Analogy Seeded Mind-Maps: A Simple and Quick Design-by-Analogy Method

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Abstract

Recent research has investigated methods based on design-by-analogy meant to enhance concept generation. While these methods are promising, they can be cumbersome and difficult to apply in engineering classrooms. This paper presents *Analogy Seeded Mind-Maps*, a new method to prompt generation of analogous solution principles drawn from multiple analogical domains. The method begins with identifying a primary functional design requirement such as "eject part." We then use this functional requirement "seed" to generate a WordTree, which is a graph of grammatically analogical synonyms. We randomly select a set of 10-15 words from each WordTree list and use the resulting word list to populate the first-level nodes of a mind-map, with the functional requirement seed as the central hub. The word list and resulting mind-map then serve as visual tools that are utilized during the concept generation process. The effectiveness of the tool in generating concepts has been evaluated in separate studies utilizing student design teams working on a wide variety of projects in both the United States Air Force Academy (USAFA), a small academic community, and at The University of Texas at Austin, a large public research university setting. In our evaluation of the method, designers first used the word list (10-15 words from WordTree) to individually generate solutions and then performed team concept generation using the analogically seeded mind-map. The total quantity of concepts was measured. Additionally, the effect of word familiarity and the number of definitions of word were investigated for their effect on the quantity of concepts generated. It was found that the *Analogy Seeded Mind-Map* method allowed students to generate a large number of concepts in a relatively short amount of time with only brief introduction and explanation of the method.

1. Introduction and Motivation

Innovation is often a primary goal during the engineering design process. Various concept generation techniques exist to help designers develop innovative solutions. Techniques such as Brainstorming, 6-3-5/C-sketch and TRIZ[8], are widely used in the engineering classroom environment. Brainstorming and 6-3-5/C-sketch require the designer to spontaneously generate ideas, but also allow for inspiration from ideas of other participants. TRIZ, on the other hand, provides a more guided approach to solving engineering problems based on addressing conflicts between competing performance parameters. One area of recent interest in concept generation research is the phenomenon of design-by-analogy. The invention of Velcro® is one of the most popular anecdotes citing the spontaneous use of analogy to solve an engineering design problem. Researchers have sought to develop formalized methods to help designers identify potential sources of design analogies[11]. Of particular interest to our research is the WordTree method developed by Linsey[6].

In this paper we present the Analogy Seeded Mind-Map tool for directed design-by-analogy. The Analogy Seeded Mind-Map method combines aspects of both spontaneous and guided concept generation. We present in detail the steps taken to form the Analogy Seeded Mind-Map tool and how it is used in an engineering design exercise. Additionally we consider factors that may play a role in determining the overall effectiveness of the words used to construct the tool.

The results of a new design study are presented and compared to results obtained in previous design studies utilizing the Analogy Seeded Mind-Map tool.

2. BACKGROUND: FORMAL DESIGN-BY-ANALOGY

Despite the anecdotal success of design-by-analogy, few formalized methods exist to assist designers in the process of design-by-analogy. Among these methods are Synetics, biomimetic concept generation, analogous design utilizing the Function and Flow Basis, and the WordTree Method. Synectics guides users in thinking about a design problem from four types of analogies: personal, direct, symbolic and fantasy[1]. While the method guides users to address the problem using analogies, it does little to guide the designers to find successful analogies. Biomimetic concept generation utilizes databases that relate the desired function to functional analogies from nature [2-4]. Design-by-analogy using the Function and Flow Basis analyzes design problems from a functional viewpoint. Analogous solutions are then found by comparing the desired functions to a database of functional models of existing products [5].

In the WordTree method, key functional requirements and customer needs are identified and synonyms of these words are then linguistically re-represented in a visual diagram known as a WordTree[6]..The WordTree is formed through a combination of rotational brainwriting and utilization of the online WordNet database (http://wordnetweb.princeton.edu/perl/webwn) to identify additional hypernyms (more general synonyms) and troponyms (more specific synonyms). The WordTree method begins by identifying key problem descriptors from customer needs, a mission statement, and/or functional models. These key problem descriptors are converted to equivalent verbs that are used as seed words in the generation of the actual WordTree.

The design team then begins to generate the WordTree based on their individual knowledge in a rotational brainwriting exercise similar to the 6-3-5 method[5]. The WordTree is set up such that more general verbs related to the initial seed word are placed in a hierarchy above the seed word and more specific verbs are placed in a hierarchy below the original seed word. Following the generation of the WordTree from the design team's personal knowledge, the WordNet database is used to find additional direct hypernyms (synonyms with more general meanings) and direct troponyms (synonyms with more specific meanings) of the seed word that were not initially identified by the design team (Figures 1 and 2). The user inputs the desired verb and selects the desired sense or definition. The user then navigates through the WordNet database by selecting direct hypernyms and troponyms of the verb and placing them on the WordTree. Navigating through different hypernyms and troponyms, and their related hypernyms or troponyms results in a tree-like hierarchy with words on the same "branch" having higher similarity than words on different "branches". During this phase, hypernyms and troponyms that are unusual or unfamiliar are specifically sought since they are typically associated with very domain specific verbs in distant but analogous domains[6]. An example of a completed WordTree for the verb "hold" can be found in Figure 3. Upon completion of the WordTree in this manner, the team reviews the WordTree for potential analogies (potential solutions) and analogous domains (categories of solutions that share similar relationships). The design team proceeds to research the identified analogies and analogous domains in order to become familiar with them. The design team then uses the identified analogies to generate possible solutions using an idea generation method, such as 6-3-5.

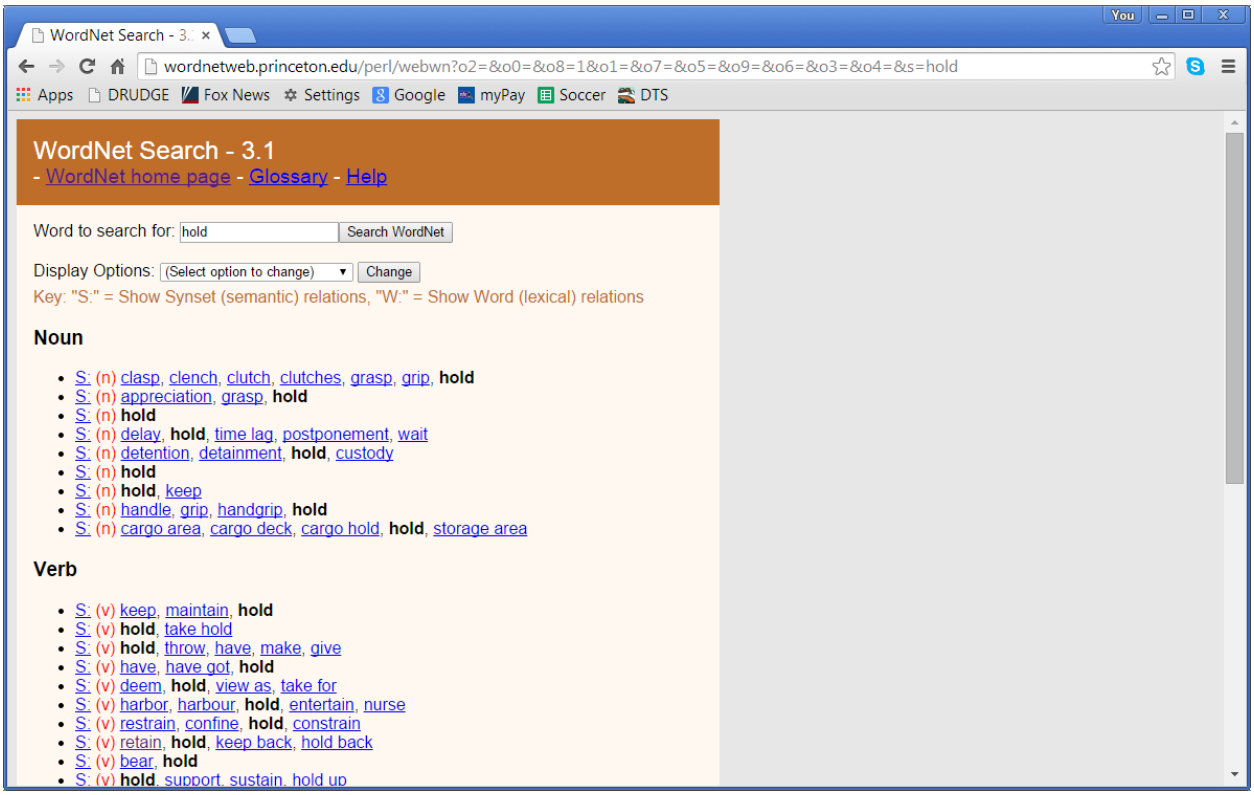

Figure 1: WordNet Word Input Example

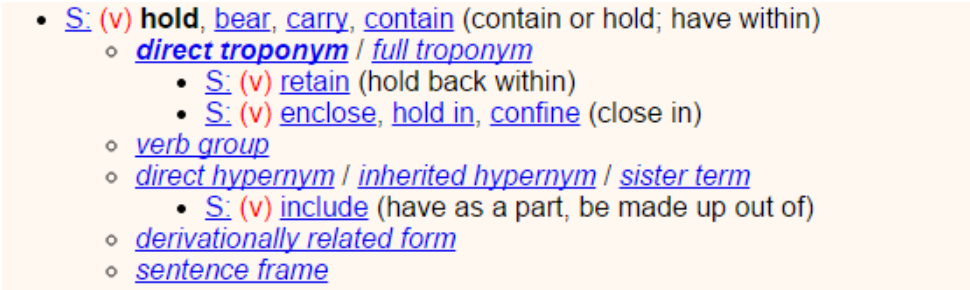

Figure 2: Example of Direct Hypernyms and Troponyms

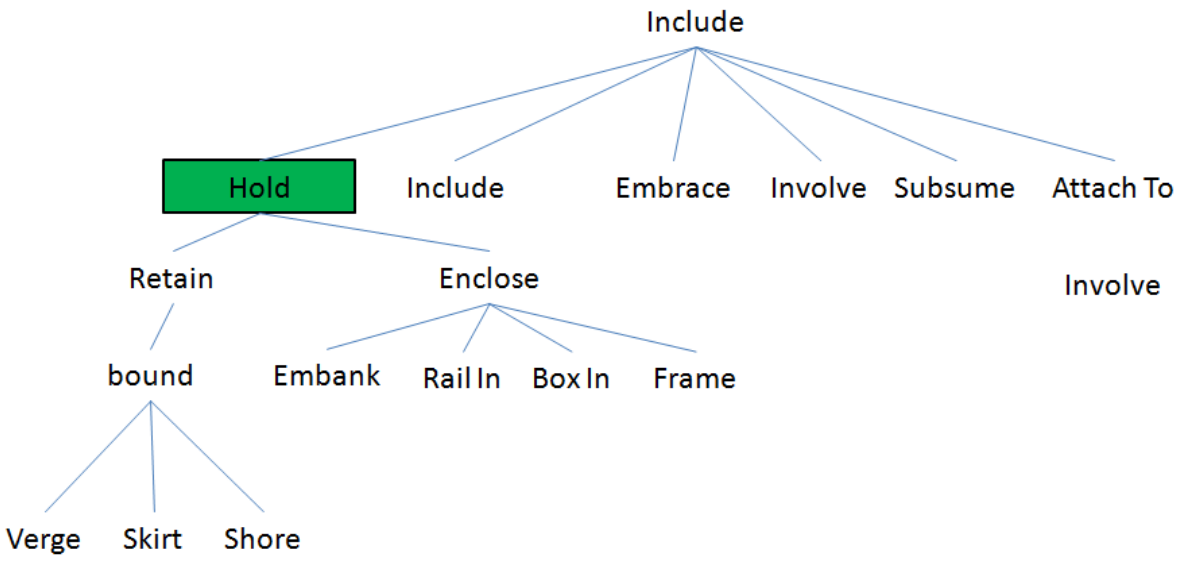

Figure 3: WordTree Example

The WordTree method, when properly applied, has been shown to increase the number of identified analogies compared to a control group asked to generate analogies intuitively and to produce unexpected, useful analogies[6]. However, the correctness with which the method was applied varied among the test groups (i.e., some groups failed to translate their key problem descriptors into verb form for use in WordNet or did not use the WordTree resulting from WordNet). Additionally, very few of the test groups in the study carried the results from the WordNet into subsequent concept generation steps. In an effort to simplify the application of the method and to remove sources for potential error, the WordTree Express tool was developed to automate the WordTree generation process[7].

WordTree Express (WTE) takes as input the key functional requirement or customer need as an action verb that is used as a seed word for generating the WordTree. The user then selects the desired sense of the seed word and the program generates a complete WordTree of all of the input verb's hypernyms and troponyms in the WordNet database. The program outputs a visual representation containing all hypernyms and troponyms of the seed word that can be viewed and used to identify potential analogies and analogous domains. A study was conducted to compare application of the traditional WordTree method and the WordTree method utilizing WTE. The study showed that participants expressed a statistically significant higher opinion of the WordTree method with WTE versus the original, non-automated WordTree method7.

A potential limiting factor to the usefulness of the WTE tool is the size of the resulting WordTree. The size of the generated WordTree can vary from approximately 30 words to nearly 1000 words, depending on the initial seed word. While a WordTree of 1000 words is likely to contain numerous possible analogies and analogous domains, it is impractical to use in an actual application. An example of a complete WordTree generated using WTE can be found in Figure 4. We address this issue, as well as the tendency of teams to ignore WordTree results in further concept generation, with the development of the Analogy Seeded Mind-Map method.

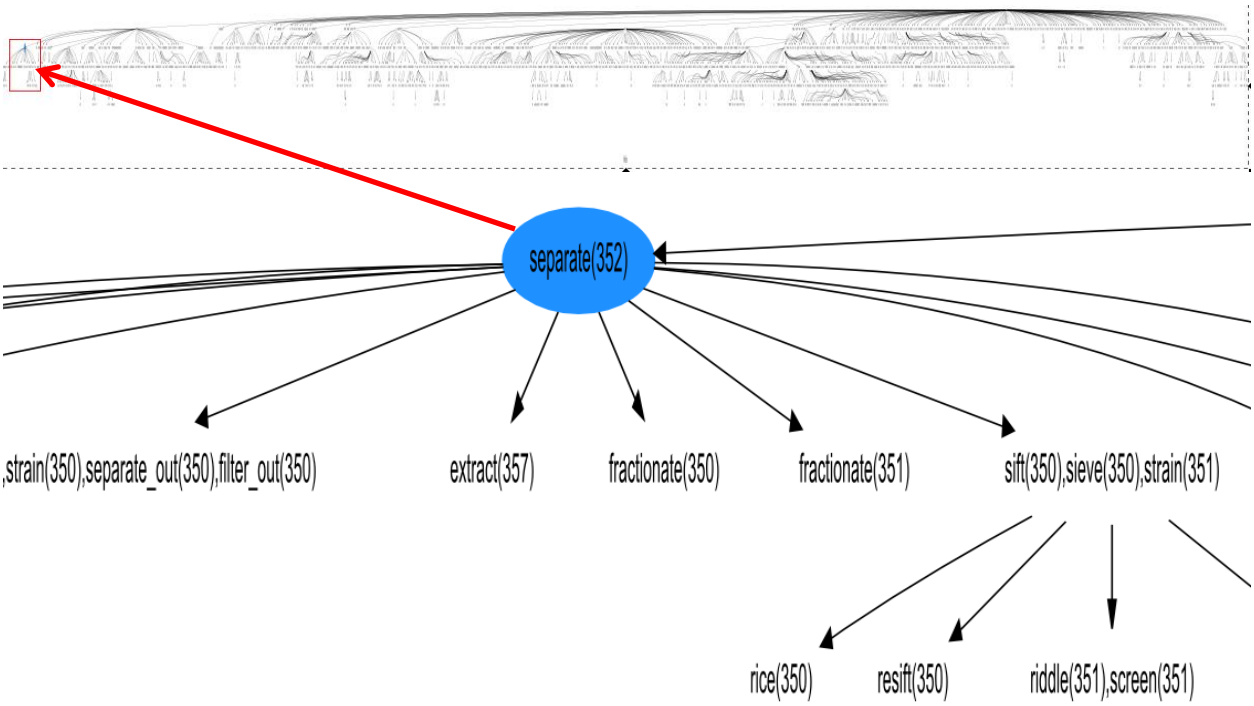

Figure 4: Complete WordTree Generated Using WTE and Enlarged Subset

2. ANALOGY SEEDED MIND-MAPS

2.1 Purpose

The purpose of the Analogy Seeded Mind-Map tool is to simplify the WordTree construction process and to limit the number of words presented to designers to a usable set. The Analogy Seeded Mind-Map method combines elements of the WordTree method with the well-known mind-map approach for visually organizing the results of brainstorming. The mind-map is a graphical representation of the brainstorming process in which a key word is placed toward the center of a graph and related information is organized in categories connected by arcs to the central node[9].

The "pruning" of the WordTree is currently done in a random manner. We have investigated the effect of different factors in an attempt to better understand the productivity (the number of concepts generated by that word) of words for generating ideas. By identifying factors that relate to the productivity of a word, the potential effectiveness of the Analogy Seeded Mind-Map tool can be increased. These results of evaluating these factors are presented below.

2.2 Construction

The overall Analogy Seeded Mind-Map Process can be seen in Figure 5. Steps 1 through 4 represent the construction portion of the process. Currently, the construction portion of the

process is being handled solely by the research team. The Analogy Seeded Mind-Map construction process begins by identifying the key functional requirement the design team wishes to focus on during the concept generation session. From this key functional requirement, the verb portion is isolated and used as input into the WordTree Express program. The desired sense of the word is selected from the given choices in WTE and then used to generate the WTE output file. This output file consists of both a graphic file that shows a visual representation of the completed WordTree as well as the text file used by the program to generate the graphic file. The text file is then imported into Microsoft Excel and edited to remove the formatting necessary to form the graphic file, leaving only the generated words. A random set of words is then chosen from this word list and used to form the Analogy Seeded Mind-Map. This is done by placing the initial seed verb as the central hub and arranging the selected words around it to form the first level of nodes surrounding the hub. Figure 6 shows an example of a completed Analogy Seeded Mind-Map.

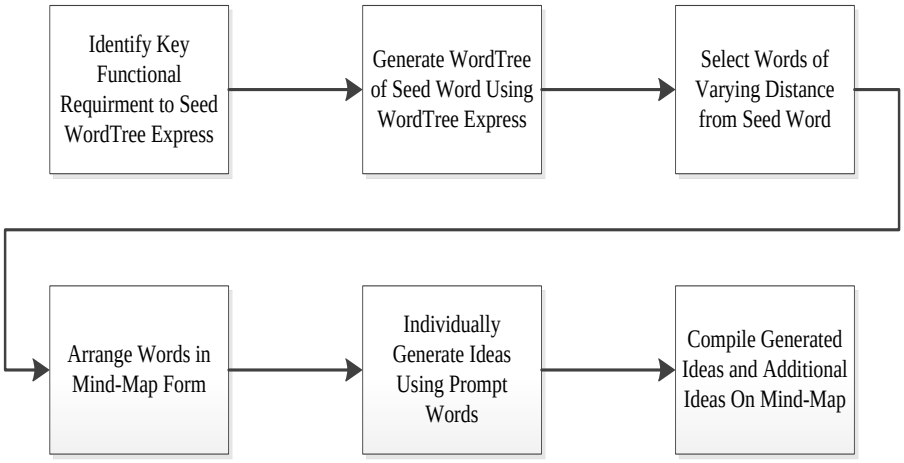

Figure 5: Analogy Seeded Mind-Map Process Flow

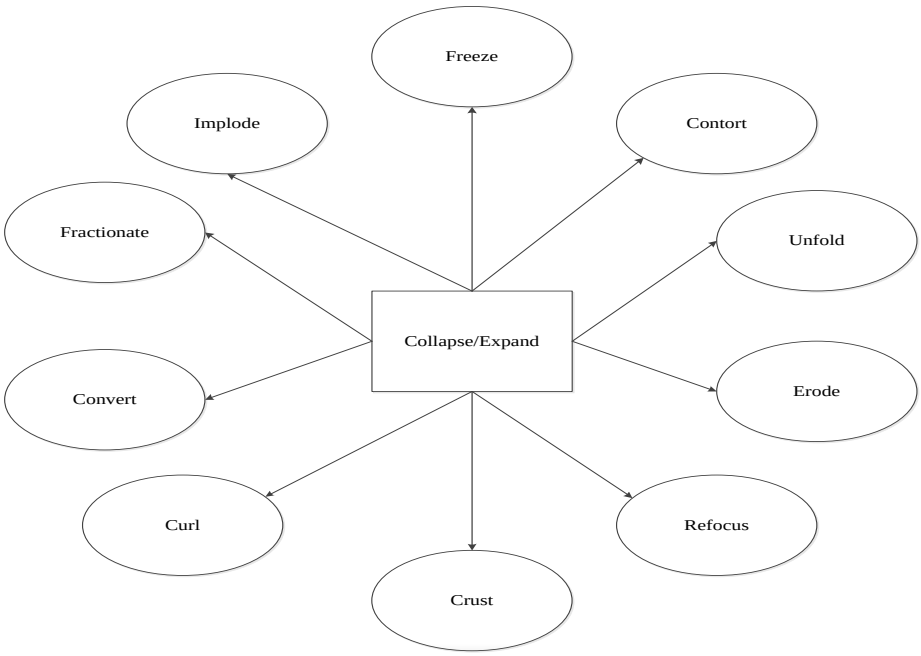

Figure 6: Example Analogy Seeded Mind-Map

2.3 Application

Once the Analogy Seeded Mind-Map tool is constructed, the design team is ready to use the tool to generate ideas. The concept generation portion of the method is split into both individual and group portions (Figure 7). First, the design team distributes the word list among the team members, who then individually generate ideas a set amount of time. The individual phase allows team members who are not as comfortable in the overall group setting to participate equally in the exercise. Following individual concept generation, the design team then conducts group concept generation. The goal of this phase is for the team to compile all ideas generated during the individual phase and to generate new ideas through discussion and piggybacking off other team members' ideas.

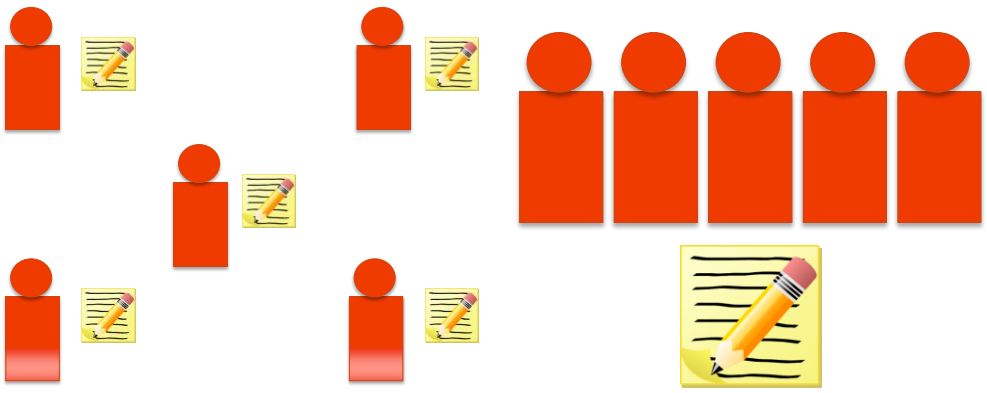

Figure 7: Concept Generation Portion of Analogy Seeded Mind-Maps Process

3. Analogy Seeded Mind-Maps

3.1 Previous Studies and Results

The Analogy Seeded Mind-Maps process was evaluated previously in two separate design studies. The method was found to show an increase in the number of concepts generated compared to the original WordTree Method when used by design teams working on similar design problems at USAFA[12]. The method was also quickly learned and effectively applied by small groups of volunteer students from a large public university. The studies also showed that there was not a direct or significant link between the analogical distance (defined as the shortest path length between the seed word and the selected prompt word) and the quantity of concepts generated for a particular prompt word. This result led the research team to investigate alternative properties of the prompt words for their relation to the quantity of words generated. A new study was conducted in order to gauge the effect of word familiarity and the number of definitions for the word on a prompt word's effectiveness for generating concepts. We hypothesized that the relationships between familiarity and the number of definitions for a word and the quantity of generated concepts to be:

Familiarity: We expect the number of concepts generated from a given prompt word to increase with an increase in the designer's familiarity with the prompt word and its definition related to the seed word.

Number of Definitions: We expect the number of concepts generated from a given prompt word to increase in proportion to the number of possible definitions for the prompt word.

3.2 Evaluation of the Hypotheses

The research team conducted a study to further evaluate the Analogy Seeded Mind-Maps process. The study was conducted at USAFA in a manner similar to the previous study. The design teams consisted of upperclassmen enrolled in the capstone engineering design class. The teams worked on the following design projects:

1. Replacement for land mines
2. Debilitating function in hard deeply buried targets
3. Personal cooling system for special operations teams
4. Composable/fractionable munitions
5. Fatigue testing system for mimicking flight profiles
6. Bridge corrosion monitoring
7. Disabling maritime vehicles

The student design teams submitted a list of functional requirements to the research team. From this list, the research team selected a single functional requirement to construct an Analogy Seeded Mind-Map for each design team to use in concept generation. The study procedure was as follows:

Step 1. The students were given a 15 minute lecture to provide background for the design study. Included in the lecture was a brief introduction to the Analogy Seeded Mind-Map process and its relevant background. The lecture also provided an outline for how the design study would be conducted and an example of its application.

Step 2. The students split into their design teams and were given the materials they needed to complete the design study: a prompt word list generated for each team's specific design project, a mind-map skeleton consisting of the seed word and generated prompt words, a word familiarity survey and extra sheets of blank paper to be used in the design study.

Step 3. The students were asked to complete a brief survey to gauge their familiarity with the words on the prompt word list and their definitions related to the seed word.

Step 4. The teams were instructed to distribute the prompt word list among the team members and to spend 15 minutes individually generating design solutions using the prompt words as inspiration.

Step 5. Following the individual concept generation, the teams were instructed to spend 30 minutes as a team compiling their generated design solutions using the given mind-map skeleton as a basis. They were expected to generate additional solutions as a team.

Figure 8 is an example row of the survey given to the students. The students were asked whether they were familiar with the word and particular definition, familiar with the word but NOT the particular definition, or if they were NOT familiar with the word or definition.

	Prompt Word List	Definition	Not familiar with word or usage	Familiar with word, but NOT definition	Familiar with word AND definition
1	take control	assume control			

Figure 8: Word Survey Example Row

3.2.1 Analysis Method

The results from each team were collected and the resulting quantity of concepts was counted for both the individual and team portion of the study. Quantity is a relatively quick and simple measure of an ideation method's effectiveness[10]. The total quantity of concepts has also been shown to have a positive effect on the number of quality ideas generated[9].

To gauge the effect of word familiarity on the quantity of concepts generated, the research team tallied the word familiarity survey by assigning a value of 1 for the answer of "not familiar with word or usage", 2 for the answer of "familiar with word but NOT usage" and 3 for the answer of "familiar with word AND usage". The average familiarity of a word was then calculated for the team. The words were split into groups corresponding to low familiarity (average familiarity 1.667 or less), medium familiarity (average familiarity between 1.667 and 2.333) and high

familiarity (average familiarity of 2.333 or higher). The average number of concepts was calculated for each familiarity group.

The words were sorted by the quantity of concepts generated by the design teams in the study and then evaluated for the number of definitions for each word. The average number of definitions for the top performing words was then compared to the bottom performing words.

3.3 Results

3.3.1 Quantity Results

The study again showed an increase in the average number of concepts generated using the Analogy Seeded Mind-Map process compared to the standard WordTree Method used in a similar environment at the small undergraduate institution. The design teams averaged 62 concepts generated as a team, which is comparable to the number of concepts generated in the previous study despite having a tighter control on the time allotted for conducting the exercise. Additionally, when compared to a study conducted at the same institution using design teams working on similar problems, more concepts were generated using the Analogy Seeded Mind-Map process compared to those generated using the original WordTree method ($p=0.07$).Table 1 shows a breakdown of the number of concepts generated by each individual, the total number of concepts across the individual sheets for a team and the total number of concepts on the team's final group mind-map. The majority of teams showed at least a moderate increase in the number of concepts present on the final group mind-map compared to those on the individual sheets. This is a positive result compared to the previous study where the majority of teams exhibited a noticeable decrease in the number of concepts between the group sheet and the individual sheets. It is unclear why Team 7 exhibited a significant decrease in the number of concepts from their individual sheets to their final team sheet. This may be attributed to the design team using the group portion to evaluate and eliminate ideas rather than to combine and generate additional ideas.

Table 1: Total Quantity of Concepts Generated

	Individual									Team
	1	2	3	4	5	6	7	8	Total	Total
Team 1	0	7	12	17	22	8	0	9	75	70
Team 2	26	29	14	-	-	-	-	-	69	73
Team 3	13	23	5	14	9	-	-	-	64	67
Team 4	15	15	15	0	0	-	-	-	45	66
Team 5	22	9	10	21	-	-	-	-	62	70
Team 6	10	9	23	7	-	-	-	-	49	76
Team 7	12	9	13	23	-	-	-	-	57	16
					Average				60.1	62.57

3.3.2 Word Familiarity Effect

The average number of concepts per word for high and medium familiarity words was comparable with a noticeable drop for words deemed to be of low familiarity (Table 2). This result is interesting in that it seems to show that general familiarity with a word is as good as

specific familiarity of the word and how it relates to the seed word, but lack of familiarity with a word can limit the usefulness of the word in the method. Statistical support for this observation is currently lacking ($p = 0.23$ comparing the high and low familiarity means) and additional data is needed to determine if this relationship holds or if it is just an aberration in this particular study.

Table 2: Average Number of Concepts by Familiarity

Familiarity	Average
High	4.27
Medium	4.25
Low	3.30

3.3.3 Word Definition Effect

It was found that the top 10 performing words had an average of 2.9 definitions while the bottom 10 performing words had an average of 2.4 definitions ($p=0.55$). The difference between the two sets is miniscule and thus unlikely to provide any insight into picking productive words *a prioi*.

3.3.3 Limitations of the Study

While the results of the study seem promising, they thus far lack statistical significance. Additional studies are needed to determine the statistical significance, if any, of the factors that have been evaluated in this study.

Single function concept generation is by its nature limited compared to multi-function concept generation. Ideating on a single function without regards to the interaction with additional functions can lead to complications later in the design process. Currently, in the Analogy Seeded Mind-Maps method is designed to be used in single function concept generation. Teams are encouraged to consider additional functions and customer needs during concept generations, but additional functions are not explicitly included in the method. Additional development of the method is needed in order to explicitly incorporate additional, related functions.

3. Conclusion and Future Work

The Analogy Seeded Mind-Maps method has proven to be a productive tool in the concept generation process. The method encourages teams to ideate and consider words that would otherwise be ignored due to their apparent dissimilarity to the engineering design problem being addressed. The method has been shown to be usable by both established design teams working on projects they are familiar with and teams made up of volunteers working on a problem they are seeing for the first time.

The research team has to this point evaluated the effects of analogical distance, familiarity and the number of definitions of the prompt word on the quantity of concepts generated. Neither analogical distance nor the number of definitions have proven to be effective predictors for the expected quantity of concepts generated by the prompt word. Familiarity showed an interesting result in that general familiarity was as effective as specific familiarity in generating ideas using

a prompt word. While this is a worthwhile result, familiarity is a property that can only be obtained after the user has evaluated the prompt word and is thus not a great candidate for selecting prompt words *a priori*. Notably, the studies conducted have shown that an Analogy Seeded Mind-Map consisting of randomly selected can used to generate a large number of concepts in a short amount of time.

Besides the continued research to identify the desirable properties of the selected prompt words, the research team is also working on streamlining and automating the construction process to increase the overall usability of the method. An automated process will allow the design team to input their particular seed word and select the desired number of output prompt words. Identifying predictive properties of the prompt word will enable automatic generation of high performing Analogy Seeded Mind-Maps.

4. Acknowledgements

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