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Design by Analogy: A Study of the WordTree Method for Problem Re-Representation

This paper presents a novel approach, referred to as the WordTree design-by-analogy method, for identifying distant-domain analogies as part of the ideation process. The WordTree method derives its effectiveness through a design team's knowledge and readily available information sources (e.g., patent databases, Google) and does not require specialized computational knowledge bases. A controlled cognitive experiment and an evaluation of the method with redesign projects illustrate the method's influence in assisting engineers in design-by-analogy. Individuals using the WordTree method identified significantly more analogies and searched outside the problem domain as compared to the control group. The team redesign projects demonstrate the WordTree method's effectiveness in longer-term, more realistic, higher validity team projects and with a variety of different design problems. Teams successfully identified effective analogies, analogous domains, and analogous patents. Unexpected and unique solutions are identified using the method. For example, one of the teams identified a dump truck and panning for gold as effective analogies for the design of a self-cleaning cat litter box. In the controlled experiment, a cherry pitter was identified and implemented as a solution for designing a machine to shell peanuts. The experimental results also highlight potential improvements for the method and areas for future research in engineering design theory.
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Keywords: analogy, conceptual design, innovation, design method, idea generation

1 Introduction

Recently much attention has been focused on increasing the capacity of engineers to innovate in design [1,2]. Successful products often have multiple innovative features [3]. Analogies are frequently a source for innovative design as demonstrated by both anecdotal and empirical sources [4–8]. This paper presents a new method for increasing engineering innovation through design-by-analogy. The method systematically guides the engineer to new linguistic representations for their design problems leading to potential analogies and analogous domains. This paper begins with a discussion of the cognitive processes involved during analogical reasoning, explores the empirical evidence highlighting the extensive use of analogy in design, and finally, describes the currently available methods and tools supporting analogous design. Next, the WordTree design-by-analogy method is presented along with the guiding principles derived from experimental evidence. A controlled experiment then measures the effectiveness of the method. Results from implementing the WordTree method on a series of redesign projects are also shown to provide data with greater validity. Finally, conclusions are drawn, and directions for future work are explored.

2 Motivation and Prior Work

The WordTree method is guided by substantial research in cognitive psychology on how people reason with analogies, informed through empirical work on design-by-analogy and moves beyond existing methods for design-by-analogy. Each of these areas is detailed in the following sections.

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2.1 Cognitive Process Model for Analogical Reasoning. Extensive research in psychology [4–7] has sought to understand how people reason by analogy (see Fig. 1). Analogy has traditionally been viewed as a comparison between two items in which their relational or causal structure match [9–13]. The problem domain is typically called the target of the analogy and the domain of prior knowledge provides a potential solution to the problem, the source. Sources are often retrieved from memory, but external resources such as databases could also be used. The human reasoning by analogy process begins with the source analogs being stored in memory, encoded. The next, and often most difficult, step is to retrieve an appropriate analog from memory [9,10,14–18]. Next, the person must find a mapping between the

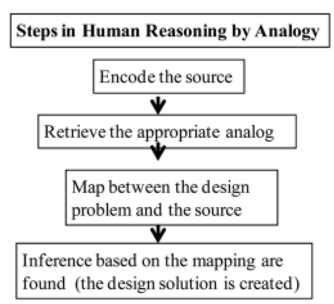

Fig. 1 Steps in human reasoning by analogy

design problem (target) and the source analog. Inferences (design solutions) are then generated.

Retrieval of an appropriate source poses difficulties, and thus databases along with other retrieval tools have great potential to enhance design by analogy. Even expert designers have limited knowledge and thus can benefit from the vast resources available in various databases. The WordTree method assists designers with this step to retrieve appropriate source analogs from both their own memory and from databases. The WordTree method guides the designers in identifying key words in cross-domains so that existing databases can be leveraged to identify potential sources for analogies.

2.2 Empirical Work on Design-By-Analogy. Empirical work on design-by-analogy demonstrates that professional designers often use analogies [5,6,13,19,20]. Engineers in particular often employ cross-domain analogies in their idea generation process [4,6,19]. Close-domain analogies in the form of references to past design are often used in process planning, cost estimation, and evaluation of concepts for a new product [5]. Both novices and expert designers employ analogies, but the impact can be different [20]. Visual analogies can improve design problem solving for both novice and expert architects but has greater impact for novices [4]. Experts use significantly more analogies than novices do and novices tend toward more case-driven analogies (analogies where a specific concrete example was used to develop a new solution) rather than schema-driven analogies (more general design solutions derived from a number of examples) [20].

Controlled experiments also provide guidance on how analog retrieval may be enhanced. Analogs are more easily retrieved when they are remembered within more general linguistic representation that applies both in the source and target domains [21,22]. The analogies and problems used in these experiments were not specific to any domain of expertise and used fantasy problems relying only on linguistic descriptions. Results were replicated with engineering students and representation can increase the probability of success up to 40% [23–25]. Further work explored the interaction between the problem and source analog representation [23–25]. The representation of the design problems has a clear effect on the ability of the designer to retrieve and use an analogy but the representation with the highest probability of success depends on how the analogous product was learned initially.

Controlled experiments also provide insight, cross-domain analogs, and reasons why designers may not implement identified analogs. Cross-domain (far-field) analogs increase the novelty of solutions produced from the analogs [26]. The timing of when analogically similar information is presented affects how frequently it is incorporated into an open-ended design problem. A distant domain analogy is most likely to be implemented if it is presented after the problem has been presented and while the participant has been unable to solve the design problem [27]. This suggests that distant domain analogies are most likely to be implemented by designers when they are having difficulty solving a design problem.

2.3 Formal Design-By-Analogy Methods. Formal design-by-analogy methods and tools have the potential to enhance experts' abilities and minimize the effects of experience gaps. A number of methods and tools have been developed including Synectics [28], French's work on inspiration from nature [29,30], biomimetic concept generation [31,32], IDEA-INSPIRE [33,34], and analogous design through the use of the Function and Flow Basis [35]. Synectics is a group idea generation method that uses four types of analogies to solve problems: personal (be the problem), direct (functional or natural), symbolic, and fantasy. Synectics gives little guidance to designers about how to find successful analogies. French's work shows the importance of analogies to nature and series of examples [28] but provides little guidance on the process.

Recent work assists designers in finding analogies. Biomimetic concept generation provides a systematic tool to index biological phenomena through functional requirements and then referencing to an introductory college textbook [31,32]. Analogies can also be retrieved based on customer needs and the Functional Basis [31,32,36]. Biological analogies can further be identified through the Functional Basis and the use of the newly developed Biology Thesaurus [35,37]. Specialized tools and databases have been created for analogy retrieval [38]. IDEA-INSPIRE [33,34], based on the function or behavior of a device, retrieves analogies from nature or other devices. DANE [39] also retrieves biologically inspired analogies based on the function, structure, or behavior of a system. All of these tools either do not provide assistance on retrieving analogies or require specialized databases that must be created. The WordTree method is designed to leverage existing databases.

3 Wordtree Design-By-Analogy Method Overview

There is significant anecdotal and experimental evidence [6,19,40] for the importance of analogy in design, but there is little work on systematic methods for promoting the retrieval and use of analogies to facilitate innovation. The lack of applicable design methods causes the teaching of this influential technique to be limited to little more than interesting examples with accompanying direction to simply "try to find analogies." Simply trying to "think of" analogies and analogous domains is difficult even for experienced engineers. Yet this ability, based on both anecdotal and empirical evidence, is clearly important and a critical path to innovation.

One of the main principles for enhancing analogical retrieval provided by prior experimental work is that design problems need to be represented in multiple forms ranging from very domain specific to domain independent, thereby providing a variety of related effective retrieval cues [23–25]. By creating a variety of related retrieval cues at various levels of abstraction, the likelihood of identifying relevant analogies is increased. The WordTree method creates multiple linguistic representations by focusing on alternative functional representations.

The WordTree design-by-analogy method systematically re-represents a design problem, assisting the designer in identifying analogies and analogous domains. Figure 2 overviews the method's basic steps: re-represent key problem functions at multiple levels of abstract through a WordTree, identify and research potential analogies along with analogous domains, and finally use this information to generate ideas.

Example analogies for the design problem of laundry folding include dousing a sail, reefing a sail, and cogging. The two identified analogous domains are sailing (specifically mechanisms for

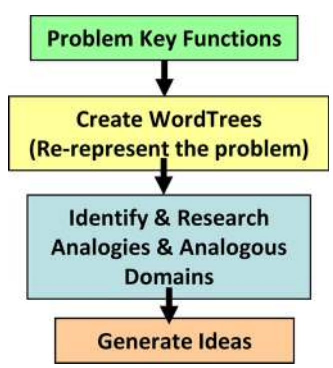

Fig. 2 Basic steps of WordTree design-by-analogy method

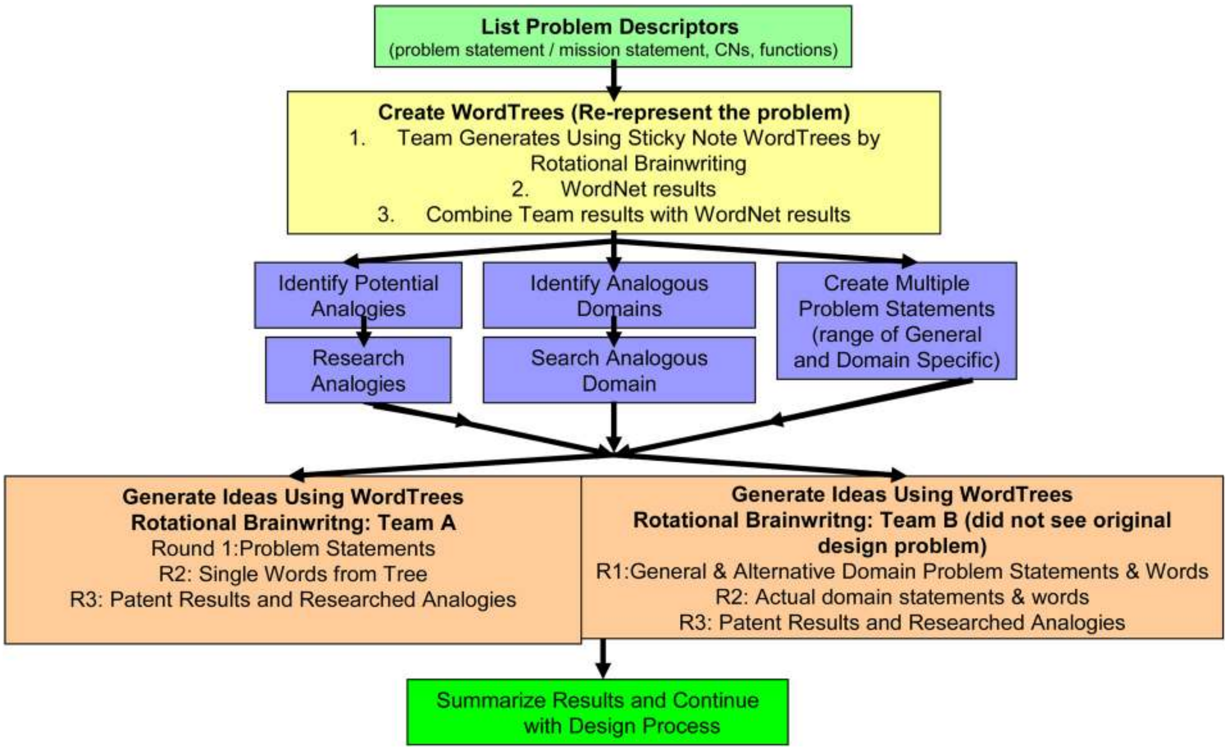

Fig. 3 Detailed View of the WordTree design-by-analogy method

collapsing and storing a sail) and smoothing machining processes. The next step in the WordTree method is to research potential analogies and the analogous domains. In parallel, new problem statements ranging from very domain specific in multiple domains to very general statements are also written. Finally the analogies, patents, analogous domains, and new problem statement are implemented in a group idea generation session. This session further refines the method's results into conceptual solutions to a design problem and provides additional inspiration for the designers.

3.1 Details of the WordTree Design-By-Analogy Method. This section will provide a detailed application of the method to the problem of a device to fold laundry (Fig. 3). The WordTree method begins by defining the *key problem descriptors*. The key problem descriptors are single word action verbs derived from the functions and customer needs for a design problem. Prior research found that transitive verbs, which are action verbs, are more effective stimuli for idea generation than other verbs [41]. The key problem descriptors are defined from the customer needs, mission statement, function structure, and black box model. Key problem descriptors that should be considered are the following: (1) single word describing the overall function of the device (often in the Box Black), (2) critical or difficult to solve functions, and (3) important customer needs transformed into single action verbs. Normally the customer needs are a combination of an adjective and a noun. To be used in the WordTree method, they must be converted to equivalent verbs. For example, the verb form of the customer need "easy to open a door" would be "change force." Some of the customer needs for a device to fold laundry are to smooth the laundry, to be rugged, to be easy to use, and to be easily portable. Some of the key problem descriptors for this device are fold, prepare (laundry for storage), store, and smooth.

The next step is to re-represent the key problem descriptors using WordTrees through both the knowledge of the design team and using a database, WordNet[1]. First, the design team use rotational brainwriting to create sticky note WordTrees (Fig. 4) dividing the key problem descriptors evenly. Rotational brainwriting is very similar to 6-3-5 [42] except that each team member receives three sheets of paper and develops one WordTree per sheet (Fig. 5). Each person spends ten minutes creating the WordTrees. The WordTrees are then rotated clockwise around the table and the next person spends five minutes adding to the WordTrees. The goal is to generate new linguistic representations of the problem that will later lead to more ideas. The sticky notes allow for additional layers to be added and words to be rearranged. Verbs within the English language tend to be hierarchically structured with more general verbs and more specific verbs. More specific verbs for a given word are known as troponyms, and more general instances are known as hypernyms. For example, some of the troponyms for the word "fold" are "bend, 1/2 fold, and crease" and hypernyms are "change surface" and "change shape." More general verbs are placed above, and more specific are placed at lower levels (Fig. 4). A rotational brainwriting method was chosen, because a prior group idea generation experiment showed this type of approach results in a greater number of ideas [43].

After the team generates the sticky note WordTrees using rotational brainwriting, WordNet is used to find additional results. The sticky note WordTrees can also serve as additional seed words for WordNet since some words in WordNet produce few results. The WordNet and sticky note WordTrees are then combined. WordNet was originally developed as a database to support natural language processing and computational linguistics [44]. It is similar to a thesaurus since it gives synonyms for words but hierarchically structured with general word meanings at the top and more domain specific below. Prior research has shown the potential for lexical database to assist in identifying linguistic analogies [45], but WordNet has not been used previously to

[1]Please see http://wordnet.princeton.edu/perl/webwn.

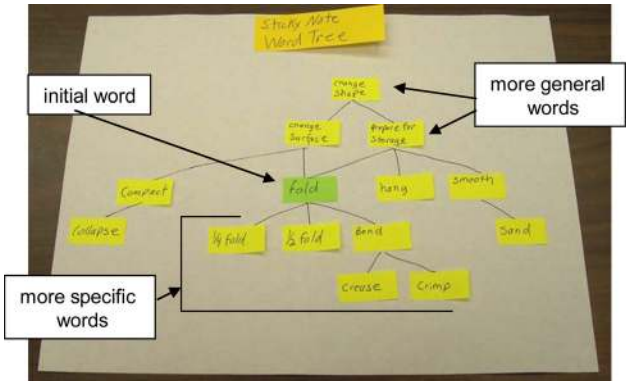

Fig. 4 Sticky-note WordTree

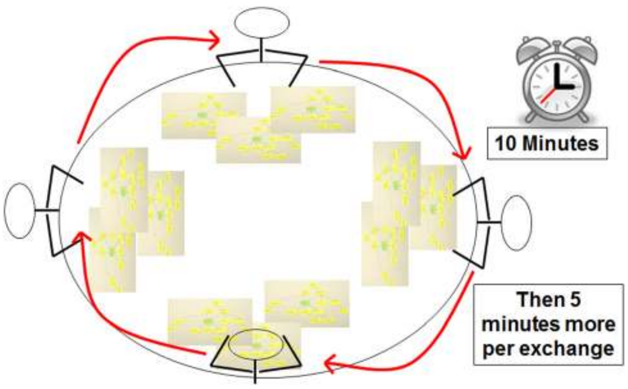

Fig. 5 Rotational brainwriting

identify design analogies. If the words are unusual or unfamiliar, it is useful to include these in the WordTree since they are frequently very domain specific verbs (functions) in distant but analogous domains. If working with a multilingual team, WordTrees can be created in multiple languages using both the team's knowledge and WordNet available in many languages (e.g., German, Hindi, French). Each language will produce a different representation, different analogies, and will inspire different ideas.

Both the design teams' knowledge and WordNet create different re-representations. WordNet provides similar words based on how verbs are used within the English language. The design team will implicitly incorporate their prior experience and knowledge of the design problem. For example for the folding device, a more general representation of "fold" within the context of the design problem is "to prepare for storage." This particular re-representation would not be provided by WordNet because WordNet does not account for the context of the design problem. In contrast, unlike taxonomies of nouns (e.g., from biology-mammals, reptiles, etc.), people cannot typically describe hierarchies of verbs [46].

Next, the team reviews the WordTrees looking for potential analogies and analogous domains. The team also uses the WordTree to assist them in creating a multiple problem statement. An analogy is a potential solution that shares functional similarity with the design problem and an analogous domain is a category of solutions that share similar relationships. Analogies can occur anywhere in the WordTree and frequently occur as words that are both nouns and verbs or as verbs whose meaning is unfamiliar (e.g., "brail, to roll up sails") (Fig. 6). Many analogies occur at the ends of the branches, the "leaves of the tree." Analogous domains frequently occur on parallel branches, which contain multiple potential analogies. In Fig. 6, potential analogies are highlighted in yellow, and sets of analogies that form analogous domains are circled. For example, "douse a sail" and "reef a sail" indicate that sailing is an analogous domain for the problem of folding laundry. Many mechanisms for dousing a sail are also effective solutions for folding laundry since they fold, roll, or otherwise compact fabric. These unexpected analogies and analogous domains are in areas likely unfamiliar to most designers make the WordTree method highly effective. The WordTree method is only one possible linguistic re-representation, and others should be researched including visual representations. TRIZ also linguistically re-represents a design problem as the conflict between generalized engineering parameters [47,48].

Very often designers will not be familiar with the basic principles of the identified analogies, and therefore the analogies are researched along with searching for solutions in analogous domains. Google Image is an effective and efficient tool for identifying information about a potential analogy. Figure 6 illustrates two mechanisms identified as analogies for the laundry folding problem. Patents in analogous domains should be searched also. Design fixation is a potential risk anytime a solution is presented to a designer. The search results have the potential to cause fixation, but prior experimental results suggest it is unlikely for this method. Searching for analogies and patents in analogous domains can be completed prior to idea generation by a team since uncommon solutions, the type of solutions analogies should provide, tends to increase the number of ideas generated, the novelty of the ideas, and does not cause fixation [49,50].

Finally, teams use the analogy results to generate more ideas. Any idea generation method is acceptable but a rotational brainwriting (a graphical version of 6-3-5) is recommended to maximize results [43]. Two separate teams of designers are recommended to base their idea generation sessions on the results from the WordTree method (bottom of Fig. 3). The first team is the original team who owns the design problem and who generated the WordTree. The second team is unfamiliar with the problem and is given the general and alternative domain problem statements along with the WordTrees. When using analogies, individuals tend to focus too much on the surface and unimportant features of the problem rather than the causal structure [17,51]. It is believed that the second team will be less likely to focus on unimportant features of the original design problem because they will be shown a series of analogous problems, which will tend to focus them on the deep structure and not the surface information. After each team's idea generation, the results are summarized using any number of methods such as morph matrices or mind maps [47]. The team combines the results with other ideation techniques and then continues with the design process moving on to idea selection.

4 Research Questions Regarding the WordTree Method

The WordTree Method is founded on prior experimental results [23,25] and theory. This basis increases the likelihood of an effective technique but does not guarantee it. A series of evaluations is thus needed to understand the outcomes of the WordTree method and provide guidance for further refinement. This need is addressed through two studies based on the following research questions:

- Question 1: Does the WordTree method increase the number of analogies identified relative to a control group who are asked to generate analogies intuitively? The hypothesis is that the WordTree method does increase the number of analogies identified since this is what the method was designed to do. It will ease analogy retrieval by identifying cross-domain functions.
- Question 2: Does the WordTree method produce unexpected, useful analogies? It is possible that the WordTree method could produce analogies that are either typical solutions that would be thought of without the method or analogies that are not useful for solving the design problem.

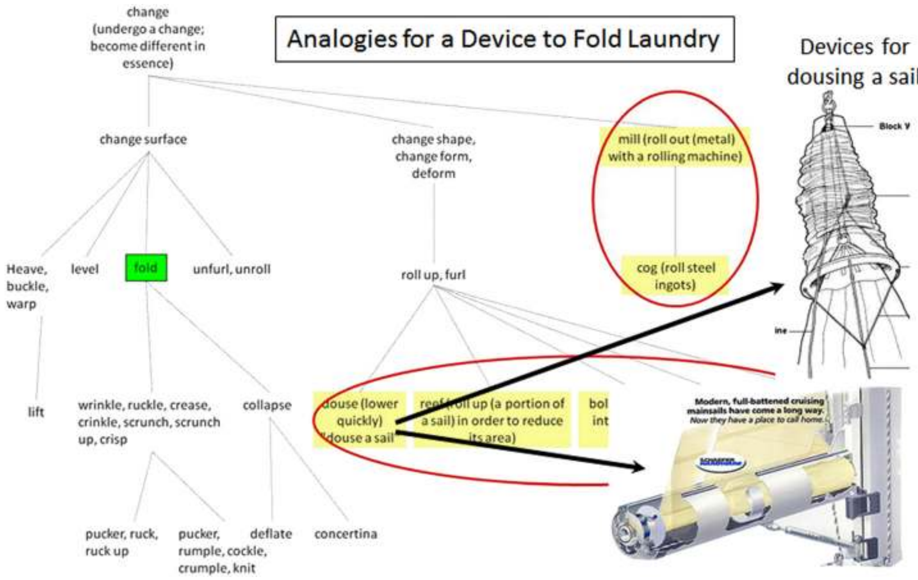

Fig. 6 Creation of the WordTree allows analogies and analogous domains to be identified. A partial WordTree for the function of "fold" is shown. Analogous domains for folding include sailing (douse a sail, reef a sail) and machining processes (cog: roll steel ingots). Two analogies based on mechanism for dousing a sail that are effective for solving the laundry folding problem are shown.

- Question 3: Does the WordTree Method change the search terms designers use with databases thus seeking more cross-domain analogies?

The WordTree method was evaluated using two approaches: (1) a controlled experiment of individual designers solving a novel design problem and (2) with teams working on the redesign of commercial products. The teams working on the redesign of commercial products provided a more realistic design setting but afforded less control. The experiment facilitated good control but also limited the time that could be spent on a design problem. The team design projects also allowed the effects of the WordTree method to be evaluated on a wider range of design problems and over a longer time period since teams worked on their own.

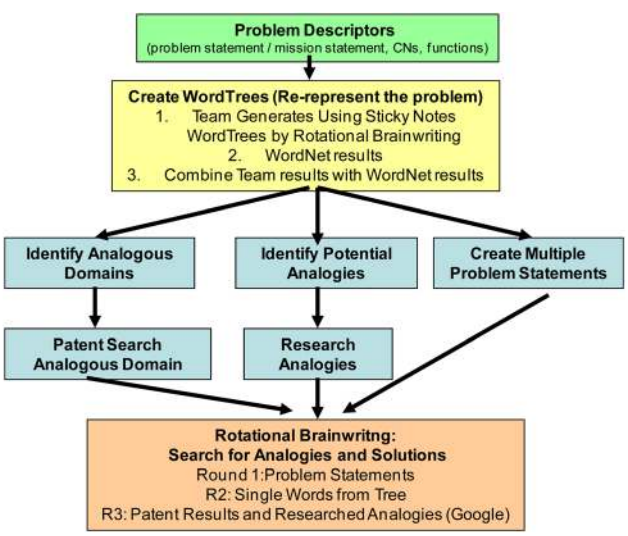

Fig. 7 WordTree method as presented to the experiment participants during lecture

5 Controlled Experiment Method

The controlled experiment compared the WordTree method to having participants generate ideas without the method. Both groups were familiar with design-by-analogy and had been exposed to a few different idea generation techniques as a part of their mechanical engineering junior year design methods class.

5.1 Procedure. The WordTree Method was taught to the senior capstone design course during one 50 min lecture (Fig. 7). Participants were recruited from the senior capstone design course prior to the lecture on the WordTree method. They were given extra credit for their participation and were told the amount of extra credit would depend on their effort and results. The opportunity was offered at the University of Texas at Austin approximately one month into the semester and approximately half of the students chose to participate. The control group session occurred pre-lecture and the WordTree conditions occurred post-lecture. To reduce biases due to when participants chose to sign-up for sessions, half of the participants were randomly emailed sessions that occurred as control groups prior to lecture and the other half received session times after the WordTree method lecture. Participants who missed their first session time or signed up later were assigned to available time slots. Two participants assigned to the WordTree group sessions did not attend the WordTree method lecture, so they were run in the control condition, and their data were not included in the results. Participants knew this was a new method being evaluated.

The design problem was to develop a device to shell peanuts for use in third world countries (Fig. 8) and had been used in previous experiments (see Fig. 9) [25,43]. Both conditions were guided by the experimenter using scripted instructions. The version of the method implemented for the experiments did not include idea generation with a design team who had not seen the original design problem (this aspect of the method was not evaluated). The limited experimental time did not allow for these aspects of the method to be tested. The experiment was completed with individuals rather than teams. The reduced method explored in this experiment is shown in Fig. 8.

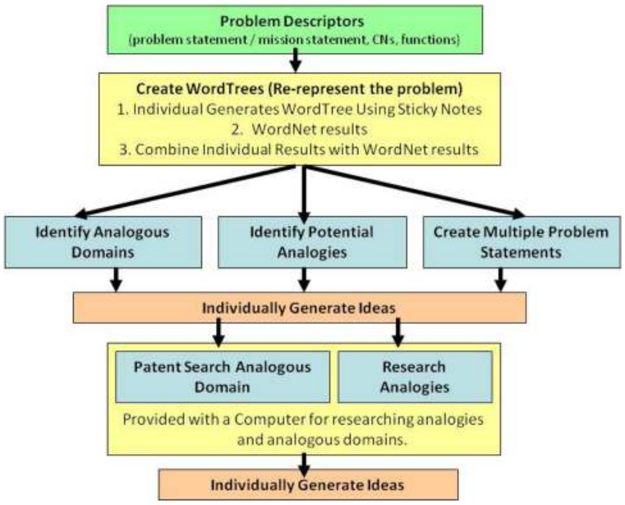

Fig. 8 Modified WordTree design-by-analogy method implemented for the controlled study

Device to shell peanuts

Problem Description

In places like Haiti and certain West African countries, peanuts are a significant crop. Most peanut farmers shell their peanuts by hand, an inefficient and labor-intensive process. The goal is to build a low-cost, easy to manufacture peanut shelling machine that will increase the productivity of the peanut farmers. The target throughput is approximately 50 kg (110 lbs) per hour.

Customer Needs:

- Must remove the shell with minimal damage to the peanuts.
- Electrical outlets are not available as a power source.
- A large amount of peanuts must be quickly shelled.
- Low cost and easy to manufacture.

Functions:

- Import energy to the system
- Break peanut shell
- Separate peanut shell from the nut

Fig. 9 Peanut sheller design problem for the experiment

Participants in both conditions were told they could end idea generation at any time, moving on to the next task or they could spend the entire time generating ideas. They were also reminded their amount of extra credit depended on effort and results. After 45 min, participants were also allowed to use a computer to search for ideas and solutions. If they found a useful idea, they were asked to reference it. When participants decided to end idea generation, the time was recorded, they were given a sheet asking them why they ended the sessions, and then a second sheet stating that most people could generate ideas after they thought they had run out of ideas. It was hoped that this could give a measure of time on task and the influence of other participants' actions would be minimal. Instead, the other participants' actions had a large influence on when participants decided to end the idea generation session. One to five participants worked individually in the same room. They were given a 5 min break after 60 min. This first session lasted about two hours.

At the end of the session, participants were asked to record their search strategy including a list of the terms they searched for and the search engines they used. If participants left the web browser open on the computer, the webpage history was recorded to provide further insights into their search approach.

Participants in the control group were told to generate ideas and analogies whereas the WordTree group was guided through WordTree. The control group was also instructed that they could use any method they learned in the design methods class if desired. The control group had a total of 90 min for idea generation and database search, but only the first 60 min is included in the analysis to match the WordTree group. Throughout the entire session for both groups, the color of pens being used was switched every fifteen minutes so that temporal changes were documented. The first 60 min was designed for comparison between the conditions, and the additional time in the control was to observe their behavior over a longer time period. Both conditions required two hours during the first session and a one-hour follow-up session. Our experience has been that it is difficult to obtain participants for more than three hours, and therefore both conditions were limited to this.

A series of slides with a script guided the participants through the WordTree method. Each step in the process had a time limit as follows:

- Create sticky note WordTrees for the following key problem descriptors (20 min):
  - Shell
  - Remove
  - Separate
  - Import energy
- Combine sticky note WordTrees with WordNet WordTree (5 min)
- Identify and list potential analogies and analogous domains (10 min)
- Write new problem statements (10 min)
- Generate ideas (45 min)
- Generate ideas and use database support if desired (15 min)

The sticky note WordTrees were recorded prior to combination with the provided WordNet WordTree. Two WordNet WordTrees for "shell" and "separate" were created by the experimenter and provided in finished form (Fig. 10). The WordTrees are filtered versions of the words provided by WordNet and were chosen as a combination of possibly relevant and random words.

During a second hour-long session, participants in both groups documented the analogies they had generated, put all of their ideas into a morph matrix [47], and filled out a post experiment survey. The matrix contained some common predefined functions for the peanut shelling machine, but participants were encouraged to add additional functions as needed. The participants' documentation facilitated measurement. When participants finished the list of analogies, morph matrix, and the survey, they were told to spend any remaining time generating ideas. This step prevented participants from rushing through these final steps.

5.2 Measures. The controlled experimental setup allowed for quantitative and qualitative measures to be made including the number of ideas, number of analogies, within or outside domain search strategy, and quality of concepts. The condition information was removed as much as possible during evaluation. The number of ideas generated was based on the number of boxes filled in for the morph matrix by the participants.

The number of analogies identified by the participants is critical for the evaluation of the WordTree method. An analogy was defined to the participants during class lecture as "The mapping of features of one thing to a design problem you are trying to solve." It was further explained as anytime you take information from an example you have seen before and a series of examples were presented including: a sail for a cargo ship based on a bat wing [52–54], the Oxo Good measuring cup and a previous patent showing a very similar design, and an inch worm built from Legos based on a child's wind-up toy.

The number of analogies was calculated with two approaches. The first was based on all analogies the participants listed during the second session. It was noticed that many of the participants in the WordTree condition did not list the potential analogies and analogous domains they had identified during the first session. A second measure was made of the number of nonredundant analogies listed in either the first or second session. The number of analogies was scored by one of the authors and a second evaluator. Evaluation by the second evaluator for the number of

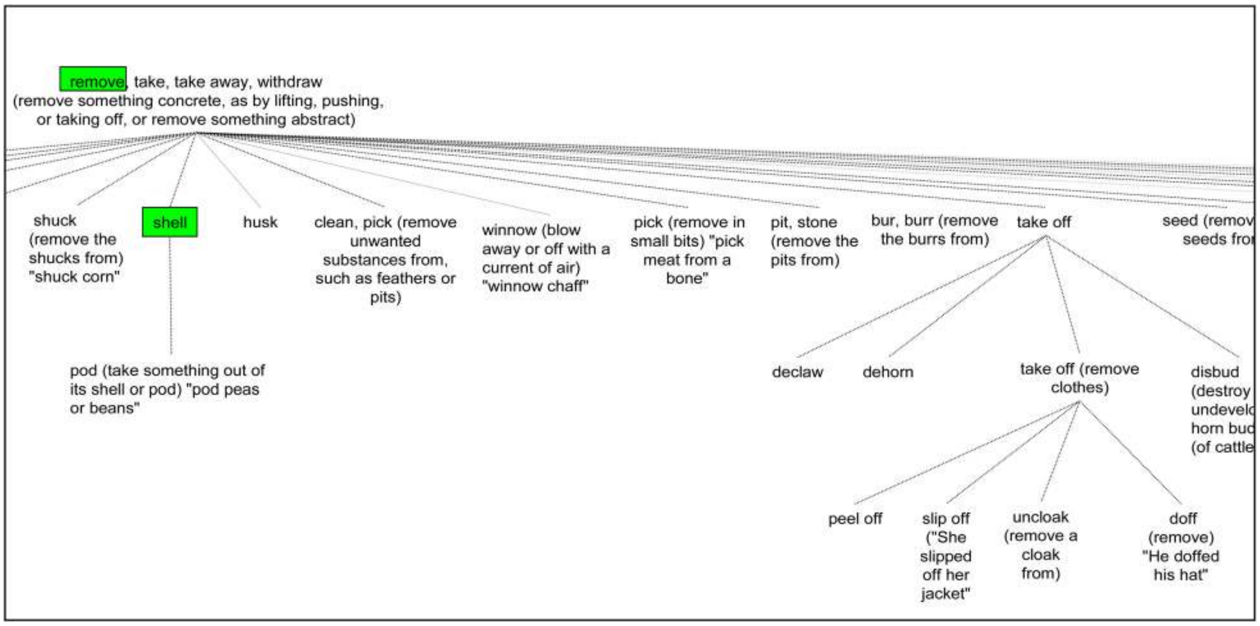

Fig. 10 Part of the WordTree provided to the participants

Fig. 11 Another analogy identified and implemented by a participant in the WordTree group was a cherry pitting device. The participant's solution is shown on the right.

analogies revealed a mistake for the number of analogies for one participant as reported in Ref. [55], but inter-rater agreement for the number of nonredundant analogies was still very high with a Pearson's correlation of 0.97.

The search strategy used by the participants was scored for containing words outside the domain of peanut shelling or not. For example, searching for "pitting cherries" (see Fig. 11) or "pod peas" was outside the domain and "nut cracker" was within the domain. Not all of the participants chose to use databases to assist them and a few of the participants' search strategies could not be determined based on the information they provided. The two participants who missed the lecture on The WordTree method were included in the search strategy data but not for the rest of the measures.

Quality, as defined by Shah et al. [56,57], is a measure of a concept's feasibility and how well it meets design specifications. In this paper, quality is measured on a three-point rating scale. Each concept generated by a participant received a quality score. Prior work [43] has shown this scale to be reliable with Cohen's Kappa [58] of 0.42 demonstrating fair level of inter-rater agreement. Two participants included Mindmaps [59] in their concept generation and each was evaluated as a single concept. A coarse (three-point) highly defined rating scale is used rather than an unanchored rating scale since our prior work showed difficulties in applying an unanchored scale (low correlation between raters) [60]. An unanchored rating scale has an expert evaluator rate a concept on a spectrum, for example, 1-7 with 1 lowest quality and 7 highest quality, without specifically defining each point on the scale.

5.3 Participants.

The participants were senior undergraduate students at the University of Texas at Austin taking their capstone design course. There were two females. All students had completed a design method course the prior semester. The participants' average GPA of 3.4 for their design methods class and 3.7 overall is higher than the general class average. Participants' survey results indicated that they had an average of half a year of work experience in engineering.

5.4 Controlled Experiment Results and Discussion.

The number of ideas generated, number of analogies, and the percentage of implemented analogies measured the WordTree Method's

Table 1 Number of Analogies as Scored by the Participants and the Evaluator

	Number of Analogies (S.D.)	N
Mean Control	7.6 (4.8)	10
Mean WordTree	23.3 (12.2)[a]	10

[a]Statistically significant difference $p < 0.01$.

Table 2 The participants implemented only a small fraction of the analogies that they identified

	Percentage of identified analogies that were used to find solutions
Mean Usage	42%
Min. Usage	15%
Max. Usage	64%

Table 3 Number of participants who searched outside the domain of peanut shelling

	Outside Peanut Shelling Domain	Only Within Domain of Peanut Shelling
Control	0	4
WordTree	6	2

effects on idea generation. Participants in the WordTree condition found significantly more analogies than the control group, ($t(18) = 3.8$, $p < 0.01$, Table 1). The participants were asked to list analogies at two different stages, after finishing the WordTree Method and after generating ideas. Often participants would list analogies on one but not both lists even though participants were instructed to list all analogies on the final list. An evaluator combined the two lists removing redundant analogies, and this was the score used for analysis. While the WordTree method assists in identifying more analogies, participants are not using the potential analogies to find solutions to the design problem (Table 2). All results shown are calculated for the first 60 min of idea generation. The control group had 90 min, whereas there was only 60 min for the WordTree group.

There are a number of reasons why the participants may not be implementing the presented analogies and further work needs to explore this issue. They may be having trouble mapping from the source analog to the target problem. Novices may not have sufficient knowledge of the problem domain in order to make the connection to the analogs or to re-represent the problem domain to align with the source analog. Similar the finding of Tseng et al. [27], participants may need to work on the design problem for some time and be in a state of being unable to solve it before they will attempt to use distant domain analogies. Other studies have shown that participants may judge distant domain analogies as not relevant, but in reality they are just as relevant as closer domain analogies [61]. An experiment by Benami and Jin showed a similar result with participants having difficulty creating design solutions based on linguistic functional descriptions [62]. Participants may need visual images and additional information about the analogies before they can create solutions. The team design projects allow for additional information to be gathered on the reasons why participants may not have implemented the analogies in the controlled experiment.

A coarse evaluation of the results indicated no difference in novelty, variety, or quality was likely between the two conditions and since the participants appear to not be using their listed analogies to finds solutions; therefore, no difference between conditions is expected for these metrics. A more robust quantitative assessment of novelty, variety, and quality was not undertaken.

5.4.1 Results From Database Searches. Table 3 summarizes the number of participants in each condition who searched outside the domain of peanut shelling and those who only searched within the domain. Examples of the search results from both conditions are shown in Figs. 11–14. The WordTree method supports participants in finding novel cross-domain analogies and substantially modified their search strategy. Semantic distance using WordNet::Similarity [63] would be one quantitative approach for determining the degree of similarity between two concepts. Unfortunately, semantic distances cannot be calculated for sets of words, which is what is needed for determining if certain search terms are very close to the original problem domain or not. Terms that were considered within domain were the terms contained within the original problem statement including “peanut, shell, remove” along with their common synonyms of “sheller = nut cracker.” Example terms that were considered outside the domain were peel, panning, and winnowing, which are not obvious analogies for peanut shelling. Participants in the control conditions did find useful information for the peanut shelling problem, but the information they found was all closely related to peanut shelling. Participants in the control condition located the current solution for this problem, the Malian peanut shelling machine (Fig. 14), and industrial large-scale solutions for peanut shelling.

All available data are shown for the entire time participants spent searching databases to highlight the significant impact the WordTree method had on participants’ search strategies. Even though the WordTree group had a maximum of 15 min whereas the control group had 45 min with most using at least 30 min, the control group still did not search outside the peanut shelling domain. It was expected that participants would first search a close domain and then expand their search to other domains so participants in the control group would be more likely to search outside the domain. Not all participants chose to use the assistance of databases. Web history information was also used to evaluate

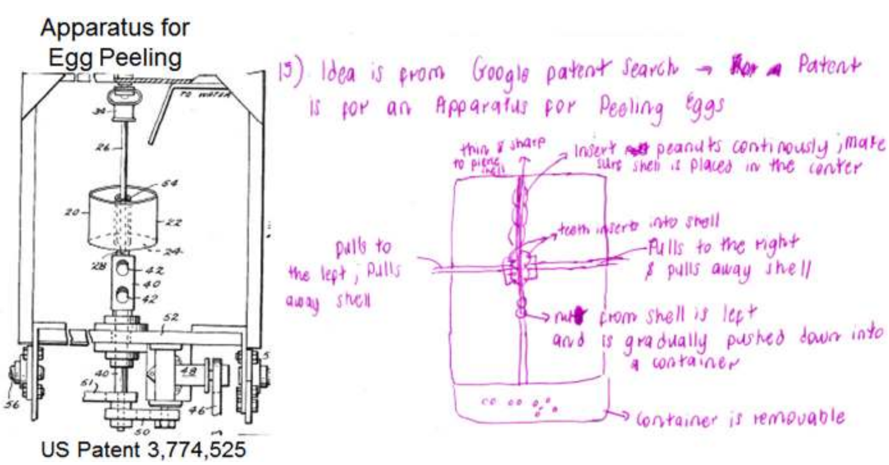

Fig. 12 An analogous solution found (right) based on an egg peeling device (left) by a participant in the WordTree group

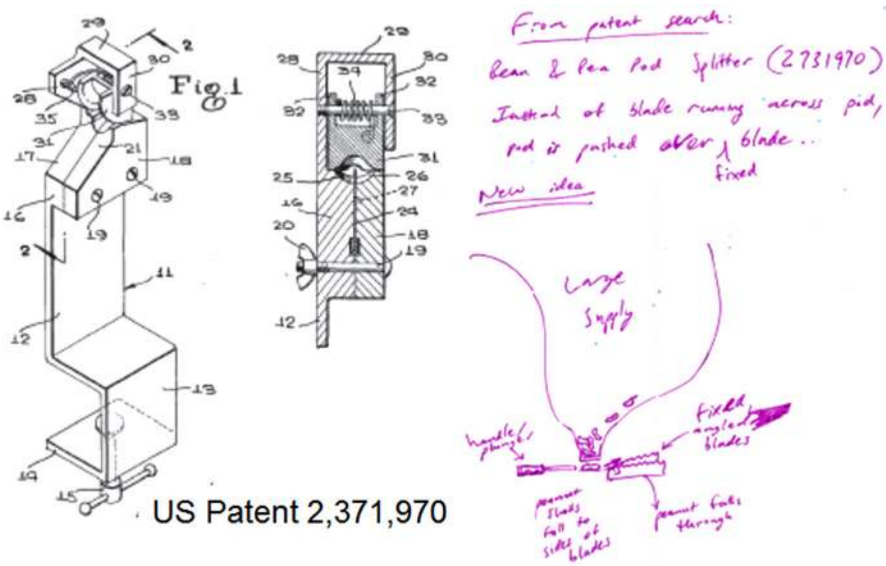

Fig. 13 A device to split bean and pea pods (left), located by one of the WordTree condition participants, provides an analogous solution (right) to the peanut shelling problem

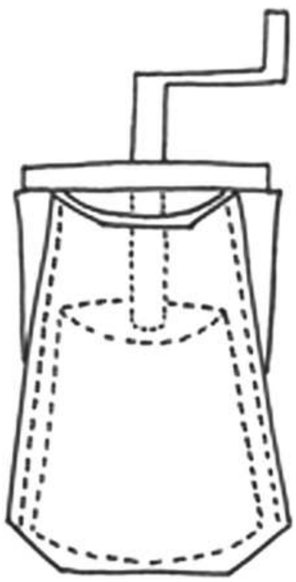

Fig. 14 Participants in the control group only found within domain solutions to the peanut shelling problem. This solution is a hand-powered device that removes the shell from the peanuts ("Full Belly Project," 2006).

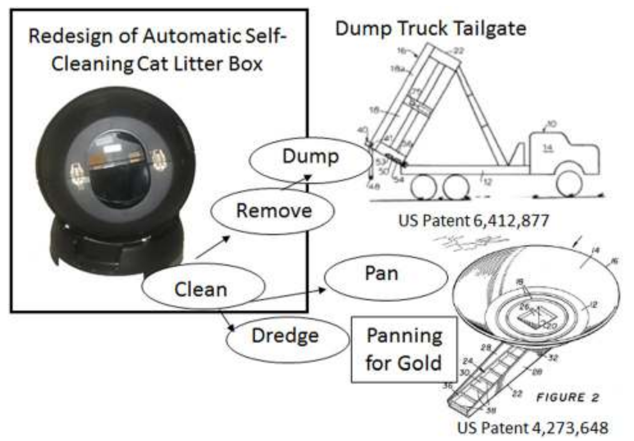

Fig. 15 Analogies and analogous domains identified by a team who was redesigning a self-cleaning cat litter box

the search strategy. Web histories were available for six of the participants.

6 Team Design Project Results

To further evaluate the WordTree design-by-analogy method and explore it in a more realistic design setting with a longer time scale, it was taught in the senior design methods course. Multiple-case studies from the team design projects allows additional data to be gathered, which can be compared with the results from the controlled experiment. The team project data demonstrates the WordTree method's effectiveness on a broader range of design problems. Hypotheses about why the participants did not implement the analogies into solutions in the controlled study can be further explored with the multicase studies. One of the authors taught the WordTree method as part of a lecture series on idea generation, which included brainstorming, 6-3-5, MindMapping, and TIPS/TRIZ [47]. The method was not presented as a new method.

6.1 Team Design Projects: Procedure. As part of their design methods class, 92 senior mechanical engineering students were required to use the WordTree Method. In the senior design methods class, teams of four to six students redesign a commercial product that they choose. The entire semester is spent learning and applying various design methods starting with identifying the customer needs through embodiment design [47]. To simplify the WordTree method for the class, the steps of creating new problem statements and using a second team to assist in generating ideas were not included (Fig. 7 without the create multiple problem statement step). The teams learned the method in one 50 min lecture and then spent a second lecture to complete the method. During the second lecture, an author reminded the teams of the process steps, answered questions, and guided them through the method. Many of the teams had their WordTrees finished and were left to research the analogies at the end of the second lecture

Table 4 Additional Typical Examples of Analogies and Analogous Domains Identified Using the WordTree Method

Design Problem	Identified Analogies		Patents	Analogous Domains
An automatic casting system for a fishing rod	• catapult	• hurl	• 5,383,442 pump action pellet gun	• catapult
	• loft • throw • shoot • sling	• hurtle • gun • machine gun	• cross-bow • pellet and paint ball	• shoot
Improved cleaning capacity robotic vacuum	• brush • sterilize • spray • water-wash	• retract • sponge up • suck	• brush assembly in vacuum 6381802 • liquid sprays in a battery operated hand vacuum 5970572 • sterilizing system in a vacuum 20060236496	• pull in
A portable washing machine which runs on alternative power	• hydrate		• drilling machine with pneumatic control- pre-filled compressed air tank	• nature
	• sporulate • feed • heat		• mechanical-thermal solar power system • wind energy apparatus	• prefabricate

period. Teams were required to hand in, as a part of their design report, at least one WordTree with at least thirty words, five analogies, two analogous domains, and five useful patents from their research. For extra credit, teams individually filled out an opinion survey.

6.2 Team Design Projects: Results and Discussion. In general, the teams were able to identify useful analogies, analogous domains, and patents using the WordTree method. Each team was required to identify five analogies, two analogous domains, and three patents. Eleven out of twelve teams identified at least five analogies (mean 7.4, minimum 4, and maximum 12). Nine teams identified at least two analogous domains (mean 1.6, minimum 0, and maximum 3). Nine teams also found at least three useful patents for their design problem (mean 1.6, minimum 0, and maximum 3). There were a total of thirteen teams, but one team's results were not recorded before being returned to the students. Fig. 15 shows one team's resulting analogies and analogous domains for the redesign of an automatic cat litter box and Table 4 lists examples for other teams. The team who redesigned the automatic cat litter box sought analogies for cleaning a cat litter box and created a WordTree for "clean." The WordTree method provided the team with analogies to a dump truck, panning for gold, and dredging items from the sea floor. Panning for gold suggests using water to separate the cat waste and litter. The CatGenie® self-washing self-flushing cat box is a commercially available solution, which uses this principle. These results are one example of a handful of very good results obtained by the teams. Table 4 displays the variety of results obtained by the teams. The WordTree generation was generally carried out correctly and teams produced useful results, but there was also some variation in the resulting analogies and solutions. Some teams had more disappointing results for a number of different reasons. Other teams, like the cat litter box team, found very novel analogies and unexpected analogous domains.

A few teams obtained poor sets of analogies such as the domain of "pull in" for an improved vacuuming robot (Table 4), even though the procedure of the method was correctly applied. Many teams had difficulty identifying distant analogous domains within the WordTrees. They tended to identify close-domain analogies. One reason for this may be the teams were focused on finishing this method quickly, and the choice of more distant analogies has a higher risk of not obtaining useful results but greater potential for innovation. One solution to this issue is to alter the grading structure such that students believe the reward is worth the possible risk.

Correctness of the method implementation varied. One team focused on changing the esthetics, usability, or ergonomics of the device rather than the function. Analogies can be made to the aesthesis of a device, but the WordTree method is tuned for function. Other difficulties arose with using the wrong sense of the verb or creating WordTrees using the constraints of the design problem rather than functions or customer needs. Some of the customer needs, which are adjectives, were not converted to verbs and therefore WordNet provided a dismal set of results. Another team used the team generated, "sticky note" WordTree to identify their analogous domain rather than the WordNet generated one. In addition, most teams had very focused problem statements, such as "extending battery life" or "reducing weight" rather than focusing on more general problems.

There was one generally consistent issue for almost all of the teams with the WordTree method with a few exceptions such as the cat litter box team. The resulting words, analogies, analogous domains, and patents were usually not carried to the next step in the process of 6-3-5 brainwriting. The teams did not connect their idea generation sessions to their previously generated analogies and possible solutions. This also likely means the ideas provided by the WordTree Method will not appear in the final solutions. From this evaluation, it is not clear why this occurred, but the issue will be investigated. The cat litter box team carried the results from WordTree through to idea generation.

7 Addressing the Research Questions

The results from the controlled study and implementation of the WordTree method with design teams provide insights into the effectiveness and benefits of the WordTree method. These results provide answers to the research questions.

Question 1: Does the WordTree Method increase the number of analogies identified? The WordTree method provides designers with a systematic tool to identify effective analogies for obtaining innovative solutions. It increases the number of analogies identified by the designers through linguistic re-representation of a design problem that also allows for the location of analogous domains. Analogous domains provide an avenue to search for existing solutions that are outside the problem domain. The controlled experiment showed a statistically significant increase in the number of analogies identified.

Question 2: Does the WordTree method produce unexpected, useful analogies and solutions? The WordTree method does assist designers in producing unexpected, useful analogies and solutions. Participants redesigning existing commercial products identified a number of unusual and effective analogies found for the design problems. One team redesigning a cat litter box identified dredging and panning for gold as analogies for their problem of cleaning a litter box. These are not analogies that most designers would expect. In a controlled experiment, a series of unique and effective analogies were identified for the peanut shelling problem.

Unexpected analogies included an egg peeling machine and cherry pitting. The control group did not produce this.

Question 3: Does the WordTree method change the search terms designers use with databases thus seeking more cross-domain analogies? Designers who were using the WordTree Method as compared to the control used a distinctly different strategy for seeking analogous solutions. They expanded their searches to analogous domains, which then provided novel analogies for them.

8 Conclusions and Future Work

The WordTree design-by-analogy method provides a systematic approach for identifying analogies and analogous domains for a given design problem. It leverages a design team's knowledge and existing databases to provide unexpected, effective analogies and analogous domains. Through the re-representation of a design problem, unexpected analogies and analogous domains can be explored. This is consistent with prior data that indicates representation affects the retrieval of analogies [21–23,25]. The controlled experiment shows that this method allows designers to identify a greater number of analogies and alters their search approaches leading to more unusual analogous solutions being located. Teams working on the redesign of commercial products successfully implemented the WordTree method on their projects locating unexpected analogies and analogous domains. One team redesigning a cat litter box identified dredging and panning for gold as analogies for their problem of cleaning a litter box. The WordTree method is a powerful approach for the re-representation of design problems.

Many other avenues for enhancing design-by-analogy are possible and will be future research. For example, even though the WordTree method guided the participants in identifying analogies, only a small percentage were incorporated into solutions even though participants felt they had run out of ideas before time was over. Referencing the cognitive model for analogical retrieval [12,15,18], based on the fact that participants are listing the analogies, it is likely they are having difficulty in either mapping between the source analogy and the design problem or they are not drawing inferences. Future research will focus on understanding why designers quickly disregard provided information and evaluate if designer experience is a factor. Future work will also explore in more detail how the WordTree method modified the participants search strategies.

As with any new method, there are avenues for improvement. Many steps of the WordTree method can be automated or facilitated by an automated, computational tool. For example, the entire process of creating the WordTrees from WordNet, selecting analogies, and researching them could be completed by an automated tool. The results including images could then be presented to the designer to immediately provide inspiration and by-passing most steps of WordTree. For reasons that are not completely clear, the engineers are not effectively using the analogies they identify, and these reasons must be explored with further work. The WordTree method needs to support this process better.

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References

[1] National Academy of Engineering, 2005, *Educating the Engineer of 2020: Adapting Engineering Education to the New Century*, The National Academies Press, Washington, DC.
[2] National Academy of Engineering, 2004, *The Engineer of 2020: Visions of Engineering in the New Century*, The National Academies Press, Washington, DC.
[3] Saunders, M. N., Seepersad, C. C., and Holtta-Otto, K., 2011, "The Characteristics of Innovative, Mechanical Products," J. Mech. Des., **133**(2), 021009.
[4] Casakin, H., and Goldschmidt, G., 1999, "Expertise and the Use of Visual Analogy: Implications for Design Education," Des. Stud., **20**(2), pp. 153–175.
[5] Eckert, C. M., Stacey, M., and Earl, C., 2005, "References to Past Designs," Proceedings of Studying Designers 2005, Key Centre of Design Computing and Cognition, Sydney, Australia.
[6] Christensen, B. T., and Schunn, C., 2007, "The Relationship of Analogical Distance to Analogical Function and Pre-Inventive Structures: The Case of Engineering Design," Mem. Cognit., **35**(1), pp. 29–38.
[7] Kelley, T., and Littman, J., 2001, *The Art of Innovation*, Doubleday, New York.
[8] Linsey, J., Tseng, I., Fu, K., Cagan, J., Wood, K., and Schunn, C., 2010, "A Study of Design Fixation, Its Mitigation and Perception in Engineering Design Faculty," ASME J. Mech. Des., **132**(4), 041003.
[9] Falkenhainer, B. F., Forbus, K. D., and Gentner, D., 1989, "The Structure Mapping Engine: Algorithm and Examples," Artif. Intell., **41**(1), pp. 1–63.
[10] Gentner, D., and Markman, A. B., 1997, "Structure Mapping in Analogy and Similarity," Am. Psychol., **52**, pp. 45–56.
[11] Hummel, J. E., and Holyoak, K. J., 1997, "Distributed Representations of Structure: A Theory of Analogical Access and Mapping," Psychol. Rev., **104**(3), pp. 427–466.
[12] Gentner, D., Holyoak, K. J., and Kokinov, B., 2001, *The Analogical Mind*, The MIT Press, Cambridge, MA.
[13] Blanchette, I., and Dunbar, K., 2001, "Analogy Use in Naturalistic Settings: The Influence of Audience, Emotion, and Goals," Mem. Cognit., **29**(5), pp. 730–735.
[14] Holyoak, K. J., and Thagard, P., 1989, "Analogical Mapping by Constraint Satisfaction," Cogn. Sci., **13**(3), pp. 295–355.
[15] Gentner, D., 1983, "Structure Mapping - A Theoretical Framework," Cogn. Sci., **7**, pp. 155–177.
[16] Holyoak, K. J., and Koh, K., 1987, "Surface and Structural Similarity in Analogical Transfer," Mem. Cognit., **15**(4), pp. 332–340.
[17] Gick, M. L., and Holyoak, K. J., 1980, "Analogical Problem Solving," Cogn. Psychol., **12**, pp. 306–355.
[18] Markman, A. B., and Gentner, D., 1993, "Structural Alignment During Similarity Comparisons," Cogn. Psychol., **25**(4), pp. 431–467.
[19] Leclercq, P., and Heylighen, A., 2002, "5,8 Analogies Per Hour," Proceedings of Artificial Intelligence in Design 2002.
[20] Ball, L. J., Ormerod, T. C., and Morley, N. J., 2004, "Spontaneous Analogising in Engineering Design: A Comparative Analysis of Experts and Novices," Des. Stud., **25**(5), pp. 495–508.
[21] Clement, C. A., Mawby, R., and Giles, D. E., 1994, "The Effects of Manifest Relational Similarity on Analog Retrieval," J. Mem. Lang., **33**(3), pp. 396–420.
[22] Clement, C. A., 1994, "Effect of Structural Embedding on Analogical Transfer: Manifest Versus Latent Analogs," Am. J. Psychol., **107**(1), pp. 1–39.
[23] Linsey, J., Wood, K., and Markman, A., 2008, "Modality and Representation in Analogy," Art. Intell. Eng. Des. Anal. Manuf., **22**(2), pp. 85–100.
[24] Linsey, J., 2007, "Design-by-Analogy and Representation in Innovative Engineering Concept Generation," Ph.D. thesis, The University of Texas at Austin, Austin, TX.
[25] 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.
[26] Chan, J., Fu, K., Schunn, C., Cagan, J., Wood, K., and Kotovsky, K., 2011, "On the Benefits and Pitfalls of Analogies for Innovative Design: Ideation Performance Based on Analogical Distance, Commonness, and Modality of Examples," J. Mech. Des., **133**(8), 081004.
[27] Tseng, I., Moss, J., Cagan, J., and Kotovsky, K., 2008, "The Role of Timing and Analogical Similarity in the Stimulation of Idea Generation in Design," Des. Stud., **29**(3), pp. 203–221.
[28] Gordon, W. J. J., 1961, *Synectics: The Development of Creative Capacity*, Harper and Brothers, New York.
[29] French, M., 1996, *Conceptual Design*, Springer-Verlag, London, UK.
[30] French, M., 1988, *Invention and Evolution: Design in Nature and Engineering*, Cambridge University Press, Cambridge, UK.
[31] "Proceedings of the ASME Design Engineering Technical Conferences and Computer and Information in Engineering Conference," Montreal, QC, Canada, August 15–18, 2010.
[32] Chiu, I., and Shu, L. H., 2007, "Biomimetic Design Through Natural Language Analysis to Facilitate Cross-Domain Information Retrieval," Artif. Intell. Eng. Des. Anal. Manuf., **21**(1), pp. 45–59.
[33] Chakrabarti, A., Sarkar, P., Leelavathamma, B., and Nataraju, B. S., 2005, "A Behavioural Model for Representing Biological and Artificial Systems for Inspiring Novel Designs," Proceedings of the International Conference on Engineering Design.
[34] Chakrabarti, A., Sarkar, P., Leelavathamma, B., and Nataraju, B. S., 2005, "A Functional Representation for Aiding Biomimetic and Artificial Inspiration of New Ideas," Artif. Intell. Eng. Des. Anal. Manuf., **19**(2), pp. 113–132.
[35] Mcadams, D., and Wood, K., 2002, "A Quantitative Similarity Metric for Design by Analogy," ASME J. Mech. Des., **124**(2), pp. 173–182.
[36] Shu, L. H., Hansen, H. N., Gegeckaite, A., Moon, J., and Chan, C., 2006, "Case Study in Biomimetic Design: Handling and Assembly of Microparts," Proceedings of the ASME IDETC (International Design and Engineering Technical Conferences).

[37] Shu, L. H., Cheong, H., Stone, R. B., Mcadams, D. A., and Chiu, I., 2011, "Biologically Meaningful Keywords for Functional Terms of the Functional Basis," J. Mech. Design., **133**, 021007, in press.
[38] Nagel, J. K. S., Stone, R., and Mcadams, D., 2010, "An Engineering-to-Biology Thesaurus for Engineering Design," Proceedings of the ASME IDETC.
[39] Goel, A. K., and Bhatta, S. R., 2004, "Use of Design Patterns in Analogy-Based Design," Adv. Eng. Inf., **18**(2), pp. 85–94.
[40] Ahmed, S., and Christensen, B. T., 2009, "An in Situ Study of Analogical Reasoning in Novice and Experience Design Engineers," J. Mech. Des., **131**(11), 111004.
[41] Chiu, I., and Shu, L. H., 2007, "Understanding the Use of Language Stimuli in Concept Generation," Proceedings of the ASME IDETC.
[42] Pahl, G., and Beitz, W., 1996, *Engineering Design - A Systematic Approach*, Springer, New York.
[43] Linsey, J., Clauss, E. F., Kurtoglu, T., Murphy, J. T., Wood, K. L., and Markman, A. B., 2011, "An Experimental Study of Group Idea Generation Techniques: Understanding the Roles of Idea Representation and Viewing Methods," ASME J. Mech. Des., **133**(3), p. 031008.
[44] Veale, T., 2006, "Re-Representation and Creative Analogy: A Lexico-Semantic Perspective," New Gener. Comput., **24**(3), pp. 223–240.
[45] Fellbaum, C., 1998, *Wordnet, An Electronic Lexical Database*, The MIT Press, Cambridge, MA.
[45] Gentner, D., 1981, "Some Interesting Differences Between Nouns and Verbs," Cogn. Brain Theory, **4**(2), pp. 161–178.
[47] Otto, K., and Wood, K., 2001, *Product Design: Techniques in Reverse Engineering and New Product Development*, Prentice Hall, Upper Saddle River, NJ.
[48] Altshuller, G. S., 1984, *Creativity as an Exact Science*, Gordon and Breach Publishers, Luxembourg.
[49] Dugosh, K. L., and Paulus, P. B., 2005, "Cognitive and Social Comparison Processes in Brainstorming," J. Exp. Soc. Psychol., **41**, pp. 313–320.
[50] Perttula, M., and Sipila, P., 2007, "The Idea Exposure Paradigm in Design Idea Generation," J. Eng. Des., **18**(1), pp. 93–102.
[51] Gentner, D., and Landers, R., 1985, "Analogical Remindings: A Good Match Is Hard to Find," Proceedings of the International Conference on Systems, Man, and Cybernetics.
[52] "Wings Take to the Water," 2000, BBC News, http://news.bbc.co.uk/1/hi/sci/tech/1011107.stm
[53] Reed, J., 2006, "The Future of Shipping," Pop. Sci. May, pp. 50–51
[54] Dryden, R., 2004, "A Proposal: Modular Sailing Rigs to Provide Wind Assistance for Larger Vessels," The Naval Architect, September, pp. 112–114.
[55] Linsey, J., Wood, K., and Markman, A., 2008, "Increasing Innovation: Presentation and Evaluation of the Wordtree Design-by-Analogy Method," Proceedings of the ASME IDETC Design Theory and Methodology Conference.
[56] 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," J. Mech. Des., **122**, pp. 377–384.
[57] Shah, J. J., Smith, S. M., and Vargas-Hernandez, N., 2003, "Metrics for Measuring Ideation Effectiveness," Des. Stud., **24**(2), pp. 111–134.
[58] Clark-Carter, D., 1997, *Doing Quantitative Psychological Research: From Design to Report*, Psychology Press, UK.
[59] Buzan, T., and Buzan, B., 1996, *The Mind Map Book: How to Use Radiant Thinking to Maximize Your Brain's Untapped Potential*, Plume, New York.
[60] Kurtoglu, T., Campbell, M., and Linsey, J., 2009, "An Experimental Study on the Effects of a Computational Design Tool on Concept Generation," Des. Stud., **30**(6), pp. 676–703.
[61] Lopez, R., Linsey, J. S., and Smith, S., 2011, "Characterizing the Effect of Domain Distance in Design-By-Analogy," Proceedings of the ASME IDETC-Design Theory and Methodology Conference.
[62] Benami, O., and Jin, Y., 2002, "Creative Stimulation in Conceptual Design," Proceedings of the ASME Design Engineering Technical Conferences and Computer and Information in Engineering Conference, Montreal, QC., Canada.
[63] Pedersen, T., 2011, "Wordnet::Similarity," http://wn-similarity.sourceforge.net/