NSF GRANT CMMI-0555851
NSF PROGRAM NAME: Engineering Design

Ideation Methods Building on Fundamental Studies in Design by Analogy

Christina K. White
Teachers College
University of Columbia

Kristin L. Wood and Jason Weaver
Manufacturing and Design Lab
The University of Texas at Austin

Abstract: This project seeks to investigate, develop, test, and implement innovative design methods for generating concepts through analogies. Design-by-analogy is the area of idea generation in which proven solutions from a given domain provide visual, aesthetic, geometric, or functional similarity for problem-solving in another domain. The existence of this area is noted throughout recorded history. The first steam locomotives, for example, were based on analogies to the horse-drawn stage coach. While the existence of analogies as inspiration for creative design is well known, the cognitive processes used in design-by-analogy, especially for complex problems such as in engineering, is far from understood. This paper uses results from our fundamental studies of design-by-analogy and considers a study of alternative ideation methods. In particular, the design methods, known as Transformation Design and WordTree Design-by-Analogy, seek to reformulate design problems so that multiple effective analogies may be developed. A full-factorial analysis was used to compare the effect of using the two design methods. Results from the design teams were evaluated quantitatively by the number concepts generated.

1. Introduction

Design-by-analogy is a powerful tool for developing ideas. Designers frequently base their designs on concepts or systems they have seen before [1-4]. Numerous examples of innovative products based on analogies are included in various forms of media such as technical magazines, literature, even films, and also in nature and other areas that are not as obvious prompts for connectivity. We seek in this paper to explore concept generation techniques that support Design-by-Analogy.

In design, concept generation is a dynamic area that continues to undergo development. Numerous portrayals of the design process describe [5-8] concept generation as a key part of any approach. Over time, concept generation transforms from vague ideas of brainstorming to fleshed-out formal methods such as mind-mapping [7], morphological matrices [7], 6-3-5/C-Sketch [7], and TIPS/TRIZ [9].

In this project, we pursue research on several different fronts related to concept generation and the design process in general. The first area of research examines Design-by-Analogy techniques and formulates a method for concept generation using a common verb terms found in natural languages. The second area deals specifically with systems that can transform between different configurations in order to perform multiple functions. A large number of analogous "transformers" are examined, and information gleaned from them can be used in the design of new systems.

2. Background

2.1 WordTree Design-by-Analogy. Designers are often inspired by analogies in the process of developing new ideas. In fact, a large portion of innovation is derived directly from analogy. However, much of this process is *ad hoc* or serendipitous. The challenge and purpose of a formal Design-by-Analogy method is to lead the designer to useful, but non-obvious analogies. This guiding process usually involves re-representing the problem from a different point of view. For example, some methods present the problem in terms of similar biological systems [10,11], while others describe its key functions and flows [12]. Synectics may challenge the designer "to be" the problem or look at it symbolically [13].

WordTree Design-by-Analogy is a recent development in design methodology [14-16]. In this method, key words such as functions or customer needs are used to seed a linguistic representation of the problem. This representation is developed both through an extended brainstorming approach and with the help of WordNet, a tool developed at Princeton University [17,18]. The WordNet database functions by returning a list of words related to a

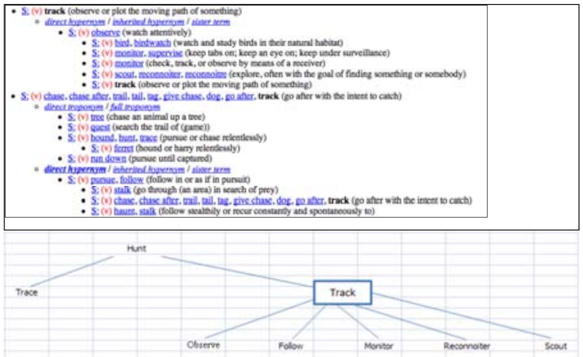

Figure 1: Exemplar WordNet results and WordTree for key word "track" [17].

user-supplied seed word. WordNet works similarly to a thesaurus, but gives much more functionality and structure. For each input word, WordNet returns a set of troponyms (sub-types or more specific synonyms), hypernyms (overarching or more general synonyms), and sister terms (other words stemming from a common hypernym). An example WordNet entry for the verb "track" is shown in Fig. 1. The information retrieved from WordNet can easily be assembled into a graphical representation called a WordTree, with hypernyms and troponyms branching off of the seed term like roots and branches. An example WordTree based off of the same key word "track" is shown in Fig. 1.

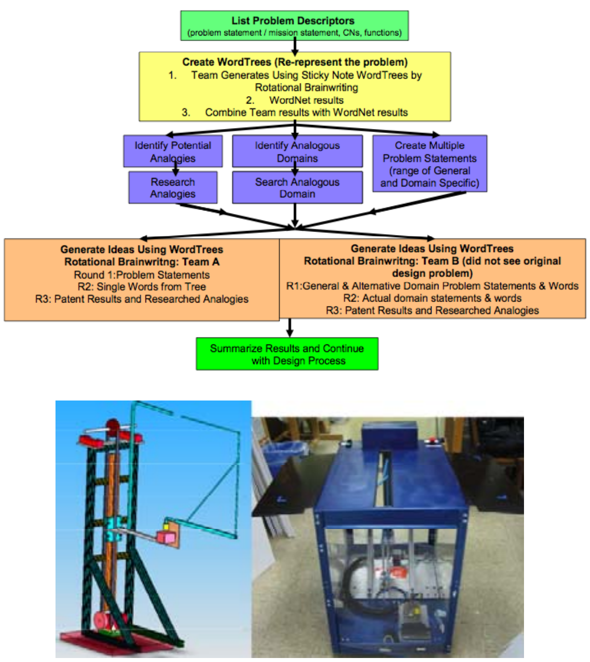

Figure 2: Complete WordTree Design-by-Analogy Methodology and Exemplar Result [16,17].

Hence the name, the information in a WordTree can be used to branch out from known functions and customer needs into far-field applications. For example, a sample design problem may require the function "track," as in Fig. 1. The associated WordTree terms may lead the designer to explore current applications of "hunt" (perhaps hunting for a solution to a problem or hunting for a lost item). It would also lead to ways to "scout" or "reconnoiter" (methods and skills used by explorersor pioneers), and tools to "monitor" or "trace" (to view the situation from different vantage points – perhaps through electronics). These trains of thought would reveal specific, real-world examples that might have otherwise gone unnoticed. By exploring multiple WordTrees, the designer is led towards a wide swath of related concepts and applications far-removed from the initial problem, i.e., design-by-analogy.

Figure 2 shows a more extensive and complete form of the WordTree Design-by-Analogy method. Notice that the method provides scaffolding by systematically guiding a designer or design team through the exploration of analogous verb terms and analogous domains. An exemplar design result is also shown, providing design concepts for the problem of assisting persons with disabilities in folding clothes as part of their daily jobs.

2.2. Transformation Design. Transformation, in a mechanical sense, can be defined as changing state (or configuration) in order to provide new functionality [19,20,21]. Transforming, or reconfigurable systems occur frequently in design, ranging from vehicles to furniture to toys and tools. From the comics to toy chests to the movie screen, the principles and facilitators of transformation tap the imagination of many who may not have initially been intrigued by and been exposed to the elegant engineering concepts. This 20th century a pop culture phenomenon of *Transformers* is a scaffolding tool that potentially connects to teaching and learning 21st century engineering.

A basic example of a transformer is shown in Fig. 3. Here, a chair transforms into a stepstool by folding half of the structure about a hinge.

Table 1: Transformation principles and facilitators [20].

Principles					
Expand/Collapse  [23]		Expose/Cover  [22]		Fuse/Divide  [24]	
Facilitators					
Conform with Structural Interface	Flip	Interchange Working Organ	Roll/Wrap/Coil	Share Power Transmission	Utilize Composites
Enclose	Furcate	Modularize	Share Core Structure	Shell	Utilize Generic Connections
Fan	Inflate	Nest	Share Functions	Telescope	

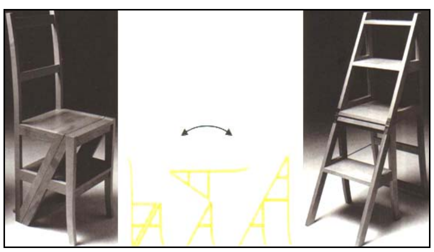

Figure 3: Transforming chair/stepstool [22].

Transformers can be complex and difficult to execute, yet their historic design has been mostly *ad hoc*, relying on serendipitous analogies and previous experience to create smooth, functional transformation processes. Over the past three years, extensive research has been conducted to better understand how transformation works, how it is currently designed, and how a better, more formalized design process could be applied. Over the course of this research, a theory of transformation design has been developed which identifies a set of principles and facilitators relevant to the process of transformation (Table 1). These principles and facilitators represent meta-analogies to generate concepts for design problems.

Additional research shows that these principles and facilitators occur in consistent, predictable patterns [20,21]. These trends and interrelationships can be utilized to assemble transformation processes that operate smoothly and robustly, while still having the freedom to pursue unconventional match-ups among the principles and facilitators.

3. Research Experiment

A controlled experiment was designed with the aim of comparing the effect of using WordTrees and/or Transformation Design methods in the concept generation process. To focus on these two methods, other parts of the process were controlled as much as possible.

Design teams of three to six members generated concepts for a design problem; specifically to create a system that can tag and track a vehicle for emergency purposes, then perform an effect on the target when desired, in this scenario, to aid the search and rescue team in events to help with hostage situations. An illustration of this scenario is shown in Fig. 4. Team members followed a script outlining the methods to be used and recorded all concepts for subsequent analysis.

3.1 Source of Participants. Forty-one participants were assembled into nine teams of three to six people for this study. All participants were volunteer undergraduate students at The University of Texas at Austin. Approximately 75% of them were male, 25% were female. The volunteers' ages ranged from 21-27. At the time of the study, they were enrolled in a senior-level mechanical engineering capstone design class, where they had previously learned common concept generation techniques such as mind-mapping and 6-3-5. The volunteers had experience typical of undergraduate engineering students, with some receiving additional training through internships, co-ops, previous jobs, and research opportunities. Because of their general engineering experience and common level of understanding of design as taught in the class, it was assumed that they would have comparable backgrounds coming into the test study.

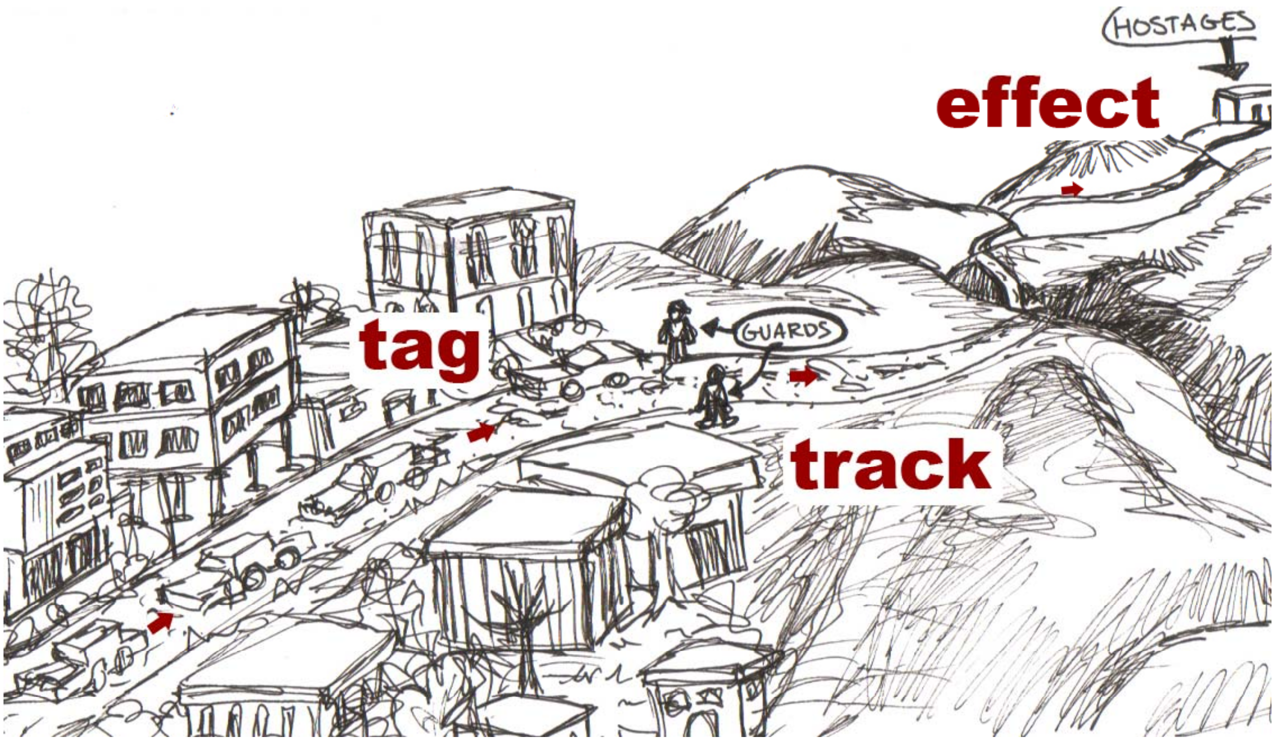

Figure 4: Example scenario involving "tag, track, and effect" design problem.

3.2 Factorial Organization. The study was formulated as a basic 2^2 factorial experiment with four different conditions. The two controlled variables were the use of the WordTree Design-by-Analogy method and the use of the Transformation Design method.

In the first trial (- -), neither WordTrees nor transformation heuristics were used. This condition corresponds to a control. After a brief introduction, a design problem was given, after which the participants spent 25 minutes brainstorming with a mind-map. This was followed by 30 minutes of 6-3-5. In the final stage of the process, each participant searched the Internet (through patents, images, videos, and design websites) for additional information on analogies uncovered during the earlier stages. A research assistant introduced each step of the process, using a script for consistency in language and timing. The complete outline for this "control" variation is given in the next section.

In the second trial (+ -), a WordTree Design-by-Analogy method was inserted before the mind-mapping. This method is also outlined in the next section. The third trial (- +) inserted an introduction to transformation principles and facilitators, with information on how to use them. The fourth trial (+ +) used both WordTrees and transformation heuristics

3.3 Outline of Experiment. Each instance of the experiment followed the outline shown below. The control (- -) trial follows the steps as listed, excluding 3A and 3B (shown in italics). The other variations inserted steps 3A (for WordTrees) and/or 3B (for Transformation Design) as appropriate. The assistant leading the session was given a script to read to the participants, and each stage was given a set time period, with the total session lasting two hours.

1. Introduction to "transformers" – The students are given a definition and brief explanation of transformation, and they are invited to give examples of transformers to demonstrate understanding.

2. Introduction to analogies – The students are given a brief explanation of how analogies are often used cognitively in design and how actively searching for analogies can lead to benefits in the design process.

They are invited to give examples of products easily linked to specific analogies.
3. Design statement – A specific design statement is given to the group. In this case, the participants were given a problem to create a system to "tag," "track," and cause an "effect" of some sort on a target or target vehicle (Fig. 4). Novelty and the use of transformation and analogies are specifically encouraged, in this case, to be able to identify the location of hostages by tracing the path of a target vehicle

3A. (For Transformation Design)

Introduction to principles and facilitators – Explain each principle and facilitator, and pass out papers with definitions and examples. Explain that research has shown common groupings of principles and facilitators, and pass out papers with tables of groupings.

3B. (For WordTree Design-by-Analogy)

Introduction to WordTrees – Explain that the purpose of Design-by-Analogy is to re-represent the problem, and one way to do this is through relationships in terminology. Demonstrate a sample WordTree and instruct the members to create their own WordTrees (Each person chooses a seed word, preferably "tag," "track," "effect," transformation principles, or other appropriate descriptors). Have the team members switch WordTrees with each other several times and add onto them. Pass out WordTrees compiled from WordNet on the same key words.
4. Brainstorm with mind-mapping [7] – The participants are instructed to generate concepts for the design problem and record them on a mind-map. Each member uses a different color on a dry-erase board so that individual contributions can be recorded. The participants are free to organize their mind-map however they want. If WordTrees or transformation heuristics are used, they are suggested as possible center nodes for the mind-map. The papers passed out on WordTrees/transformation heuristics may be used as references during the process. The members are also asked to make note of any useful analogies they discover and how they were identified.
5. 6-3-5 brain-writing [7] – One round of conventional 6-3-5 is followed. Each member draws three concepts on paper, based on the brainstorming session. After 10 minutes to develop their own ideas, members rotate papers and add to their teammates ideas for 5 minutes. Each member uses a different color ink to differentiate contributions. Rotations continue every 5 minutes until the papers have rotated completely around the table, allowing each member to enhance the original concepts or add new ones.
6. External analogy search – The participants are asked to identify concepts, key words, or ideas that may lead to existing analogous products or systems. Each participant is assigned a computer and is given a list of useful websites and tools, such as web searches (Google, Yahoo), patent searches (Google Patents, FreePatentsOnline.com) and Industrial Design websites (YankoDesign.com, Coolest-Gadgets.com). They are allowed 20 minutes to freely search the Internet, "leap-frogging" and "piggybacking" from concept to concept and recording what they find.
7. Exit survey – The participants are asked to fill out a one-page survey asking how innovative they feel their concepts are, how well they fulfill the design problem, what their favorite concepts are, what analogies they found useful, which concept generation method they preferred, and how completely they feel they covered the design space. All papers are collected, and results from the mind-map, 6-3-5, and external analogy search are recorded.

A sample result from the 6-3-5 portion of the study is shown in Fig 5. Note the extensive use of both analogies (spiders, drills, etc) and transformation processes.

4. Results

The effectiveness of the four conditions was assessed on the quantity of concepts developed in each session. Research shows a positive correlation between improved innovation and the number of concepts developed with a concept generation method. [26-28]. The experiment was quantitatively evaluated by conventional Design-of-Experiments using Yates standard form of the factorial set-up [25], analyzing several different organizations of the data.

4.1 Means of Analysis. The mind-map, 6-3-5, and external analogy search results for each individual and team were compiled in a spreadsheet, detailing each unique concept generated, who contributed it, and during which stage it was generated. A concept was characterized as a solution/embodiment of a function or a specific form/configuration. For example some generated concepts that fulfill the function "track" were the use of satellite or GPS, leaving chemical traces that could be tracked by a dog, tracking credit card purchases, using a radio beacon, and using a high frequency sound to make flocks of birds or bats follow the target. Because of the wide scope of the design problem (no specifications on the target or the mission objectives) the solutions returned were similarly of wide variety in application and feasibility. A concept was judged "unique" if it had not been presented in the same form by a different member of the group. If the same concept was listed twice in the same stage (e.g. mind-mapping), only one contribution was recorded. If a different team member significantly developed the concept at a later stage (such as 6-3-5), this contribution was also recorded, but was not considered unique. Thus, the data as a whole can be examined by the total number of concepts generated or the number of unique concepts generated.

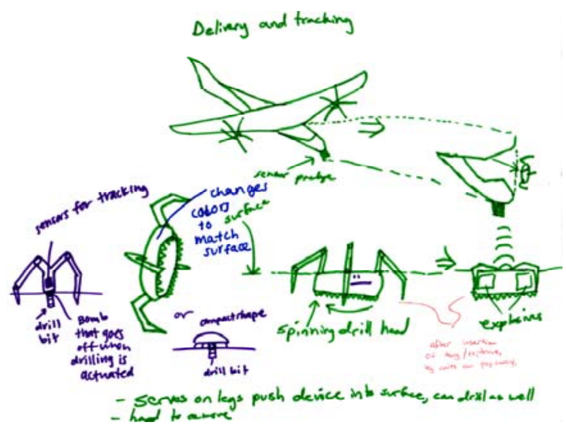

Figure 5: Sample 6-3-5 result showing burrowing tag

Because the number of participants varied among different groups from three to six, it is useful to approach the aggregate data from several different angles. We chose to evaluate the experiment using three different aspects of the data:

1. The *total* number of concepts generated by each group (including multiple instances).
2. The number of *unique* concepts generated by each group.
3. The number of concepts generated by each *individual.*

In this way, we avoided several issues with the data. If we only look at totals for the groups, the results may be skewed because of differences in group size. By looking at data for both groups and individuals, we can make full use of a larger population size but still observe group-specific trends.

4.2 Statistical Analysis of Data by Group. The first analysis of the data examines the total number of concepts generated by each group. Of the nine groups, eight are included here, with two groups at each data point. The last group is a third case of using WordTree, and was omitted because it is the only group with 6 people. The results can be organized for Design-of-Experiments as shown in Table 2.

Design-of-Experiments provides a least-squares estimate for the effect of each factor and interaction in the experiment. In the table above, the numbers of concepts generated by each of the eight included groups are listed under p1 and p2. The effects of the variables d1 (WordTrees) and d2 (Transformation Design), as well as the interaction between them are determined by subtracting the average for all "-1" runs from the average for all "+1" runs. We see that, on average, using WordTrees tended to produce 10 less concepts than not using it, while using transformation principles and facilitators led to 29 more concepts than not using them. The interaction between the two methods gave an effect of 7 more ideas.

However, it is important to determine how much of this information is due to actual trends and how much is due to error and random variation. Because we have two replicates at each data point, we can compute the variance for each run. From this, we can find the pooled variance (S_p^2= average of variances) and the standard deviation of the effects ($S_e = 2S_p/\sqrt{m}$ where m = number of groups). A t-value for each factor effect is also determined by dividing the estimated effect by S_e. These t-values can then be compared to required t-values for four runs and confidence levels of 95% and 99%.

As shown in Table 3, the use of Transformation Design (d_2) has a t-value of 4.7, which indicates with a 99% confidence level that the effect of using Transformation Design is statistically significant. The use of WordTrees did not prove to be significant in this instance, nor did the interaction between the two methods. ANOVA calculations confirm the relative significance of the effects.

Table 3 shows the results of the second analysis of the data. Here, only the number of unique concepts is included for each group; instances where a concept is developed further later in the process are not recounted. This analysis shows that once again, the use of Transformation Design (d_2) was the only significant factor, with a confidence level of 99%.

Table 2: Factorial results using total number of concepts per group

Trial	Mean	d_1(WordTree)	d_2 (Transformation)	d_1 d_2	p_1	p_2	Average	Variance
1	+1	-1	-1	+1	77	93	85	128
2	+1	+1	-1	-1	60	76	68	128
3	+1	-1	+1	-1	108	106	107	2
4	+1	+1	+1	+1	109	99	104	50
$\Sigma\cdot\Pi$:	364	-20	58	14			S_p:	8.77
Effect:	**91**	**-10**	**29**	**7**			S_e:	6.2
t_E:	**14.7**	**-1.6**	**4.7**	**1.1**			$t^*_{95}(4)$:	**2.78**
							$t^*_{99}(4)$:	**4.60**

Table 3: Factorial results using total unique concepts per group

Trial	Mean	d_1(WordTree)	d_2 (Transformation)	d_1 d_2	p_1	p_2	Average	Variance
1	+1	-1	-1	+1	75	86	80.5	60.5
2	+1	+1	-1	-1	56	74	65	162
3	+1	-1	+1	-1	95	102	98.5	24.5
4	+1	+1	+1	+1	101	98	99.5	4.5
$\Sigma\cdot\Pi$:	343.5	-14.5	52.5	16.5			S_p:	7.9
Effect:	**85.9**	**-7.25**	**26.3**	**8.3**			S_e:	5.6
t_E:	**15.3**	**-1.3**	**4.7**	**1.5**			$t^*_{95}(4)$:	**2.78**
							$t^*_{99}(4)$:	**4.60**

Table 4: Factorial results using number of concepts per individual, blocked by group

Trial	Mean	d_1 (WT)	d_2 (Trans.)	d_3 (Block)	d_1 d_2	d_1 d_3	d_2d_3	p_1	p_2	p_3	p_4	p_5	Avg.	Var.
1	+1	-1	-1	-1	+1	+1	+1	16	25	15	21		19.3	21.6
2	+1	+1	-1	-1	-1	+1	-1	14	16	18	12		15	6.7
3	+1	-1	+1	-1	-1	-1	+1	28	34	20	26		27	33.3
4	+1	+1	+1	-1	+1	-1	-1	41	32	36			36.3	20.3
5	+1	-1	-1	+1	+1	-1	-1	17	15	20	15	27	18.8	25.2
6	+1	+1	-1	+1	-1	-1	+1	19	15	13	17	12	15.2	8.2
7	+1	-1	+1	+1	-1	+1	-1	32	22	26	14	12	21.2	69.2
8	+1	+1	+1	+1	+1	+1	+1	15	19	21	21	23	19.8	9.2
$\Sigma\cdot\Pi$:	172.6	0.1	36.1	-22.6	15.8	-22.1	-10.1						S_p:	4.9
Effect	**21.6**	**0.0**	**9.0**	**-5.7**	**4.0**	**-5.5**	**-2.5**						S_e:	1.7
t_E:	**12.8**	**0.0**	**5.4**	**-3.4**	**2.3**	**-3.3**	**-1.5**						t^*_{95}	**2.31**
													t^*_{99}	**3.36**

4.3 Statistical Analysis of Data by Individual. One challenge of interpreting this study by group is the relatively small sample size. With only two replicates for each of the four trials, uncertainty exists about the true characteristics of the population, even though the results are statistically significant. Different group sizes, personalities and interactions in the groups, and even time of day may affect the studied factors. We can increase the effective sample size if we also examine the results by individual. Now, instead of eight (or nine) samples, there are 35 (or 41) independent samples. The additional unknowns that result from different group dynamics can be controlled by using blocks to separate the individuals of different groups. Hence, the results can be arranged as shown in Table 4 (once again leaving out the 6-person group to even out the distribution of replicates throughout the experiment).

Like the group results, this analysis indicates that using the transformation principles and facilitators has a statistically significant positive effect on the design process (confidence level of 99%). The greater sample size also results in eliminating most of the effect due to the use of WordTrees. In addition, the effect of the block (members of different groups) was also found to be significant (confidence level of 99%).

Another insight resulting from this analysis of individual contributions is that there is a significant interaction between the use of WordTrees and Transformation Design. Even though WordTrees by themselves did not contribute to a rise in quantity, the interaction between the two design methods resulted in a slight increase in the number of concepts, above and beyond the effect of Transformation Design alone (confidence level of 95%).

4.4 Diversity and Novelty of Solutions. The data indicate a large degree of variation between teams in the concepts that were generated. Almost 500 different concepts were generated between the nine groups, with an average of 90 concepts per team over a two-hour period. Out of these, 352 concepts were only mentioned by one team. In fact, although a few concepts were proposed as many as 12 times, the average number of times any given concept was generated over the course of the experiment was only 1.66, showing a wide spread of diversity. This diversity was supported by the WordTree method even though the experimental results do not show an increase in quantity of ideas. Thus, the WordTree method does assist in increasing novelty and diversity.

The concepts generated seemed to fall into six categories. The majority of them fulfilled the main functions of "tag, track, and effect" from the design statement. In addition, some concepts addressed the overall form of the system, such as resembling a bird, insect, seedpod, helicopter, or animal droppings. Other concepts developed general methods of power or transportation (e.g. hovering, insect legs, digging underground), as well as transformation issues (folding wings, changing shape for camouflage, break-away modules for tagging, etc.). An example concept of looking to nature of analogous design is shown in Fig. 6, where a bird-like UAV releases a tag embedded in a substance disguised as bird droppings.

5. Discussion: Broader Impacts

The results from the previous section inform not only innovators in engineering but also engineering education. It is vital for engineering educators to have resources that integrate powerful tools of concept generation which resonate with complex and different ways of thinking as classrooms are increasingly filled with diverse learners. There is an international necessity to (re)consider innovation, imagination, and literacy as ways to develop and strengthen learning that beacons engineering education to value and address the dynamic needs of design. From representatives of the United Nations, to policy-makers, educators, economists, artists, engineers, to many in between, the importance of world citizens to be critical thinkers, innovators, and have literacy skills for the 21st century is lauded. Indeed, the Director-General of the United Nation Education, Science, Community Organization posits, "In a world increasingly shaped by science and technology, scientific and technological literacy is a universal requirement… it is vital to improve scientific and technological literacy" [29].

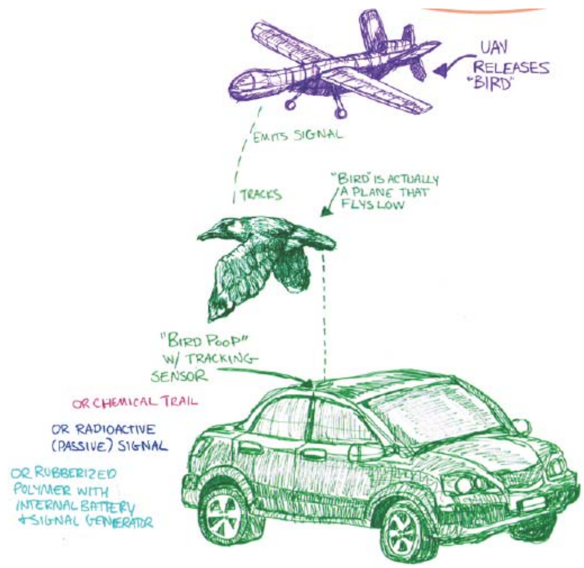

Figure 6: Exemplar concept from 6-3-5.

Whereas traditional engineering education pedagogy resonates with notions of transmitting knowledge from one person (usually the professor or engineer) to another (usually the student), DbA, WordTree DbA, Transformation design, 6-3-5, and mindmaps integrate pedagogy gleaned from education and psychology research that helps illuminate ways that designers think, generate ideas, learn, and develop literacy in science, technology, engineering, and mathematics (STEM.) This research on the development and inclusion of methods that build on psychological and educational tools to improve innovation techniques and development of literacy in engineering, integrates multiple modes of communication. With these scaffolding tools in DbA, designers are more able to describe and investigate complex engineering concepts and generate innovative ideas, thus STEM becomes accessible to a much broader range of communities having varied degrees of exposure to engineering.

Breaking down the communication barrier then opens the space for increased novel idea generation.

In this research formal definitions of terms provide a standard language by which people can discuss transformers, thereby enhancing designers' understanding of transformation processes similar to the language found in the field of kinematics and robotics. The nature of language, engineering language in this context, is heteroglossic – meaning that as more and different people engage in dialogue about engineering, the language shifts, changes, and encompasses new meanings over time [30]. Applying the principles and facilitators imaginatively to identify sub-systems of transformation, integrate these sub-systems, develop the kinematic skeleton, and finally generate the storyboarding of transformation produces multiple and varied language acquisition experiences thus increasing engineering literacy. The reading, speaking, and producing of multiple texts (spoken language, images, products, symbols) with the scaffolding of principles and facilitators definitions supports the participants in the heteroglossic discussions of engineering design and concepts.

Analogies of design relate across content and contexts. When applying strategies to generate multiple novel ideas, techniques that meet the learning styles and varied methods of communication are more fruitful. Diverse design teams come to the ideation process with many and different lived experiences. These varied experiences inform the way that each designer views and questions the world. This world, designed by engineering, is abundant with opportunities for community development through a more comprehensive understanding about effective communication of idea sharing and problem solving. At times, the hindrance in community development is a lack of communication strategies, especially about idea sharing and problem-solving. Communication barriers are community barriers by creating silences and marginalization of those not able to understand and/or be actively involved in the engineering design process. The guiding tools in this research to improve concept generation in engineering are methods of increasing ways that students in engineering education and designers are able to generate and communicate their ideas that ultimately help shape our world.

6. Conclusions

This paper focuses on the study of Design-by-Analogy concept generation techniques that build upon fundamental studies in DbA, such as the need to reformulate design problems to increase the number and diversity of analogies developed. A controlled experiment was conducted using a sample of 41 senior-level mechanical engineering students divided over nine teams. These teams each followed one of four formal concept generation approaches, incorporating two recently developed DbA design methods: WordTree Design-by-Analogy and Transformation Design. The four conditions tested were a conventional concept generation process with mind-mapping and 6-3-5, Transformation Design combined with mind-mapping and 6-3-5, WordTrees with mind-mapping and 6-3-5, and both Transformation Design and WordTrees with mind-mapping and 6-3-5. The average number of concepts generated in each 2-hour trial was 91 per group, or 22 per person. Design-of-Experiments analysis revealed that while using the WordTree method had no noticeable effect on the number of concepts generated, using the Transformation Design method yielded a consistent increase of 25-30% more concepts across all groups and individuals. Both WordTree and Transformation Design contributed to increased diversity and novelty across the design teams. These provide positive support for using advanced ideation techniques in Design-by-Analogy and have strong implications on education as broader impacts of this work.

7. Acknowledgements: The authors would like to acknowledge the support provided from National Science Foundation under Grant No. CMMI-0555851 and the Cullen Endowed Professorship in Engineering, The University of Texas at Austin.

References

[1] Christensen, B. T., and Schunn, C. D. "The relationship of analogical distance to analogical function and pre-inventive structure: The case of engineering design." Memory & Cognition, (in press).
[2] Leclercq, P. and Heylighen, A. "5,8 Analogies per Hour," Artificial Intelligence in Design '02. J. S. Gero (ed.), 285-303, 2002
[3] Casakin, H., and Goldschmidt, G., 1999, "Expertise and the Use of Visual Analogy: Implications for Design Education," Design Studies, 20(2), pp. 153-175.
[4] Linsey, J., Laux, J., Clauss, E. F., Wood, K., and Markman, A., 2007, "Increasing Innovation: A Trilogy of Experiments towards a Design-By-Analogy Method," *Proceedings of ASME Design Theory and Methodology Conference*, Las Vegas, NV.
[5] Ullman, D., The Mechanical Design Process, McGraw Hill, 1997, NY.
[6] Ulrich, K., Eppinger, S., 2000, Product design and Development, McGraw Hill, NY.
[7] Otto, K., Wood, K., 2001, Product Design: Techniques in Reverse Engineering and New Product Development, Prentice Hall, NJ.

[8] Dym, C., 2000, Engineering Design: A Product Based Introduction, Wiley, NJ.
[9] Altshuller, G. S., 1984, Creativity as an Exact Science: The Theory of the Solution of Inventive Problems, Gordon and Breach, Brussels.
[10] French, M., 1988, Invention and Evolution: Design in Nature and Engineering, Cambridge University Press, Cambridge, UK.
[11] Hacco, E., Shu, L. H., 2002, "Biomimetic Concept Generation Applied to Design for Remanufacture," Proceedings of the DETC 2002, ASME 2002 Design Engineering Technical Conferences and Computer and Information in Engineering Conference, Montreal, Quebec, Canada.
[12] McAdams, D., Wood, K., 2002, "A Quantitative Similarity Metric for Design by Analogy," ASME Journal of Mechanical Design, 124(2), 173-182.
[13] Gordon, W. J. J., 1961, Synectics: The Development of Creative Capacity, Harper and Brothers, NY.
[14] Linsey, J.S., 2007, "Design-by-Analogy and Representation in Innovative Engineering Concept Generation," Mechanical Engineering, Austin, TX: The University of Texas at Austin.
[15] Linsey, J., Wood, K., Markman, A., 2008, "Increasing Innovation: Presentation and Evaluation of the Wordtree Design-by-Analogy Method," ASME Design Theory and Methodology Conference, New York, NY.
[16] Linsey, J., Wood, K., Markman, A., 2008, "WordTrees: A Method for Design-by-Analogy," Proceedings of the 2008 ASEE Annual Conference and Exhibition, Pittsburgh, PA.
[17] "WordNet: a lexical database for the English language,"
http://wordnetweb.princeton.edu/perl/webwn.
[18] Fellbaum, C., 1998, Wordnet, an Electronic Lexical Database, The MIT Press, MA.
[19]. Singh, V., Skiles, S. M., Krager, J. E., Wood, K. L., Jensen, D., Szmerekovsky, A., 2006, "Innovations in Design Through Transformation: A Fundamental Study of Transformation Principles," DETC-2006-99575, International Design Engineering Technical Conferences, Philadelphia, PA.
[20] Weaver, J., Wood, K., Jensen, D., 2008, "Transformation Facilitators: A Quantitative Analysis of Reconfigurable Products and Their Characteristics," DETC2008-49891, International Design Engineering Technical Conferences, Brooklyn, NY.
[21] Weaver, J., 2007, "Transformer Design: Empirical Studies of Transformation Principles, Facilitators, and Functions," Mechanical Engineering, Austin, TX: The University of Texas at Austin.
[22] Mollerup P., 2001, Collapsible: The Genius of Space Saving, Chronicle Books, CA.
[23] Brute B-2 Folding Chair, 2005, http://www.buyersbox.com/deluxe_folding_chairs.html.
[24] Black & Decker model KC2002FK, 2008, http://www.lenehans.ie/lenehans/Images/DB_Detail/kc2002fk.jpg.
[25] Lawson, J., Erjavec, J., 2001, Modern Statistics for Engineering and Quality Improvement, Duxbury, CA.
[26] Shah, J. J., Vargas-Hernández, N., and Smith, S. M., 2003,
"Metrics for Measuring Ideation Effectiveness," Design
Studies, 24, pp. 111-134.
[27] Shah, J. J., Kulkarni, S. V. and Vargas-Hernández, N., 2000, "Evaluation of Idea Generation Methods for Conceptual Design: Effectiveness Metrics and Design of Experiments," Transactions of the ASME Journal of Mechanical Design, 122, pp. 377-384.
[28] Bouchard, T. J. Jr., 1969, "Personality, Problem-Solving Procedure, and Performance in Small Groups," Journal of Applied Psychology Monograph, 53(1), pp. 1-29.
[29] Mayor, F. Director-General of United Nations Education, Science, Cultural Organization, 1999, Science and technology in Africa: A commitment for the 21st century,
http://www.unesco.org/bpi/scitech/print.htm.
[30] Bakhtin, M., 1981, The dialogic imagination.
Austin, TX: The University of Texas Press.