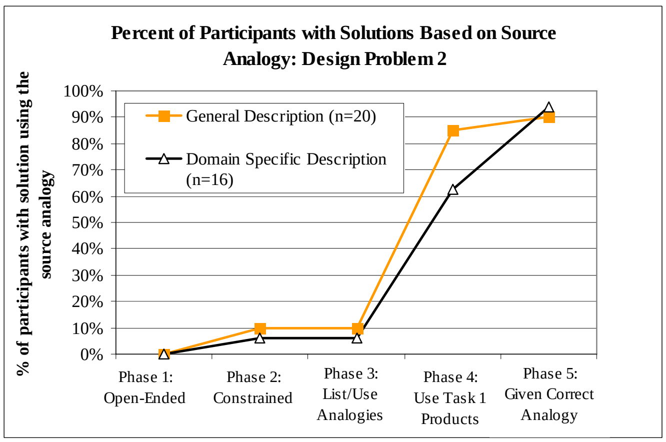

Figure 15: Percent of participants able to use the analogy to find a solution to design problem 2.

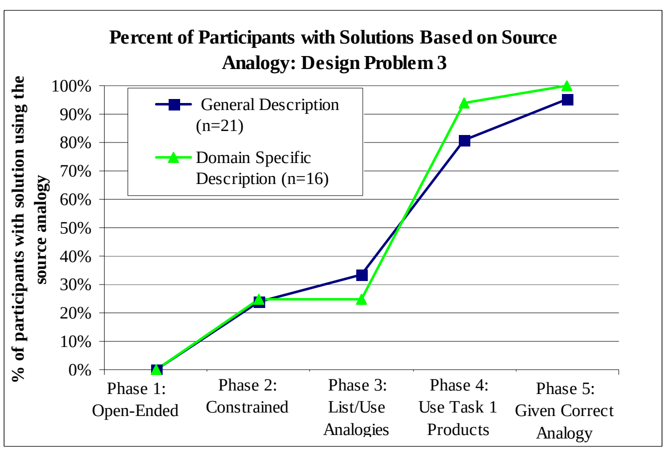

Figure 16: Percent of participants able to use the analogy to find a solution to design problem 3.

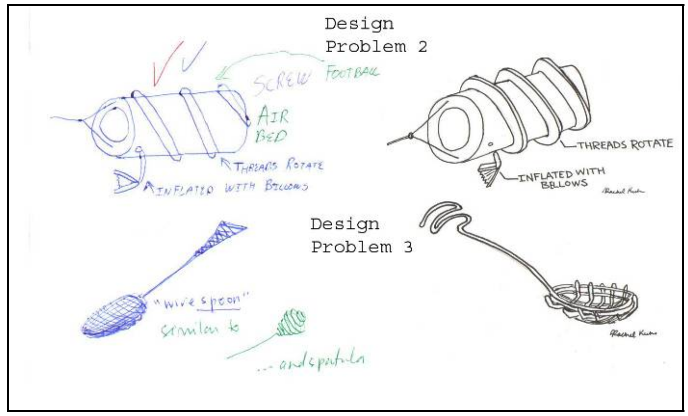

Figure 17: Two example solutions for the design problems (left) and for reference, clear artist renditions of the concept (right).

A third hypothesize relates to the difficulty of the three design problems. Design problem 1 is clearly more difficult than the other two problems (Figure 18). Design problem 3 was expected to be the easiest of the three problems since the whisk and the flour sifting design problem shared a number of similarities. Both are from the same domain and also share a number of surface similarities that are not important for making the analogy including both are kitchen devices, and are used to contain and distribute forms of flour.

Based on the upward trend of all three graphs, another insight from this data is when students are given a set of possible analogous products, they can recognized solutions they found that could have been based on the analogy, and they can also find new solutions based on the analogies. This result should not be minimized. It clearly shows that almost all participants can develop analogies from different types of information and directions provided to them. The act of designing by analogy is not exceptionally difficult nor only related to certain innate skills.

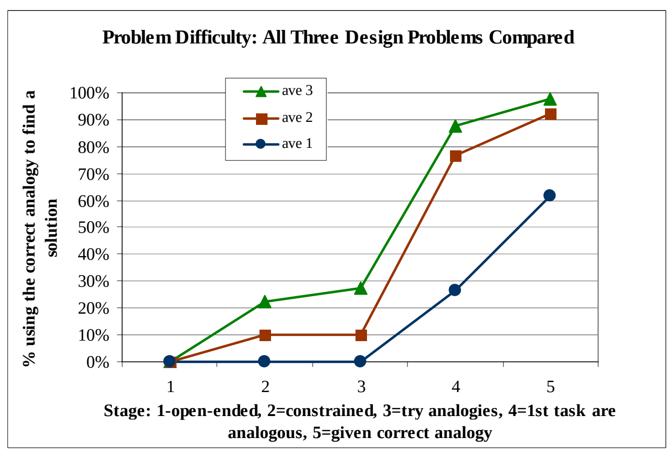

Figure 18: Relative difficulty of the design-by-analogy problems.

4.3 OBSERVATIONS AND QUALITATIVE RESULTS

Further insights were gained from the experiments. Not surprisingly, participants produced more concepts for the unconstrained problem than for the constrained design problems. Most participants used analogy without specific instructions to do so. Participants were familiar with the use of analogies for idea generation prior to the experiment. Participants tended to use analogies that shared many characteristics with the design problems and were in similar domains (Figure 19). This also caused the distracter products to be used erroneously. Typically, participants found solutions with the distracter products that did not meet the constraints of the problem,

By using the correct analogy for the constrained design problems, a few participants were able to find highly unique and unexpected solutions that meet the constraints (Figure 20). This occurred rarely, but resulted in some rather novel solutions to the problems and raises a number of research questions for future experiments. In particular, how do we assist designers in training their thought processes to generate such solutions?

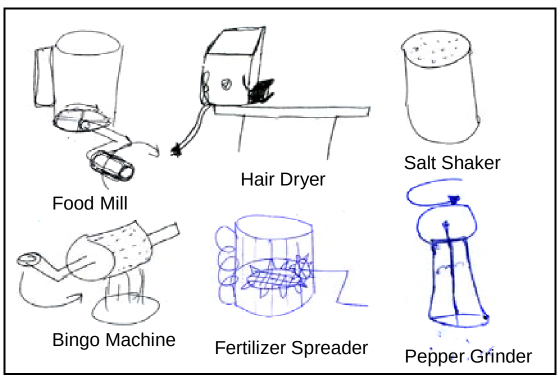

Figure 19: Other analogies used for design problem 3, device to sprinkle flour over a surface.

Based on these experiments a set of characteristics of good problems for analogy experiments has been defined. These will be used to define future design-by-analogy experiments.

- The solution is very unlikely and uncommon without using the analogy.
- The design problems should be relatively simple. (At least for studies in which people are going to solve many problems in a short time period.)
- The analogy solution is unique and useful.
- The analogy results in a clearly good solution to the design problem.
- For the design solutions, it needs to be easy to tell which characteristics are mapped.
- The solution to the design problem should be relatively easy to draw and/or explain.
- The analogy is the shortest/easiest route to the solution (this is not true of the water weight problem).

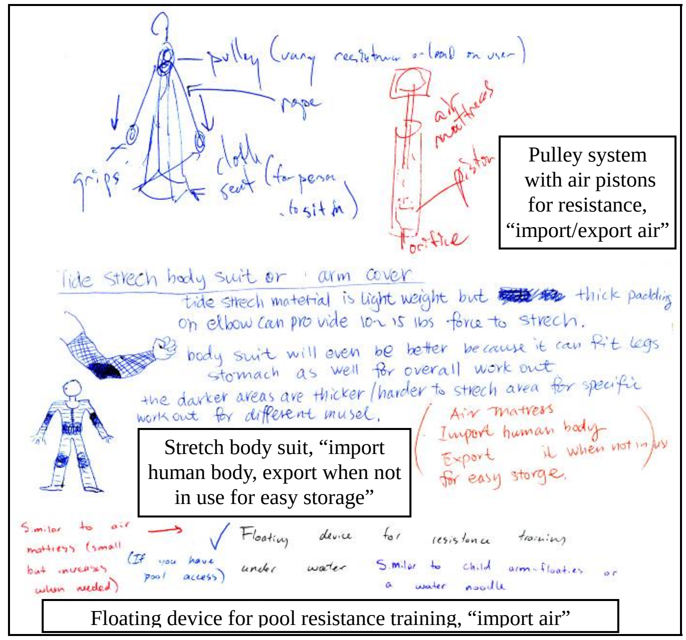

Figure 20: Unique solutions to constrained design problem 1.

5. CONCLUSION

A deeper understanding of the mechanism behind analogical reasoning and their implications within design will guide the development of drastically improved design-by-analogy methods and tools for design innovation. Representation clearly matters and seeking improved representations will enhance the innovation process. A more general semantic description of a product allows for a greater chance of using an previously experienced product as a source analogy later. Students who have been exposed to the technique of design-by-analogy will spontaneously use it when asked to generate design solutions.

The results and insights gained from the analogy in design experiments support the assertion that the form of concept representation is important in the cognitive analogy formation process. Similarly, the form of functional representation used for analogy searching in natural language-based databases and the metric for evaluating the level of analog between concepts is critical to the success of the systematic analogy search methodology. The semantic functional representation should enable easier access to information stored in textual repositories such as patent archives and websites although inherent difficulties remain in natural language processing and pertinent information retrieval.

5.1 FUTURE WORK

A number of different representations will be investigated. The experiment presented in this paper will be repeated with a new set of design analogies to further understand how the semantic and visual representations influence the design-by-analogy process. The influence of functional models will also be further investigated.

The systematic analogy search methodology will continue to be developed to improve the utility of the process and the quality of identified analogies. The quality of analogy identification will be augmented through continued refinement of the various tools discussed previously such as the EFFCT and CSS using lab-based experiments. Additionally, the utility of the methodology will be tested and enhanced using feedback and insights obtained from user-based experiments on real world design problems. The final product will be a robust design-by-analogy search methodology capable of identifying non-obvious conceptual analogies resulting in novel design solutions.

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APPENDIX A

SOURCE ANALOGY AND DESIGN PROBLEM DESCRIPTIONS

Table A1**:** General and domain specific descriptions for the functioning of an air mattress.

Sentence / **General (G) or Domain (D) Specific**									
1	**G**	The	device	is filled with	a substance	at the location	where it will be	used.	
	D	The	air bed	is inflated with	air	in the home	where it will be	slept on.	
2	**G**	The	substance	required	to cause	the device	to function	is available	at the location
	D	The	air	required	to cause	the air bed	to inflate	is available	in the home
3	**G**	The primary purpose		of the device	is to	distribute the force	of the person	during	the task
	D	The primary purpose		air bed	is to	provide a comfortable	bed for the person	during	sleep.
4	**G**	The	device	accomplishes	this by	importing, storing	and	exporting the substance	
	D	This	allows	accomplishes	this by	using the air to inflate	and	to deflate	
5	**G**		This	allows	the device	to be easily	stored.		
	D		This	allows	the air bed		put into a closet.		

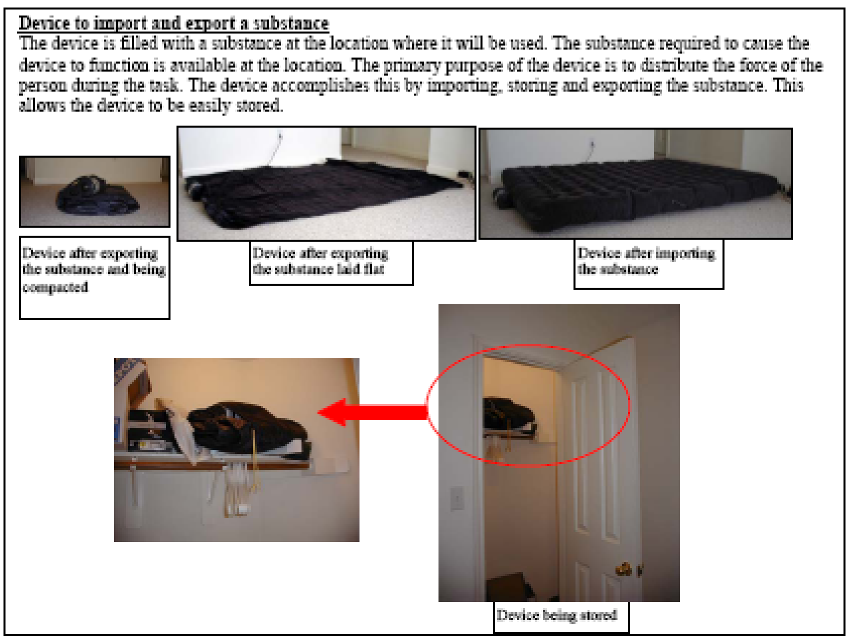

Figure A1: General description for the functioning of an air mattress.

Table A2: General and domain specific descriptions for the functioning of a football.

Sentence / **General (G) or Domain (D) Specific**								
1	**G**	Another object	imparts energy	to this device				
1	**D**	A person	throws	the American football.				
2	**G**	As it	moves	through	a substance	it	turns about.		
2	**D**	As it	flies	through	the air	it	spirals.		
3	**D**	This	spiraling	reduces	air friction	allowing	the ball	to travel	further.
3	**G**	This	motion	changes	the forces	allowing	the device	to move	more.

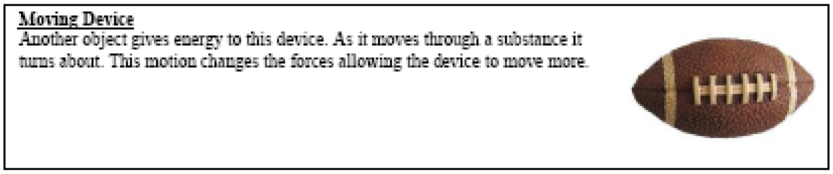

Figure A2: General description for the functioning of a football.

Table A3: General and domain specific descriptions for the functioning of a whisk.

Sentence	/ **General (G) or Domain (D) Specific**								
1	**G**	The device	imports	and holds	the	substance.			
1	**D**	The whisk	scoops up	and adheres to	the	batter			
2	**G**	The device	holds	the substance	while it is	moved	to another device.		
2	**D**	The whisk	adheres to	the batter	while it is	translated	to the waffle iron.		
3	**G**	The device	is moved	and the	clumps within the substance	are removed	as the substance	exits from	the device.
3	**D**	The whisk	is rotated	and the	clumps of batter	are strained	as the batter	drips from	the whisk.
4	**G**	The substance	is dispersed over	the secondary device.					
4	**D**	The batter	is covering	the waffle iron					

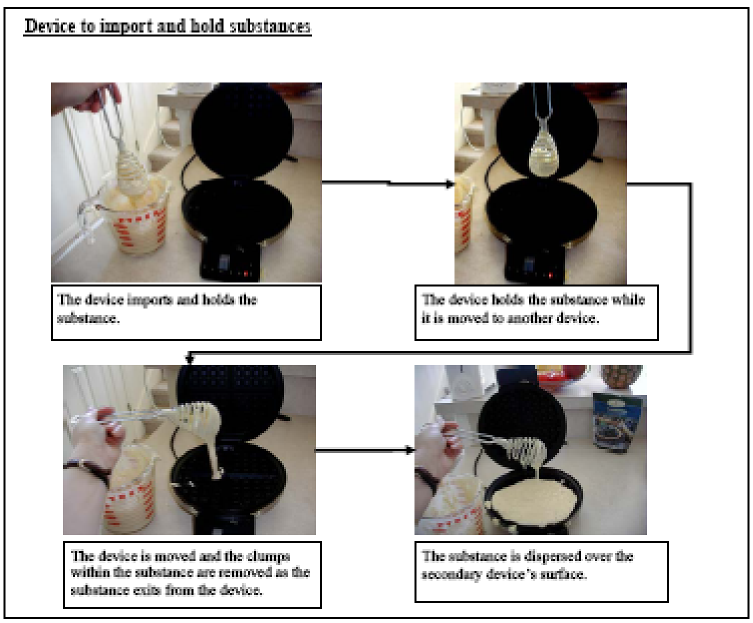

Figure A3: General description for the functioning of a whisk.

Table A4: General and domain specific descriptions for the functioning of pan cake turner.

Sentence	/ **General (G) or Domain (D) Specific**						
1	**G**	This	device	imports	the hand.		
1	**D**	This	spatula	meshes with	the hand.		
2	**G**	It	separates	two objects.			
2	**D**	It	slides between	pancake and pan.			
3	**G**	It also	dissipates the force from a object	and allows	an object	to be	moved.
3	**D**	It also	supports the pancake	and allows	pancake	to be	flipped.

Device to separate and move object

This device imports the hand and separates two objects. It also dissipates the force from an object and allows an object to be moved.

Figure A4: General description for the functioning of a pan cake turner.

Table A5: General and domain specific descriptions for the functioning of a travel cart.

Sentence / **General (G) or Domain (D) Specific**							
1	**G**	This device	positions	a large load	easily.		
1	**D**	The travel cart	carries	a large suitcase	easily.		
2	**G**	The lower support	and friction reducing features	compact	causing	the device	to change shape.
2	**D**	The bottom	and wheels	fold up	causing	the travel cart	to have a smaller volume.
3	**G**	The hand import feature	changes shape	to perform a new function.			
3	**D**	The handle	telescopes	to fit in an overhead storage bin.			

Load positioning device

This device positions a large load easily. The lower support and friction reducing features compact causing the device to change shape. The hand import feature changes shape to perform a new function.

Draw a function structure for this device. Remember each box in the function structure has a function (a verb) in it. Be sure to use the functions (the verbs) given in the device description.

Figure A5: General description for the functioning of a travel cart.

Design Problem 1
Design a piece of exercise equipment that can be carried in a suitcase.

Design Problem 1- Additional Constraints
Design a piece of exercise equipment that can be carried in a suitcase. Here are the additional requirements:

- Provides **at least 15 lbs of resistance**
- **Adds less than 4 lbs** to the suitcase
- **Maximum volume is 120 in^3** (~750 cm^3) or about half the size of a briefcase.
- It must be capable of being used for exercises normally done with hand weights (see example exercises below).
- It **can not use strips or cords of elastomer** (rubber) for resistance.

Design Problem 2
Design a device to be pulled behind a boat for a person to ride on.

Design Problem 2- Additional Constraints
Design a device to be pulled behind a boat for a person to ride on.

- This device must allow an **inexperienced rider to lie on their stomach and safely rotate 360 degrees longitudinally** while being towed behind a boat. The person will quickly and continuously rotate from lying on their stomach to lying on their back while being towed behind the boat. This requirement will make the raft more fun for the rider.
- High speed movements are desirable.

Design Problem 3
Design a device to sprinkle flour over a surface.

Design Problem 3- Additional Constraints
Design a device to sprinkle flour over a surface.

- The only material that is available to build the device from is various thicknesses of stainless steel wire.
- The entire device must be made from only one thickness of wire.
- The device must be manufactured by deforming the wire only.

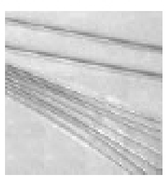

Figure A6: Design problem descriptions.