Staff Summary Sheet

	To	Action	Signature (Surname), Grade, Date		To	Action	Signature (Surname), Grade, Date
1	DFEM	Approve	[signature] 14 May 14	6			
2	DFER	Review	SSLTI, AD22, 14 May14	7			
3	DFEM	Action		8			
4				9			
5				10			

Grade and Surname of Action Officer	Symbol	Phone	Suspense Date
AD-24/Jensen	DFEM	333-7946	20 August 2014

Subject		SSS Date
Clearance of Material for Public Release	Case Number: To be Assigned USAFA-DF-PA 408	14 August 2014

Summary

1. Purpose: To provide security and policy review on the document at Tab 1 prior to release to the public.

2. Background:

- *Author(s)*: K. Scott Marshall (University of Texas at Austin), Dr. Richard Crawford (University of Texas at Austin), Matthew Green (LeTourneau University), Dr. Daniel D. Jensen (U.S. Air Force Academy)

- *TITLE*: DETC2014-35323 Analogy Seeded Mind-Maps: Testing of a New Design-By-Analogy Tool

- *Abstract (partial – see paper for full version)*:

Recent research has investigated methods based on design-by-analogy meant to enhance concept generation. This paper presents *Analogy Seeded Mind-Maps*, a new method to prompt generation of analogous solution principles drawn from multiple analogical domains.

The method was evaluated in two separate design studies using senior engineering students. The method begins with identifying a primary functional design requirement such as "eject part." We used this functional requirement "seed" to generate a WordTree of grammatically analogical words for each design team. We randomly selected a set of words from each WordTree list with varying lexical "distances" from the seed word, and used them to populate the first-level nodes of a mind-map, with the functional requirement seed as the central hub. Design team members first used the word list to individually generate solutions and then performed team concept generation using the analogically seeded mind-map. Quantity and uniqueness of the resulting verbal solution principles were evaluated. The solution principles were further analyzed to determine if the lexical "distance" from the seed word had an effect on the evaluated design metrics. The results of this study show Analogy Seeded Mind-Maps to be useful tool in generating analogous solutions for engineering design problems.

- *Release information*: Standard release of a USAFA technical report.

- *Previous clearance information*: N/A.

- *Recommended distribution statement*: Distribution A, Approved for public release, distribution unlimited.

3. Discussion:

To be released for presentation at ASME 2014 International Design Engineering Technical Conferences & Computers and Information in Engineering Conference, August 17-20, 2014.

4. Recommendation: Sign coord block above indicating document is suitable for public release. Suitability is based solely on the document being unclassified, not jeopardizing DoD interests, and accurately portraying official policy.

DANIEL D. JENSEN, PhD, USAF
Department of Engineering Mechanics

1 Tab
Article, DETC2014-35323 Analogy Seeded Mind-Maps: Testing of a New Design-By-Analogy Tool

Proceedings of the ASME 2014 International Design Engineering Technical Conferences & Computers and Information in Engineering Conference
IDETC/CIE 2014
August 17-20, 2014, Buffalo, New York, USA

DETC2014-35323

ANALOGY SEEDED MIND-MAPS: TESTING OF A NEW DESIGN-BY-ANALOGY TOOL

K. Scott Marshall
The University of Texas at Austin
Austin, TX, USA

Richard Crawford
The University of Texas at Austin
Austin, TX, USA

Matthew Green
LeTourneau University
Longview, TX, USA

Daniel Jensen
United States Air Force Academy
Colorado Springs, CO, USA

ABSTRACT

Recent research has investigated methods based on design-by-analogy meant to enhance concept generation. This paper presents *Analogy Seeded Mind-Maps*, a new method to prompt generation of analogous solution principles drawn from multiple analogical domains.

The method was evaluated in two separate design studies using senior engineering students. The method begins with identifying a primary functional design requirement such as "eject part." We used this functional requirement "seed" to generate a WordTree of grammatically analogical words for each design team. We randomly selected a set of words from each WordTree list with varying lexical "distances" from the seed word, and used them to populate the first-level nodes of a mind-map, with the functional requirement seed as the central hub. Design team members first used the word list to individually generate solutions and then performed team concept generation using the analogically seeded mind-map. Quantity and uniqueness of the resulting verbal solution principles were evaluated. The solution principles were further analyzed to determine if the lexical "distance" from the seed word had an effect on the evaluated design metrics. The results of this study show *Analogy Seeded Mind-Maps* to be useful tool in generating analogous solutions for engineering design problems.

1. INTRODUCTION AND MOTIVATION

Creating innovative solutions to engineering problems is a key enabler of successful engineering design. Concept generation techniques exist to assist designers in identifying and developing innovative solutions. Some of these techniques, like Brainstorming, 6-3-5, and TRIZ [9], are widely used in design, particularly in the engineering classroom environment. One focus of recent concept generation research is the phenomenon of design-by-analogy. There are many popular anecdotes illustrating successful innovative designs arrived at by analogies, such as the development of Velcro® and formalized methods have been developed recently in an effort to help designers identify potential sources of design analogies. Of particular interest in our research is the WordTree method developed by Linsey [4]. This design-by-analogy technique was developed to help designers identify potential analogies and analogous domains.

In this paper we explore the relationship of "distance" between synonyms in a WordTree to the quantity and quality of concepts generated by designers using the WordTree. The remainder of the paper consists of a discussion of current design-by-analogy approaches and the motivation for the development of the Analogy Seeded Mind-Map tool. Two design studies involving undergraduate students at different universities are then presented. The first was conducted within the context of a capstone design class. The participants applied the method to their particular design projects. In the second study, volunteers were all given the same design situation and ask to apply the Analogy Seeded Mind-Map method. The results of these experiments are presented and discussed.

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]. An example portion of a WordTree can be found in Figure 1.The WordTree is formed through a combination of rotational brainwriting and utilization of the online WordNet database (http://wordnet.princeton.edu/perl/webwn) to identify additional hypernyms and troponyms. 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 to be used as seed words in 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 hypernyms and troponyms of the seed word that were not initially identified by the design team. 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]. 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.

The WordTree method, when properly applied, has been shown to increase the number of identified analogies compared to a controlled group asked to generate analogies intuitively and to produce unexpected, useful analogies [6]. However, the correctness with which the method was applied varied amongst 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 method [7].

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. We chose to address this issue, as well as the tendency of teams to not carry WordTree results into further concept generation, with the development of the Analogy Seeded Mind-Map method.

2. ANALOGY SEEDED MIND-MAPS

2.1 Purpose

The Analogy Seeded Mind-Map tool was developed as a way to investigate potential "pruning" methods to reduce the overall size of WordTrees generated by WordTree Express. These WordTrees can contain hundreds of words and identifying useful analogies can be difficult. 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 that places a key word toward the center of a graph and organizes related information in categories around the central node [9].

In order to minimize the number words in a particular WordTree, we sought to investigate whether there was a relation between the analogical "distance" between generated words and the seed word and the overall quantity and quality of generated design concepts. By identifying trends in quality and quantity related to analogical distance, we hope to use this distance as a guide to pruning a WordTree to provide the designer with a subtree that promotes quantity and/or quality in the resulting

concepts. To test this approach, we provided engineering students with a pre-generated list of prompt words of various distances from the functional seed word. We hypothesized that the relationships of analogical distance with quality and uniqueness of the generated concepts would be:

Quantity: We expect the number of concepts prompted by a given word in the WordTree will decrease with increased analogical distance from the seed word.

Uniqueness: We expect the uniqueness of concepts generated from a word in the WordTree will increase with increased analogical distance from the seed word.

In addition to investigating the effect of distance on the evaluated design metrics, we also designed the Analogy Seeded Mind-Map process so that ideation occurs within the method in an effort to increase its effect on the subsequent engineering design process.

2.2 Construction

The overall Analogy Seeded Mind-Map Process can be seen in Figure 2. Utilizing the WordTree Express tool, WordTrees were generated using a functional seed word. Using the generated WordTree image file, words were selected randomly based on the apparent visual "distance" along the tree. The selected words were then evaluated for analogical distance utilizing WordNet::Similarity, an online tool created by Ted Pederson and Jason Michelizzi [8]. Analogical distance is defined as the smallest number of arcs needed to traverse the WordTree between the seed word and the prompt word, with words on the same node as the seed word having a distance of zero. For example in Figure 1, the word "fractionate" has an analogical distance of 1 from the seed word "separate" (shown with the red path) and the word "rice" has an analogical distance of 2 from the seed word "separate" (shown with the green path). After measuring the analogical distance, additional words were selected as needed to provide words of a variety of distances. These prompt words were arranged in both a list and in mind-map form to be used in the early concept generation phase. The prompt word list was used first by the design team to facilitate individual concept generation. The concepts from the individual team members were then combined to form a mind-map which was used to guide further group concept generation. For the purpose of these studies, steps 1 through 4 were performed by the research team, with the study participants only completing steps 5 and 6

3. EXPERIMENT DESIGN

3.1 Pre-Study Preparation

The Analogy Seeded Mind-Map tool was tested in two separate studies utilizing senior students enrolled in design methodology or project courses. The initial study was conducted utilizing seven senior engineering design teams that were working on sponsored design projects in a wide variety of domains. The second study was conducted with student volunteers who were given a single, simple engineering problem to which to apply the method.

For the initial study, the design teams submitted a summary of their projects to the research team prior to the design study. The summaries identified the primary functional requirements for the projects. For each team, at least one functional requirement was selected and used as a seed to generate the materials necessary for the Analogy Seeded Mind-Map using the process outlined in Figure 2. An example of the prompt words arranged in mind-map form is shown in Figure 3. Seven teams with between six and eight members participated. However, only six of the teams submitted the necessary materials to be analyzed for the study. The design projects were:

1. Covert Unmanned ariel vehicle, UAV, with identification capability
2. Easily deployable/stowable UAV
3. Man-portable heavy-lift system
4. Control system for an atmospheric testing platform
5. Remote system for monitoring bridge corrosion
6. Projectile system capable of flying in a combined and separated configuration
7. UAV deployable ground vehicle.

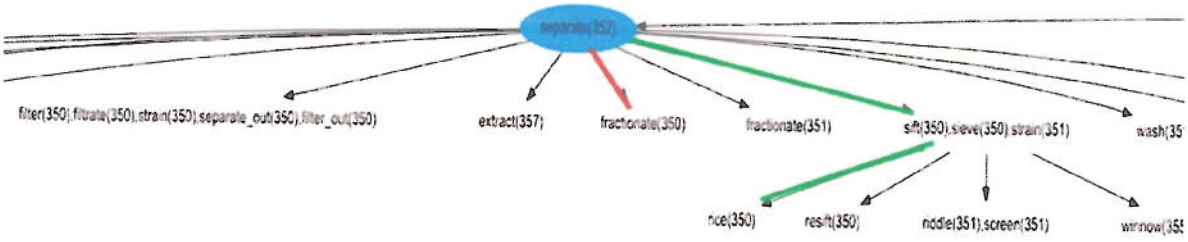

Figure 1: Analogical Distance Example

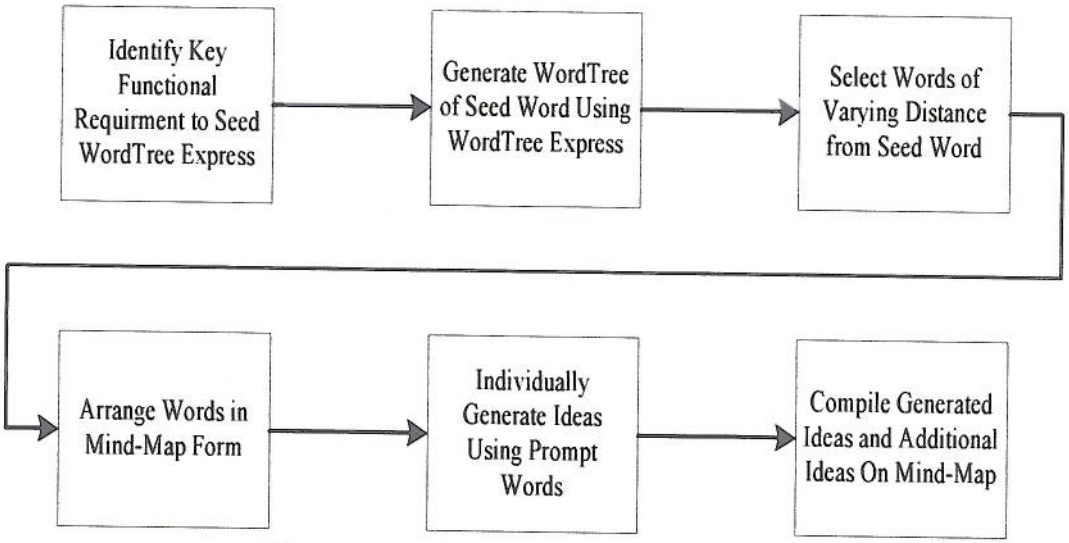

Figure 2: Analogy Seeded Mind-Map Process Flow.

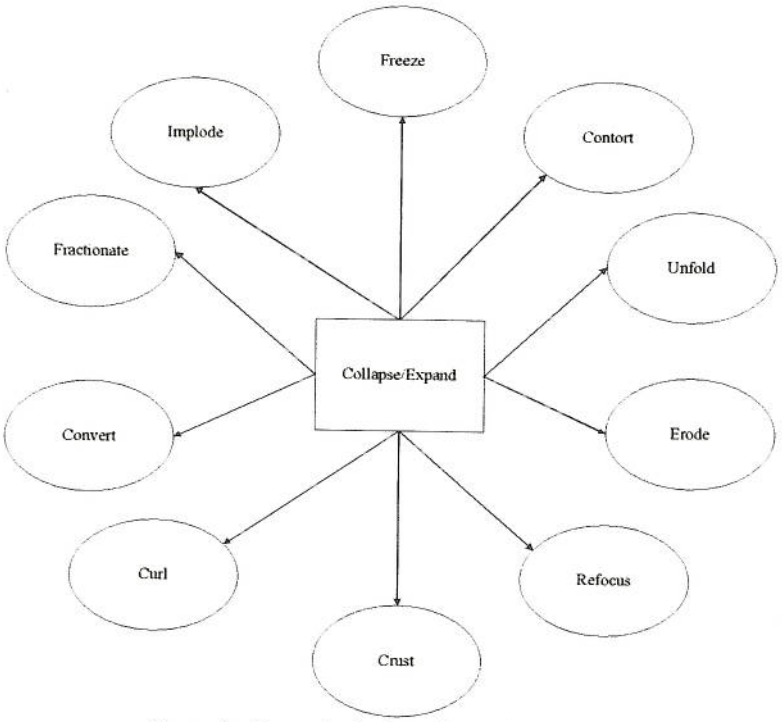

Figure 3: Example Analogy Seeded Mind-Map

The study was conducted as a part of the early concept generation phase of the teams' design projects. At this stage, the teams were still focusing on generating a large number of potential design solutions for further refinement and evaluation in the subsequent design process steps. The teams were encouraged to carry the design solutions generated in this exercise into subsequent concept generation and selection tasks.

For the second study, the volunteer students were given the task of devising a way to automatically separate a 3D-printed part from the printing substrate. The teams were given one of five prompt word lists and mind-map skeletons generated from the seed word "separate." Each prompt word list contained 10 words ranging in analogical distance from 1 to 9.

3.2 STUDY #1 PROCEDURE: Capstone Project Teams

The procedure for conducting the first study 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 WordTree Express tool and a discussion of its benefits and perceived limitations. 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, and extra sheets of blank paper to be used in the design study.

Step 3. The teams were instructed to split the prompt word list among the team members and to spend 15 minutes individually generating design solutions using the prompt words as inspiration.

Step 4. 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. Note that the majority of teams spent the remainder of the class period, approximately one hour, on the team oriented portion of the study.

The process was split between individual concept generation and group-based concept generation in an effort to make it easier for members of the team that find it difficult to participate in group settings. At the end of the class period, the team mind-maps and individual sheets were collected for evaluation.

3.3 Study #2 Procedure: Student Volunteers

The second study procedure was conducted in much the same manner as the initial study with only minor changes due to the desire to more closely control the time so that the study could be more easily repeated. The changes were 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 design-by-analogy and the original WordTree Method, as well as the WordTree Express tool and a discussion of their benefits and perceived limitations. The lecture also provided an outline for how the design study would be conducted and an example of its application.

Step 2. The students were split into design teams, ranging in size from two to four members, and given the materials they needed to complete the design study: a handout explaining the engineering problem that was to be addressed in the study, a prompt word list generated from the example engineering problem, a mind-map skeleton consisting of the seed word and generated prompt words, extra sheets of blank paper to be used in the design study.

Step 3. The teams were instructed to split the prompt word list among the team members and to spend 15 minutes individually generating design solutions using the prompt words as inspiration.

Step 4. Following the individual concept generation, the teams were instructed to work as a group for 30 minutes compiling their generated design solutions using the given mind-map skeleton as a basis. They were expected to generate additional solutions as a team.

4 RESULTS AND DISCUSSION

4.1 Study 1: Capstone Project Teams

Table 1 shows the compiled data from the design teams. The total number of concepts presented on each team member's individual sheets and on the teams' combined mind-map were counted to assess the total number of concepts generated for that word. The generated concepts were shown at a high level of abstraction, reflecting the nature of the early concept generation stage. Example concepts generated included: the seed word "conceal" led to the prompt word "masquerade" which sparked the idea "*disguising a UAV as another object*"; the seed word "connect" led to the prompt word "nest" which sparked the idea "*stackable pieces that can combine and separate*"; and the seed word "anticipate" led to the prompt word "anticipate" which sparked the idea "*forecast corrosion rates based on current state*".

The concepts generated in the individual portion of the method were evaluated for uniqueness by ignoring duplicates. The concepts generated in the individual phase were between 75% and 94% unique. Comparing the total number of unique concepts presented on the individual sheets to those presented on the mind-map indicates that a large number of unique concepts were lost in the transition from the individual phase to the group phase. When adjusted for ideas appearing for the first time on the group mind-map, *as many as 55% of the unique ideas appearing on individual sheets did not appear on the team mind-map*. This result was unexpected as the teams were encouraged to include all unique ideas and to add additional ideas during the group phase. This may be due to several factors (i.e. failure of an individual to express their ideas or elimination of impractical ideas during group discussion) and does not necessarily indicate an issue with the method in particular.

The total number of concepts that were original (new) to the teams' combined mind-map was determined by comparing the concepts presented on the mind-map to those appearing on the team member's individual sheets. The majority of teams introduced additional ideas during the group portion of the study. Since some teams had multiple word lists and others had only a single word list to utilize in the same amount of time, averages both by word list and by team were calculated. The small number of concepts generated by some teams per word list can be attributed to the team splitting the same amount of time between two separate lists instead of focusing on a single list. When compared per team as opposed to per word list, the study showed a consistently high and comparable number of concepts generated across all teams.

Table 2 shows the compiled data for teams using the same word list for three different design projects. The use of the same word list by multiple groups allowed us to look at the effect of distance on the quantity and quality somewhat independent of the actual design problem. Of note in the table, Team 3 split the team into two independent units with half of the team focusing on a different word list related to the problem and the other half working on the word list presented in the table.

Overall, total quantity seems to vary widely across words of similar analogical distance. This indicates that either distance has little effect on the overall quantity of ideas generated using the process or that there are other factors involved that influence the effectiveness of a particular word. As can be seen in the table, the highest performing word in the list is the word *camouflage*. We suspect that this may be due to familiarity with the concept and practice of camouflage due to the military background of the study #1 participants. The relatively low percentage of unique ideas compared to the other words in the list suggests that the students were accessing a common knowledge base with established means of accomplishing the desired result.

4.2 Study 2: Student Volunteers

Table 3 shows the compiled results from the study conducted using senior engineering student volunteers. The individual volunteers on average generated only about half as many concepts in the same amount of time in the individual portion of the study compared to the members of the design teams in study #1. This may be due to the increased familiarity of the study #1 design teams with their design projects as opposed to the study #2 volunteers who were only introduced to the design project in the short lecture held prior to application of the method. Additionally, the amount of time spent on the individual portion of the method was tightly controlled in study #2 using the individual volunteers, compared to the design teams who worked with less supervision and may have spent extra time on the individual portion of the method.

Table 1 – Study #1: Quantity of Concepts Generated by Each Team (Including all Prompt Words)

	Individual											Team	
	1	2	3	4	5	6	7	8	Individual Total Concepts	Individual Number Unique	Individual Percent Unique	Mind-Map Total Concepts	Mind-Map Original Concepts
Team 1 Collapse	11	12	8	-	-	-	-	-	31	28	90%	17	0
Team 1 Conceal	8	10	0	13	14	14	-	-	59	47	80%	18	0
Team 2 Identify	5	4	6	7	9	4	-	-	35	28	80%	34	11
Team 2 Conceal	7	6	9	16	6	7	-	-	51	43	84%	35	9
Team 3 Protect	12	35	12	7	3	5	-	-	74	58	78%	44	7
Team 3 Conceal	4	13	7	-	-	-	-	-	24	22	92%	22	5
Team 4 Connect	-	-	-	-	-	-	-	-	-	-	-	36	-
Team 5 Monitor	5	7	6	1	4	-	-	-	23	17	74%	16	4
Team 5 Communicate		2	6	3	5		-	-	16	15	94%	15	8
Team 6 Move	14	8	9	12	11	16	13	9	92	69	75%	36	5
				Average Word					45	36.3		27	5
				Average Team					81	65.4		47.4	9.8

Table 2 – Study #1: Quantity of Concepts Sparked by Each Word (Combining all Team Results)

		Individual																						Team						
		Team 1							Team 2							Team 3															
Word	Distance	1	2	3	4	5	6	Team Total	1	2	3	4	5	6	Team Total	1	2	3	4	5	6	Team Total	Overall Total	# Unique	%Unique	Average	1	2	3	Total	# Unique	% Unique	Average
Obstruct	1	-	-	-	1	-	1	2	2	-	-	2	-	-	4	1	1	-	-	-	-	2	8	8	100	1.3	-	3	2	5	4	80	2.5
Camouflage	2	3	7	-	4	7	2	23	1	2	5	3	1	2	14	1	5	-	-	-	-	6	43	21	49	3.3	5	7	7	19	16	84	6.3
Cloak	2	1	-	-	3	1	4	9	1	1	-	2	2	1	7	-	2	1	-	-	-	3	19	10	53	1.7	4	4	3	11	9	82	3.7
Whitewash	2	1	-	-	1	1	1	4	-	-	-	1	1	-	2	-	-	-	-	-	-	0	6	5	83	1.0	2	3	-	5	5	100	2.5
Overshadow	2	1	-	-	1	-	-	2	1	-	2	2	-	1	6	-	2	1	-	-	-	3	11	9	82	1.4	2	3	2	7	7	100	2.3
Ecplise	3	1	-	-	1	2	3	7	-	1	-	2	-	-	3	1	3	1	-	-	-	5	15	9	60	1.7	2	6	3	11	9	82	3.7
Veil	3	-	-	-	-	-	-	0	1	1	1	2	1	1	7	-	-	-	-	-	-	0	7	6	86	1.2	-	4	-	4	4	100	4.0
Masquerade	9	1	3	-	2	3	3	12	1	1	1	2	1	2	8	1	-	4	-	-	-	5	25	13	52	1.9	3	5	5	13	10	77	4.3

Table 3 – Study #2: Quantity of Concepts Generated by Each Team (Including all Prompt Words)

	Individual							Team	
	1	2	3	4	Ind. Total Concepts	Ind. Number Unique	Ind. Percent Unique	Mind-Map Total	Mind-Map Original
Team 1	8	4	12	-	24	21	88	42	18
Team 2	5	3	5	-	13	11	85	12	3
Team 3	9	5	6	-	20	15	75	20	6
Team 4	6	8	-	-	14	12	86	17	10
Team 5	6	9	-	-	15	14	93	42	28
Team 6	30	8	10	-	48	38	79	45	13
Team 7	2	2	8	8	20	19	95	25	10
Average					22	18.6	86	29	13

The results again show a high percentage of unique ideas generated during the individual portion of the study with uniqueness ranging from 75% to 95%. The trend of unique ideas from individual sheets failing to appear on the group mind-map was again seen in the volunteer study. As in the design team study, this may be attributed to group dynamic factors and are not necessarily an issue with the method. The volunteer study differed from the design team study in that teams actually increased the total number of generated unique ideas in the group portion compared to the unique ideas generated in the individual portion of the method.

Table 4 shows the individual prompt words used by the teams for the purpose of the study. The teams were given a list of 10 words with analogical distances ranging from 1 to 9 in relation to the original seed word. Each word list contained at least one word for each distance (from 1 to 6), with a few word lists containing words of distances from 7 to 9 due to the scarcity of these distant words on the original WordTree. The results again show the quantity of concepts sparked by words of the same distance varied widely, suggesting that factors other than analogical distance may be involved. The highest performing prompt words on the final mind-map on a quantity basis were of distance 5 and 3 from the seed word, with the next highest performing words having distances of 2 and 6.

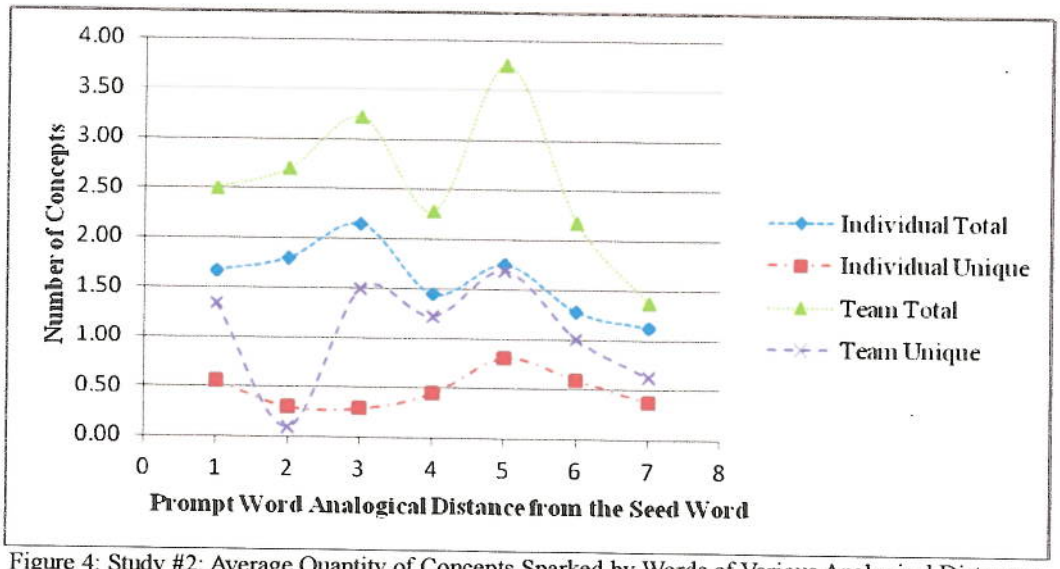

Figure 4: Study #2: Average Quantity of Concepts Sparked by Words of Various Analogical Distances

Table 4 – Study #2: Quantity of Concepts Sparked by each Word (Combining all Team Results)

Prompt Word	Distance	Individual Quantity	Team Quantity	Prompt Word	Distance	Individual Quantity	Team Quantity
Avulse	1	1	2	Rumple	4	3	2
Decompose	1	2	4	Shatter	4	0	2
Fractionate	1	2	2.5	Biodegrade	5	7	10
Macerate	1	2	1	Choke	5	0	5
Sift	1	2	4.5	Exfoliate	5	2	1
Wash	1	1	1	Overdress	5	1	4
Cook	2	2	1	Skew	5	1	2
Crack	2	3	6.5	Spin	5	1	4
Explode	2	2	2	Strangle	5	2	3
Rice	2	0	1	Vacate	5	0	1
Vaporize	2	2	3	Convulse	6	3.5	6.5
Bake	3	3	3.5	Dip	6	1	1
Burst	3	2	1	Rescale	6	2	2
Disolve	3	3	1	Sag	6	2	3
Pulverize	3	1	10	Scab	6	1	1
Puncture	3	2	2	Shrink	6	1	1
Sectionalize	3	2	4	Stretch	6	1	1
Smash	3	2	1	Unplug	6	0	2
Cut	4	1	3	Unyoke	6	0	2
Defrost	4	1	3	Incinerate	7	1	1
Erupt	4	2	3.5	Obliterate	7	1	1
Outgrow	4	1	2	Piece	7	0	0
Pop	4	3	3	Pucker	7	2.5	3.5
Regrow	4	1	0	Mangle	8	3.5	4
Revert	4	1	2	Potentiate	9	1.5	4.5

5 CONCLUSIONS AND FUTURE WORK

The Analogy Seeded Mind-Map approach to concept generation provides a method for quickly applying the WordTree design-by-analogy method. It encourages design teams to consider and ideate on words that might otherwise be overlooked and discarded due to superficial dissimilarity to the

problem they are trying to solve. The design team study showed that the application of the method was more fruitful than previous attempts to use the WordTree method in a similar setting using design teams working on projects of similar nature and complexity [10]. This study also utilized senior design teams at the United States Air Force Academy. As part of their design process, they used a suite of concept generation techniques including WordTree Design-by-Analogy. The number of concepts generated from each method was reported. For the WordTree Design-by-Analogy method, the design teams averaged a total of 26 concepts, with a high of 51 and a low of 10. In comparison, students using the *Analogy Seeded Mind-Maps* tool generated an average of 65 concepts per team, with a high of 69 and a low of 22. The teams successfully implemented the method and remained engaged and productive for a significant period of time. The students that participated in the volunteer study generated a large number of potential concepts for a new, unfamiliar design problem in a relatively short amount of time.

The effect of analogical distance on the quantity and uniqueness of the generated concepts is unclear and remains to be determined. The volunteer study provided a small glimpse into the potential relation, but further work is needed in order to draw any useful conclusions. Without knowing the effect of analogical distance on the design metrics, it is not possible at this time to suggest possible pruning methods to reduce the number of words on the WordTree overall while increasing the overall fruitfulness of the words.

The process would benefit greatly from generating the Analogy Seeded Mind-Maps in an automated manner. With an automated process, design teams would be able to input a seed word and select the desired number of output prompt words for ideation. If a relation between distance and uniqueness can be determined, the output could be further refined to generate words that are particularly tuned for quantity, uniqueness, or other concept evaluation metrics.

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