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Design-by-Analogy and Representation in Innovative Engineering Concept Generation

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Design-by-Analogy and Representation in Innovative Engineering Concept Generation

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Design-by-Analogy and Representation in Innovative Engineering Concept Generation

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Design-by-analogy is an important tool for engineers seeking innovative solutions to design problems. A new method for systematically guiding designers in seeking analogies, the WordTree Design-by-Analogy Method, was created based knowledge gained from a series of experiments and prior literature. The WordTree Method linguistically re-represents the design problem and leads the designer to unexpected, novel analogies and analogous domains. A controlled experiment and the applications of the method to a number of engineering projects prove the method's value. Designers implementing the method identify a greater number of analogies. Application of the method to a set of engineering project resulted in unexpected, novel analogies and solutions.

A set of experiments to more deeply understand the individual cognitive and the group social process employed during analogical design guides the development of the WordTree Design-by-Analogy Method. A series of three experiments shows the effects

of the problem representation and how the analogy is initially learned on a designers' ability to use the analogy to solve a future design problem. The effect of the problem representation depends on how the analogy is initially learned. Learning analogies in more domain-general representations facilitates later retrieval and use.

A fourth experiment explored group brainwriting idea generation techniques including 6-3-5, Gallery, C-Sketch and Brainsketching through a 3 X 2 factorial experiment. The first factor controls how teams represent their ideas to each other, words alone, sketches alone or a combination. The second factor determines how teams exchanged ideas, either all the ideas are displayed on the wall or sets of ideas are rotated between team members. The number, quality, novelty and variety of ideas are measured. The greatest quantity of ideas is produced when teams use a combination of words and sketches to represent their ideas and then rotationally exchange them. This corresponds to a hybrid 6-3-5/C-Sketch method.

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Chapter 1: Improving Innovation through Analogy

Science and technology drive US economic growth (National Science Board Report, 2003). Innovating efficiently and consistently is a key to this nation's successes in the future (*Final Report from the NSF Innovation and Discovery Workshop: The Scientific Basis of Individual and Team Innovation and Discovery, 2006)*. How innovation takes place, the key ingredients for innovation and increasing breakthrough ideas are primary research goals that are of priority. This work addresses these research goals, at least in part, by first developing a deeper understanding of the cognitive processes that drive successful invention at the individual level and then furnishes a novel design method, the WordTree Design-by-Analogy Method, created based on the understanding of the cognitive and team creativity processes.

To improve innovation, numerous paths can be taken. Innovation begins with an individual having an initial idea. This idea will likely be added to, modified and enhanced by their surrounding team. Creativity and therefore innovation can be improved at the individual, team, managerial, or organizational levels. Innovation can be enhanced throughout the design process. Methods exist for identifying design needs ripe for innovation (Cagan and Vogel, 2002), and for subsequently assuring that appropriate design choices are made (Pugh, 1991). Innovation is the sum of individual, team, organization, and management. The focus of this dissertation is on improving the ability of individuals and design teams to create innovative solutions that fulfill the technical needs and desires of society.

DEFINITION OF ANALOGY

A design analogy as defined by Qian and Gero (1996) is the use of features from an appropriate object for a design problem. This definition is effective but incomplete. Another similar concept is metaphors for design. Gero's definition does not effectively differentiate analogies and metaphors in design. For the more general definition of analogies and metaphors extending beyond the design realm, Gentner and Markman (1997) define the concepts within the space of two dimensions, relational similarity and the number of attributes shared (Figure 1). Analogous items share relational and structural similarity, whereas metaphors span the spectrum of relational similarity at one end, and appearance similarity at the other. These definitions do describe analogy and metaphor as used within the design context, but a key dimension is missing (Hey, Linsey, Agogino and Wood, 2007). The key difference is in the elements that are mapped between domains and how they are used in the design process. Some comparisons are both an analogy and a metaphor. Metaphors frame and assist the designers in defining the design problem. Metaphors are commonly used to map users' understanding, activities and reactions to a product. They help make sense of customer needs or physical attributes from the source of inspiration. Analogy, in contrast, primarily maps the causal structure between the source product in one domain to the target design problem being solved. The causal structure includes a devices' functional solutions, geometry or component configuration. These distinctions are shown diagrammatically in Figure 2.

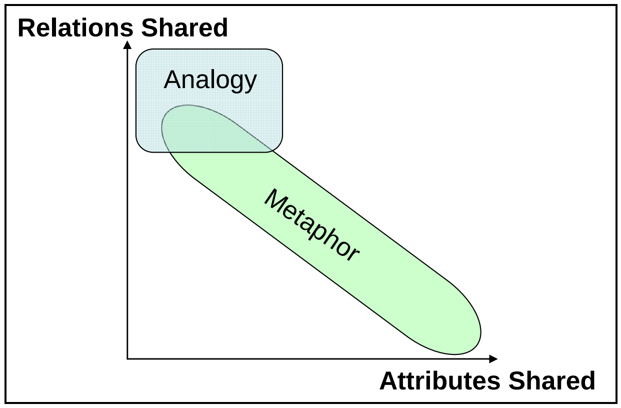


Figure 1: Definition and relationship between analogy and metaphor as present by Gentner and Markman (1997).

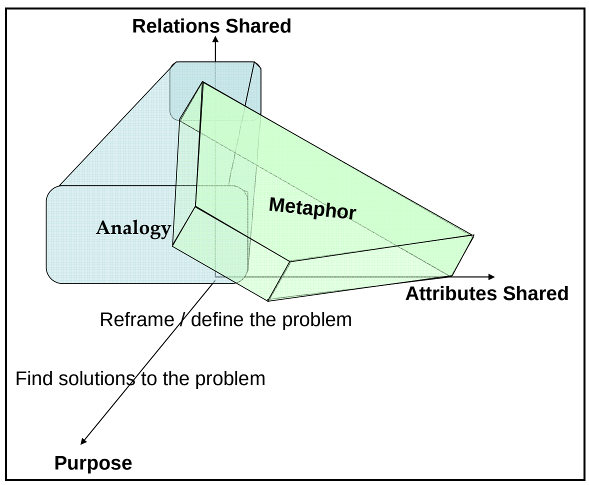


Figure 2: Definition and relationship between analogy and metaphor as used within design (Hey, Linsey, Agogino, and Wood, 2007).

ANECDOTAL EXAMPLES OF ANALOGY'S INFLUENCE IN THE DESIGN PROCESS

Anecdotally, design-by-analogy is a key strategy in the innovator's toolbox. Numerous design textbooks promote its power (Gordon, 1961; Pugh, 1991; Pahl and Beitz, 1996; French, 1996; Otto and Wood, 2001; Kelley and Littman, 2001). A quick perusal of technical journals and magazines illuminate a plethora of captivating examples. A recently formed journal, Bioinspiration & Biomimetics, dedicates each and every issue to technologies and principles derived from nature. Analogies to nature are believed to be an effective means for invention. Sources for analogies are not limited to nature but include other devices. Close domain analogies are likely to be more prolific and effective but on the average, less innovative. Innovation is possible with a close domain analogy, but not as likely. Evidence supporting the fact that an innovative new device was actually based on an analogy, and the solution path included the analogous device tends to be limited but anecdotal examples abound.

Analogies Using Nature

As illustrated by the newly formed journal, Bioinspiration & Biomimetics, inspiration through nature prototypically defines analogous design. Nature is sought to guide innovation, and examples of this are commonly found. Figures 3 and 4 represent two intriguing designs based on nature. Figure 3 shows a new design for sails on cargo ships which enable reduced fuel costs. The basis for the sail design was the structure of a bat's wing ("Wings Take to the Water," 2000; Reed, 2006). A prototype model attached to a small sailboat is shown on the left. The center is a conceptual illustration of the design's intended use on a cargo ship. The sails are unique in that they do not require additional crew members as traditional sails do.

Nature provides profound solutions in unexpected places and drastically different contexts. Enabling more effective exploration of Mars and other locations in outer space requires a more maneuverable space suit. The legs of a giraffe inspire a solution. The tight skin on a giraffe's legs assists in regulating blood pressure. A prototype design for a new space suit was based on this principle. Instead of relying on gas pressure as in a traditional spacesuit, the suit's design implements mechanical pressure.

Figure 3: The sails of this cargo ship are designed based on an analogy to a bat's wing ("Wings Take to the Water," 2000; Reed, 2006; bat wing image: "El Yunque National Forest – Wildlife Facts," 2007).

Figure 4: The ultra maneuverable and lightweight space suit, partially inspired by the tight skin of a giraffe's legs which helps to regulate blood pressure, relies on mechanical pressure rather than gas pressure to support human life in a thin atmospheric environment like mars ("A Clothes Encounter", 2007).

Analogies from One Device to Another

Distant domains such as nature effectively support conceptual design but analogy extends well beyond this area. Analogies to nature are more intriguing but analogies between devices are also very effective and likely more common. An analogy identified through the use of the function and flow basis provided an unusual and effective solution for a guitar pickup winder (McAdams and Wood, 2002). A guitar pickup is a coil of wire used to capture the mechanical vibrations of the strings. Electric guitar enthusiasts desire the ability to wind their own pickups and make adjustments in the process. An unexpected analogy to an automatic vegetable peeler provides the required functionality and product architecture. More obvious but less innovative analogies include the bobbin winder on a sewing machine or a fishing reel.

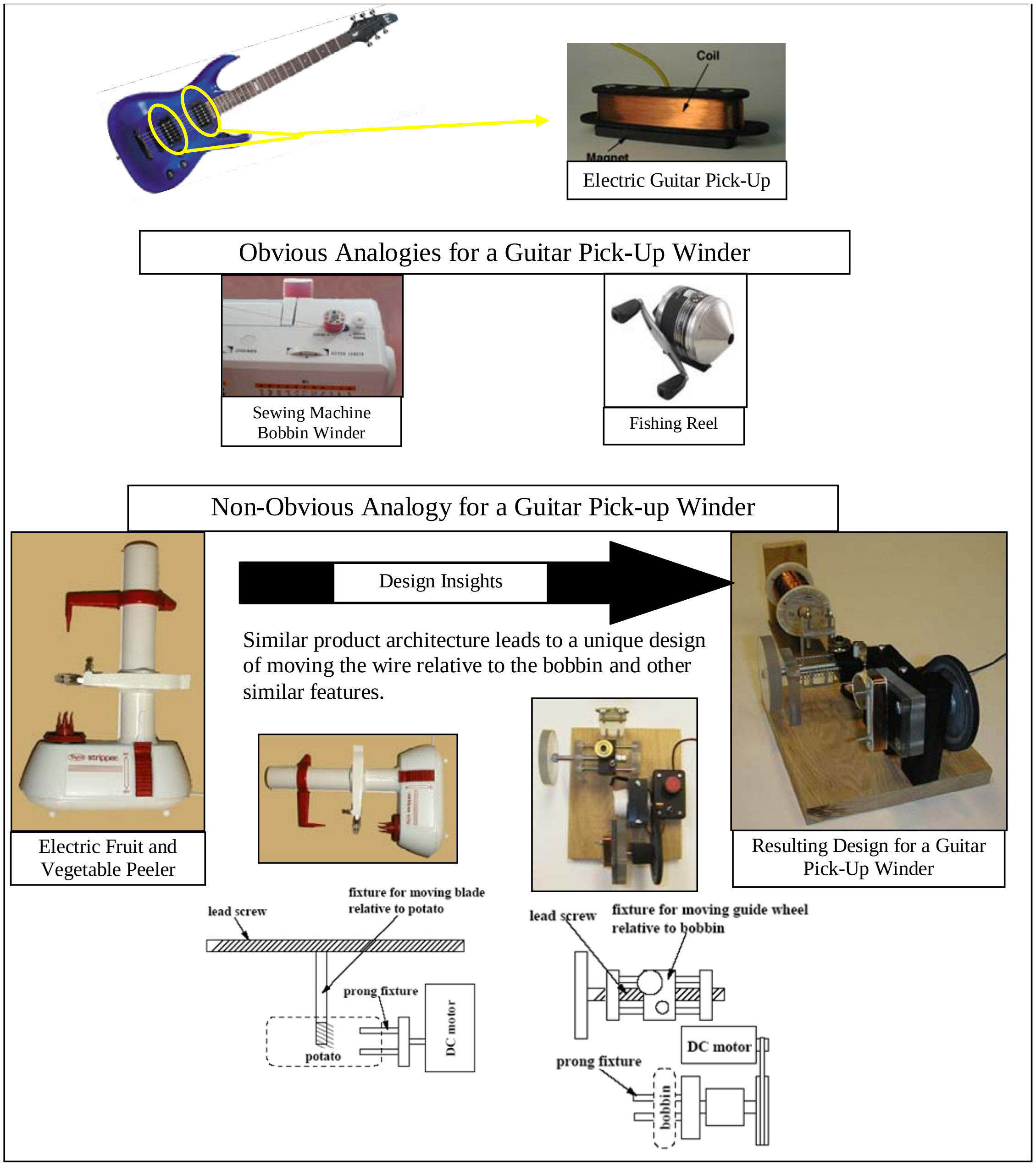


Figure 5: A non-obvious design analogy between a pick-up winder and an electric vegetable peeler resulting from functional models and formalisms known as functional and flow basis (McAdams and Wood, 2002).

Design based on analogy is not a recent phenomenon. History illustrates the power of analogy. The early design of a reel lawn mower was based on the nap trimming machines for carpets, Figure 6. Though vastly improved, this basic design for a hand-powered lawn mover still exits. Currently, these reel mowers are popular as an environmentally friendly solution.

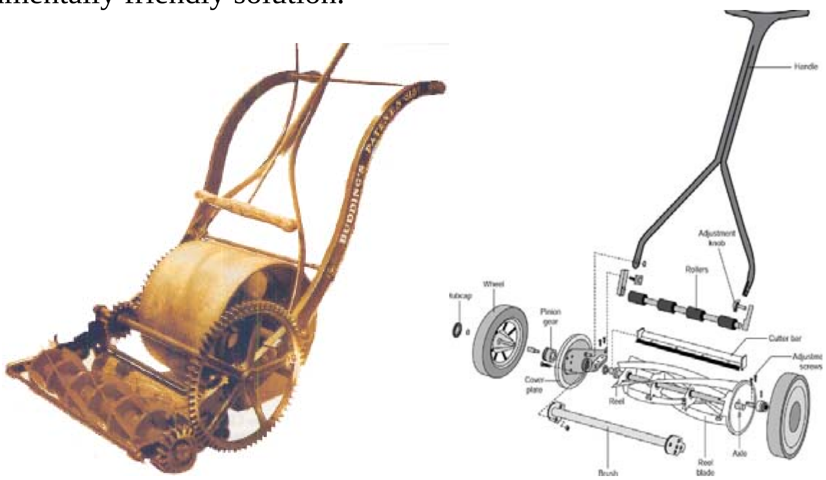


Figure 6: The inspiration for early lawn mowers came from carpet nap trimming machines (Bastyr, 2007).

Distant domain analogies may be the archetype, but close domain analogies are also possible and likely more common. Figure 7 demonstrates a close domain analogy based on an earlier design of a measuring cup which leads to rather innovative and very commercially successful product. The earlier patent is cited in the references of the Oxo Good Grips Measuring Cup patent (Maiwald, 1995, U.S. Patent 5,397,036; Hoeting and Hoeting, 2001, US Patent 6,263,732). The initial design included a stair-step measuring surface allowing accurate measurements to be made while being viewed from above. The Oxo Measuring Cup modified this feature to a smooth incline plane which maintaining the key advantage.

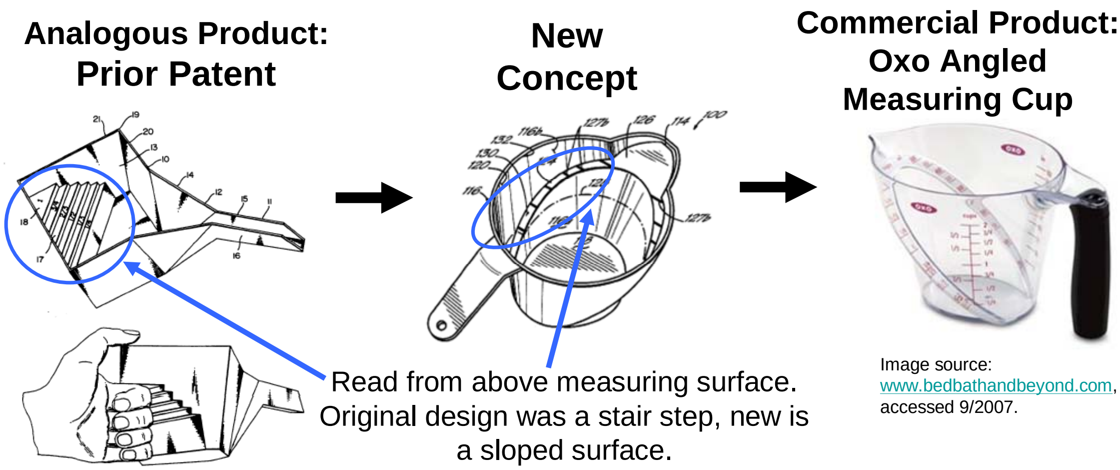


Figure 7: This is an example of an innovative and very close domain analogy.

Analogies for Explanation

Analogical power is not limited to inspiration within design. It also serves as a tool for explanation. Analogies and metaphors effectively and quickly explain technical concepts. Figures 8 and 9 provide examples of metaphors and analogies being use for explanation. The first is a metaphor describing an underwater robot used to harvest lumber which is visually similar to a sawfish. The second example includes an explanation analogy in a NSF press release for a flexible battery composed of fibers and nanotubes. The press release uses the analogy but connected material provided by the researchers references no such analogy. Prior empirical work highlights the fact that analogies are also developed to explain a new technical concept and appear as if they could have been a part of the reasoning process for creating the new device. In actuality, these analogies were created afterwards for explanation and were not scaffolding for the development process (Schunn and Dunbar, 1996).

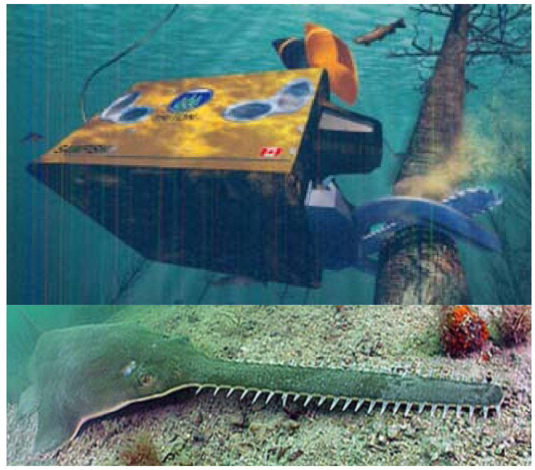


Figure 8: A metaphor to the sawfish describes an underwater robot designed to harvest lumber from reservoirs (Behar, 2007). The sawfish and the underwater robot are visually similar but share little functional similarity. The more likely analogy for the design of the underwater robot is a chain saw.

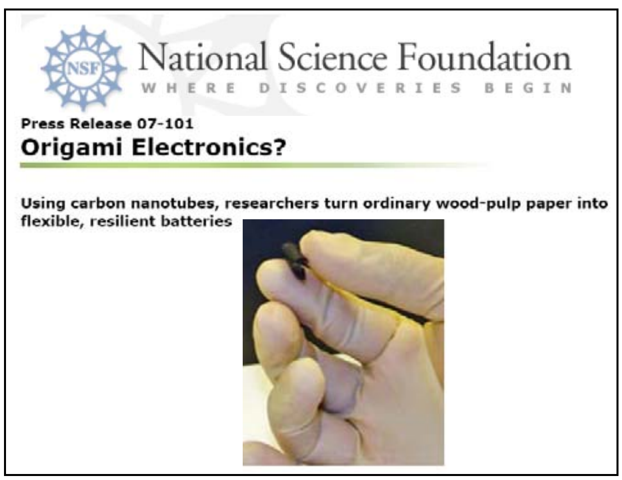


Figure 9: A recent press release used an analogy to origami in describing a new flexible battery built using carbon nanotubes (“Origami Electronics?”, 2007; “Beyond Batteries: Storing Power in a Sheet of Paper,” 2007).

EMPIRICAL EVIDENCE SUPPORTING DESIGN-BY-ANALOGY

The empirical evidence supports the use of analogy for design but is less extensive. Professional designers often use analogies (Casakin and Goldschmidt, 1999;

Leclercq and Heylighen, 2002; Christensen and Schunn, 2007). Unlike biologists who mainly use analogies within their domain, engineers employ cross-domain analogies in their design process (Christensen, and Schunn, 2007). This finding is based on protocol analysis of design team's conversations during conceptual design. Design teams frequently use close-domain analogies in the form of references to past designs (Eckert, Stacey and Earl, 2005). Eckert, *et al.* found designers use references to previous designs for more than just conceptual design. Analogies to similar products are also used for process planning, cost estimation, and evaluation of a new product.

A few controlled experiments have explored the use of analogy. Casakin and Goldschmidt (1999) found that visual analogies can improve design problem solving for both novice and expert architects. Visual analogy had a greater impact for novices as compared to experts. Ball, Ormerod, and Morley (2004) investigated the spontaneous use of analogy with engineers. They found experts use significantly more analogies than novices do. The type of analogies used by experts was significantly different from the type used by novices. Novices tended to use more case-driven analogies (analogies where a specific concrete example was used to develop a new solution) rather than schema-driven analogies (more general design solution derived from a number of examples). This difference can be explained because novices have more difficulty retrieving relevant information when needed and have more difficulty mapping concepts from disparate domains due to a lack of experience (Kolodner, 1997).

FORMAL DESIGN-BY-ANALOGY METHODS

A structured design-by-analogy method would be useful for minimizing the effects of the experiential gap between novices and experts and to further enhance experts' abilities. A few formal methods have been developed to support design-by-analogy such as Synectics (Gordon, 1961), French's work on inspiration from nature (1988; 1996), Biomimetic concept generation (Hacco and Shu, 2002; Chiu and Shu, 2005) and analogous design through the usage of the Function and Flow Basis (McAdams and Wood, 2002). 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 (Gordon, 1961). Synectics gives little guidance to designers about how to find successful analogies. Other methods also base analogies on the natural world. French (1988; 1996), highlights the powerful examples nature provides for design. Biomimetic concept generation provides a systematic tool to index biological phenomena (Hacco and Shu, 2002; Chiu and Shu, 2007a; Shu, Hansen, Gegeckait, Moon and Chan, 2006). In biomimetic concept generation the functional requirements of the problem and the keywords are first derived. The keywords are then referenced to an introductory college textbook and relevant entries can be found.

Analogous concepts can be also identified by creating abstracted functional models of concepts and comparing the similarities between their functionality. Analogous and non-obvious products can be explored using the functional and flow basis (McAdams and Wood, 2002). A case study, using this approach, of a pick-up winder for an electric guitar is shown in (McAdams and Wood, 2002). The analogy to a vegetable peeler leads to an innovative design (prototype shown in Figure **5**).

Other database supported computation tools for design-by-analogy have been recently developed. An example of such a tool is the work by Chakrabarti, *et al*. (2005a&b). They created an automated tool to provide inspiration to designers as part of idea generation process. Based on the function or behavior of a device, analogies from nature or other devices are provided as potential sources of inspiration to the designer.

Chakrabarti, *et al*., have tested the automation tool and its analogy representations with student participants as part of university design courses.

Anecdotally, the implementation of analogy is prolific. Unfortunately it tends to be an unstructured process with *ad hoc* approaches based on a designer's experience. 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.

HYPOTHESES AND OBJECTIVES

Design-by-analogy is clearly a powerful tool in the design process but numerous questions surround its use. What will make the designers more successful? What do designers not do well? What are typical wrong turns or places designers have difficulties? What makes a good analogy? What tools do designers need to support this process? Current approaches for design-by-analogy provide little guidance to the designer. This work seeks to create a systematic approach to guide designers in discovering numerous, novel and innovative solutions for design problems with a focus on analogical design. The key objective is approached by breaking it into sub-objectives and conjecturing hypotheses that are explored through controlled experiments. The goal is to first identify possible tools for promoting analogical design and then to develop them into a method to support design.

Objectives

1. **Identify avenues for improving a designer's ability to find innovative solutions to difficult design problems**. This objective will be explored by identifying and exploring representations that have potential for enhancement including linguistic representations and functional models. How the representation of a design problem can be varied in order to maximize the number, variety, novelty and quality of innovative solutions found by the designer or design team will be explored.
2. **Develop a systematic design-by-analogy method.** This method will be evaluated through controlled studies and case studies.
3. **Increase the understanding of the cognitive processes involved during design-by-analogy within the design domain.** This includes a greater understanding of the influences on the process including domain expertise and visual representations. Also important, is understanding the limitations of current cognitive models.

Hypotheses

Based on literature and prior experimentation the following hypotheses have been developed to support and guide the exploration of the research objectives. **Primary hypothesis: The conceptual design process can be improved (increased quantity, quality, novelty, variety of ideas or number of analogies) by a systematic method guiding engineers to varied, multiple and more useful representations of a design problem.**

Sub-hypotheses:

- The representations that groups use to communicate their ideas and how ideas are exchanged (all displayed gallery style or rotationally exchanged) affects the number, quality, novelty and variety of the ideas generated.

- Analogous products learned with more domain-general, linguistic representations are easier to retrieve and use to solve future design problems.
- The appropriate representation of a design problem increases a designer's success rate in finding analogous solutions.
- Appropriate design problem representations increase the number of cross domain analogies a designer can identify and implement to find innovative solutions.
- A design method, WordTree design-by-analogy, created based on the experimental results of this dissertation can increase a designer's chances of finding a unique and innovative solution for a design problem.

SCOPE AND OVERVIEW OF THE CHAPTERS

The design process begins with defining the problem to be solved, continues with concept generation moves to ideas selection and detailed design. Cagan and Vogel (2002) present methods for defining opportunities for innovative products but little guidance is available for systematically creating the innovative solutions. This dissertation defines a design-by-analogy method which systematically re-represents the design problem guiding the designer to potential analogies and analogous domains. The method founds itself on a solid understanding of the cognitive process relevant to analogous design. A series of experiments within this work focus on increasing the understanding of the cognitive processes involved in analogical reasoning for design problems and highlighting areas for supporting tools. The WordTree design-by-analogy method, defined in this dissertation, exploits only a subset of the possible avenues for influencing the conceptual design process. Other opportunities for influence are yet to be discovered.

The following chapters begin with a review of the relative psychology theory, group idea generation techniques and past experiments. Chapter 2 reviews the prior literature pertinent to this endeavor. Engineering design occurs in team settings and teams of individuals have a greater breath of knowledge than single individuals. For both of these reasons, a likely implementation of any method to enhance individual analogical reasoning would include group idea generation as a component. Chapter 3 presents a controlled empirical study designed to highlight an effective method for group idea generation. Numerous methods for group idea generation exist. Brainwriting methods, where all communication is written, are believed to be effective. Therefore a factorial experiment explores two parameters of the various brainwriting techniques, the representation used to communicate (written words, sketches or a combination) and how ideas are exchanged (all displayed gallery style or rotational exchanged). Once an effective group was identified, the fundamentals of design analogies were explored. Chapter 4 describes the first two experiments aimed at more deeply understanding the cognitive processes used in design-by-analogy and exploring analogy in a more realistic engineering setting. Six different analogous products and design problem pairings confirmed findings in psychology that more abstract representations of analogy facilitate future analogical retrieval and secondly explored other influences on the process. A third experiment, described in Chapter 5, evaluates the effects and interaction of the design problem and analogy representation. Based on the experimental results and prior literature a method to support design-by-analogy was derived. Chapter 6 illustrates the WordTree design-by-analogy method, its derivation and experimental results supporting its effectiveness including a case study of an invention. Finally Chapter 7 summarizes the results of the experiments and discusses future work.

Chapter 2: Literature Review

Innovation and design creativity processes occur at multiple levels beginning with the individual reasoning processes. In addition, the initial design phases, including conceptual design, have the most significant impact on product cost (Römer, Weißhahn and Hacker, 2001). These factors indicate the importance of conceptual design in the overall process and emphasize the need to improve individual and team based creativity. This chapter begins with a discussion of idea generation techniques with a particular focus on team-based approaches. Analogy is a central approach for innovative design and is likewise a focus of this literature review. The next section discusses the other phases of the design process which also rely on analogy. Designers use a multitude of visual and linguistic representations as they create solutions. Representation affects a designers' ability to reason. The subsequent sections define representation, present experimental work in design on linguistic stimuli, and then explore the cognitive processes and models involved in design-by-analogy. Finally, prior literature on metrics for measuring idea generation within the context of engineering design is explored.

IDEA GENERATION TECHNIQUES

Engineering creativity and innovation are combinations of individual and group processes. Numerous idea generation techniques are available to assist the engineer in this process. Over one hundred formal idea generation techniques have been developed in areas such as psychology, business and engineering (Adams, 1986; VanGundy, 1988; Higgins, 1994). One identified approach for idea generation is analogy. Analogy is recognized for its effectiveness, but limited formal method guidance is provided. Additional techniques range from the well-known Brainstorming method developed by

Osborn (1957), to engineering specific methods, such as the Theory of Inventive Problem Solving (TIPS) (Altshuller, 1984). Some of these techniques are meant to be implemented in a group setting and others are intended for solitary work. Unfortunately, little empirical data exists to guide the use of these methods for engineering design. Chapter 1 overviews the formal methods for analogical design so they will not be presented here. The following sections discuss the various group idea generation techniques and the empirical data available.

Group Idea Generation Techniques

Group processes and group idea generation play an important role in innovation. The formal group concept generation techniques may be broken down into two broad classes, brainwriting and brainstorming techniques. Brainwriting approaches consist of written communication between individuals. Brainstorming techniques use spoken communication and closely resemble the method originally created by Osborn (1957) for group idea generation. Osborn's Brainstorming technique is one of the most well-known approaches for idea generation and was an early method of group collaboration.

Osborn's Brainstorming and variations on it are just one class of approaches for group interaction. Brainwriting approaches show promise as effective means of generating a large number of ideas (Gryskiewicz, 1988; Paulus and Yang, 2000). Studies in engineering design show supporting evidence for the potential of idea exchange for promoting new ideas (Perttula and Liikkanen, 2006; Perttula, Krause and Sipil, 2006; Perttula and Sipil, 2007). Additional studies have focused on the development and evaluation of more effective idea generation methods in engineering and design related fields, including industrial design and architecture (Shah, 1998; Van der Lugt, 2002; Shah, Kulkarni, and Vargas-Hernández, 2000; Shah, Vargas-Hernández and Smith, 2003;

Vidal, Mulet and Gómez-Senent, 2004). These studies have used a mixture of sketches, verbal descriptions of ideas and physical models in the idea generation process. The vast majority of idea generation techniques focus on the sentential expression of ideas, whereas designers rely heavily on sketches to express their ideas (Römer, Weißhahn and Hacker, 2001). The discussion that follows begins by describing Osborn's Brainstorming along with the empirical data and then focuses on the remainder of group approaches that show promise for being effective approaches for design.

Osborn's Brainstorming

The term brainstorming is frequently applied to any idea generation technique and not just the technique developed and named by Osborn. Osborn's Brainstorming begins with a facilitator explaining the problem. A group then verbally exchanges ideas following four basic rules: (1) criticism is not allowed, (2) "wild ideas" are welcomed, (3) building off each others' ideas is encouraged, and (4) a large quantity of ideas is sought. This technique is less effective for generating a larger quantity or higher quality of ideas when compared with an equal number of individuals working alone using the rules of Brainstorming (Mullen, Johnson and Salas, 1991). One of the first studies using Osborn's Brainstorming method in engineering design included engineering professionals working on a realistic engineering problem and showed groups were less effective at producing a large number of ideas than the combined efforts of individuals (Lewis, Sadosky and Connolly, 1975). This result is consistent with the vast majority of studies on variations of Osborn's Brainstorming (Mullen, Johnson and Salas, 1991). Hundreds of studies have evaluated the effectiveness of Brainstorming with generally consistent results. This result clearly illustrates the need to robustly evaluate approaches to verify and improve their effectiveness.

Brainsketching

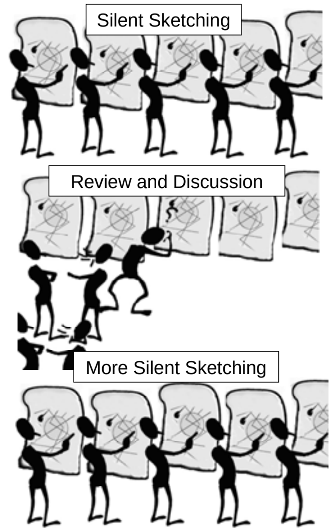


Figure 10: Illustration of Gallery Method.

In Brainsketching, individuals begin by silently sketching their ideas on large sheets of paper including brief annotations. Individuals switch drawings and silent sketching continues for another period of time (VanGundy, 1988). This technique allows for the visual means of expression making it well suited for product design. Van der Lugt used teams of advanced product design students to compare a variant of Brainsketching, which included the explanation of ideas between exchanges, to Brainstorming (Van der Lugt, 2002). Brainstorming produced more ideas, but the Brainsketching variant had significantly more connections with earlier ideas.

Gallery

In the Gallery method, individuals begin by sketching their ideas silently on large sheets of paper. After a set amount of time, participants discuss their ideas and move about the room studying others' ideas. This review phase is followed by a second stage of silent sketching (VanGundy, 1988; Pahl and Beitz, 1996). The review phase allows team members to clarify their ideas and it provides social interaction.

6-3-5 / C-Sketch

For 6-3-5 (Rohrbach, 1969; Shah, 1998; Otto and Wood, 2001) and C-Sketch (Shah, 1998), six participants are seated around a table, and each silently describes three ideas on a large sheet of paper. The ideas are then passed to another participant. The “5” in 6-3-5 represents a total of five passes or rounds. For 6-3-5, ideas are described using only words, in contrast to C-Sketch, which requires sketches only. The advantage of C-Sketch, due to its sketching only limitation, is it increases the probability one person will misinterpret another person’s ideas thus increasing the novelty and variety of concepts (Shah, Vargas-Hernández, Summers and Kulkarni, 2001). Other variations of 6-3-5 exist (VanGundy, 1988; Otto and Wood, 2001). One variation combines the use of sketches with short annotations (Otto and Wood, 2001). In an experimental comparison, C-Sketch and Gallery outperformed 6-3-5 (words only) for variety, quality and novelty (Shah, *et al.*, 2001). This study used groups of mechanical engineering undergraduates, professional designers and mechanical engineering graduate students.

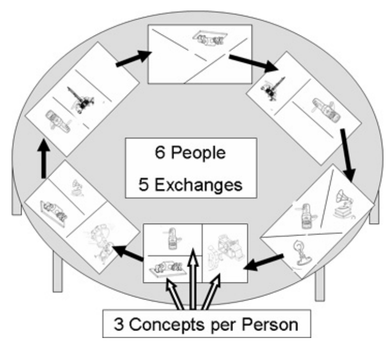


Figure 11: Illustration of 6-3-5 and C-Sketch. Six people silently describe three ideas on a sheet of paper and then exchange concepts.

DESIGN REUSE IN PRODUCT DEVELOPMENT

A closely related concept to analogy is design reuse. The spectrum of analogy overlaps with design reuse but does not encompass. Analogy mappings range from very distant domain to very near domain. Design reuse that involve analogies are examples of a very near-domain analogies. It is also possible for design reuse to not constitute an analogy. To be an analogy there must be a mapping of features from the one item to another. References to past design may be analogies to create ideas or for explanation. Based on a series of empirical studies, Eckert, *et al*., (2005) find evidence for the use of references to past design in a number of different design activities. First, existing designs are frequently modified to meet new customer needs. References to past designs also guide process planning, cost estimation and the evaluation of solutions. Design references also serve to communicate design solutions. Eckert, *et al*., also note the use of analogies to competitor's products and prior solutions within the company in deriving solutions. This dissertation focuses on the use of analogy within conceptual design but acknowledges that analogy is used in other phases of the process, and the experiment results from this dissertation may apply to other uses of analogy within the design process.

REPRESENTATION

Understanding the design process requires understanding both the internal mental representations of designers as well as the external representations (e.g., sketches, function and flow basis diagrams) that are used during the design process. A representation is a physical or mental item that stands for another thing. Hence, there are four necessary parts to a mental representation: the physical or mental item serving as the representation, the domain being represented, rules (usually implicit) that map parts of the item being represented to the parts of the representation, and a process (also usually not stated) that is capable of performing the mapping and using the information (Markman, 2002). Understanding the design process requires understanding both the internal mental representations of designers as well as the external representations (e.g., sketches, function and flow basis diagrams) that are used during the design process.

Much work within design research has investigated the use of sketches (Goldschmidt, 1991; Purcell & Gero, 1998). Little work, with the exception of Vidal *et* *al.*, (2004) and Christensen, and Schunn (2007), has investigated the role of physical models in conceptual design. Understanding the design process requires understanding both the internal mental representations of designers as well as the external representations (e.g., sketches, function and flow basis diagrams) that are used during the design process.

LINGUISTIC STIMULI FOR IDEA GENERATION

A few studies have evaluated the influence of related linguistic stimulus to support idea generation. Chiu and Shu (2007b) presented undergraduate engineers with a series of verbs semantically related to the main function of a design problem. They implored WordNet (Fellbaum, 1998), a lexical database, to derive the series of hierarchically related verbs. They generally found more specific verbs to be more useful as stimuli and that more abstract verbs tended to only be useful when used in conjecturing with lower level verbs. Less useful verbs tended to be ones which had intransitive dominate senses, in other words, verbs that tend not to be commonly used with direct objects, such as the verb "sleep". This observation is consistent with the functional basis's verb-object format (Stone and Wood, 2000). Chiu and Shu also observed issues with participants invoking the wrong sense of a word for the given design problem. For example, for the design problem of orientating an egg, the word "stem" was intended to be in the sense of "to cause to turn inward" not as in the sense of "a part of a plant".

In a separate small sample study (n=3), Chiu and Shu (2007c) implemented a protocol study to evaluate the use of language during conceptual design. They found the student designers used nouns more frequently but that verbs appeared to lead to more new ideas. While the sample size is too small to drawn definitive conclusions, it provides preliminary support for linguistic inspiration.

Segers, *et al.*, (2005) built an electronic tool which captures an architectural designer's annotations on a drawing and then presents word graphs (Figure 12) with related words from WordNet. They evaluated the tool with professional architects and found a generally positive attitude about the tool but no difference in the level of creativity as evaluated by experts. It is important to note that this study did not report inter-evaluator correlations (an indication of a reliable metric). An interesting comment by the authors from this study stated they found hypernym and hyponym semantic relationships to often be too abstract.

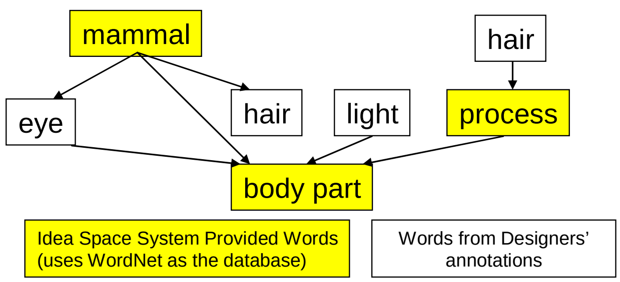


Figure 12: Word graph created by the Idea Space System (Segers, *et al.*, 2005).

PSYCHOLOGICAL MODELS RELEVANT TO ANALOGOUS DESIGN

Psychological models and prior research deliver a fundamental knowledge and explanation of human cognition and behavior much the same way the physical sciences are fundamental to engineering product design. Psychology is a newer science, and human cognition and behavior tends to be complex therefore many models are limited in their detail and explanation capability. The following sections illustrate the cognitive models that are important for understanding design-by-analogy. This section begins by exploring models of analogical reasoning, the key high-level reasoning process involved in designing with analogies. Next some key findings regarding linguistic and perceptual cognitive representations are discussed. Engineers use a combination of sketches and semantic representation during conceptual design. Finally a brief overview of memory models is given with an illustration of one of the network models being discussed in more detail. Ultimately, most of the information used by designers is retrieved from their memories, therefore understanding how human memory works guides the development of methods to support analogous design.

Cognitive Process Models for Design-by-Analogy

Understanding the cognitive process involved in the formation of analogies is important for understanding the concept generation process. Analogy can be viewed as a mapping of knowledge from one situation to another enabled by a supporting system of relations or representations between situations (Gentner, 1983; Falkenhainer, Forbus and Gentner, 1989; Chiu, 2003). This process of comparison fosters new inferences and promotes construing problems in new insightful ways. The potential for creative problem solving is clearest when the two domains being compared are very different on the surface (Gentner and Markman, 1997).

Research has been carried out in the field of psychology to understand the cognitive processes people use to create and understand analogies (Falkenhainer, Forbus and Gentner, 1989; Gentner and Markman, 1997; Gentner, Holyoak and Kokinov, 2001; Blanchette and Dunbar, 2001; Hummel and Holyoak, 1997; Gick and Holyoak, 1980). Figure 13 shows the basic process steps involved in reasoning by analogy, the most cognitively challenging step, and the design methods that are available to support each step.

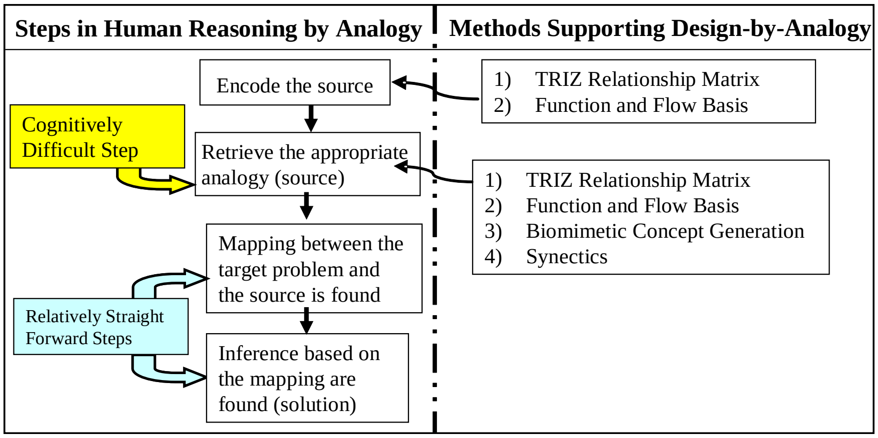


Figure 13: Steps in human reasoning by analogy and the current methods available to support those processes.

Analogy has traditionally been viewed as a comparison between two items in which their relational, or causal structure, but not the superficial attributes match (Gentner, 1983; Gentner and Markman, 1997). For example, an airplane wing and a hydrofoil can be viewed as analogous because of how they work; the colors they are painted is irrelevant. This process of comparison fosters new inferences and promotes construing problems in new, insightful ways.

In the psychological literature, there has been a great deal of interest in the roles of analogy and expertise in problem solving. When working with undergraduate students who have no specialized domain knowledge, a classical finding is that analogies are helpful in solving insight problems, but are difficult to retrieve from memory (Gick and Holyoak, 1980). Conversely, naturalistic research with experts typically finds that analogies are often used (e.g., Dunbar, 1997; Leclercq and Heylighen, 2002; Casakin and Goldschmidt, 1999). This dichotomy may reflect that experts can see the deeper, logical structure of situations while those without domain expertise are mainly aware of only the superficial features (cf. Chi, Feltovich and Glaser, 1981; Gentner and Landers, 1985; Novick, 1988).

Cognitive Memory Representation

Many cognitive models of memory theorize at least two types of knowledge being stored: perceptual (non-verbal) and conceptual (verbal) (Barrlett, Till & Leavy, 1980; Loftus & Kallman, 1979; Paivio, 1986). The verbalization of perceptual information can interfere with the retrieval of perceptual information from memory (Schooler, Fiore and Brandimonte, 1997). This effect is known as *verbal overshadowing*. Prior studies have evaluated an individual's ability to recall a number of different types of complex perceptual information including memory of faces. The general format of these experiments is participants are asked to study a series of faces and then either asked to verbally describe the faces or not. Finally participants' recognition of the faces is tested. These experiments consistently show the interference between the verbalization of perceptual information and memory retrieval of perceptual information. Verbal idea generation techniques may suppress some of the perceptual information in memory, thus giving sketching based techniques a possible advantage.

Cognitive Models of Memory: Retrieving Analogies

Numerous models of human memory are currently present in the cognitive science literature. Ultimately, none of the currently available models describe and explain the psychological experimental findings sufficiently (Markman, 1999). A series of principles are known and generally agreed upon about memory. Memory is organized and structured. Analogy is the partial overlap of memory representations. There is a hierarchical structure of language and this in turn influences memory. The principle of *encoding specificity*, generally states that a memory is retrieved when there is sufficient similarity between the retrieval cues and the information that was originally encoded in memory. Model like MAC-FAC (Forbus, Gentner and Law, 1995) incorporate a first pass feature match in memory retrieval. Many models, including ACT-R (Anderson, 1993) and LISA (Hummel and Holyoak, 1997) propose a network structure to memory.

Semantic Memory Retrieval Model

Semantic memory refers to the storage of meaningful, factual information. Semantic memory is contrasted with the storage of personal experiences (episodic memory) or skills (procedural memory). The semantic memory model is not considered to be an accurate description of memory but it is effective for illustrating the general idea of a network model for memory. In the psychological literature, the structure of human semantic memory is often conceptualized as a network of concepts that are associated with each other. For example, in Figure 14, the concept of "exercise equipment" is represented by a node in a somewhat chaotic web of associations. When one thinks about exercise equipment, the node representing that concept becomes active, and this activation can spread along its associative links to other connected ideas. Another concept is remembered when it becomes sufficiently activated. However, nodes pass along only a fraction of their activation to neighboring nodes, and so the activation weakens as it gets more distant from the source of activation. The probability that a concept will be remembered increases as the path distance (i.e. number of links traversed) shortens, or if multiple active paths converge on it. Nodes that are more general concepts, such as "substance", tend to be connected to a much greater number of other nodes, becoming hubs in the network. Thus, linking new concepts through them shortens path distances, increasing the probability of retrieval (Collins and Loftus, 1975; Anderson, 1983; Roediger, Marsh and Lee, 2002; Markman, 2002).

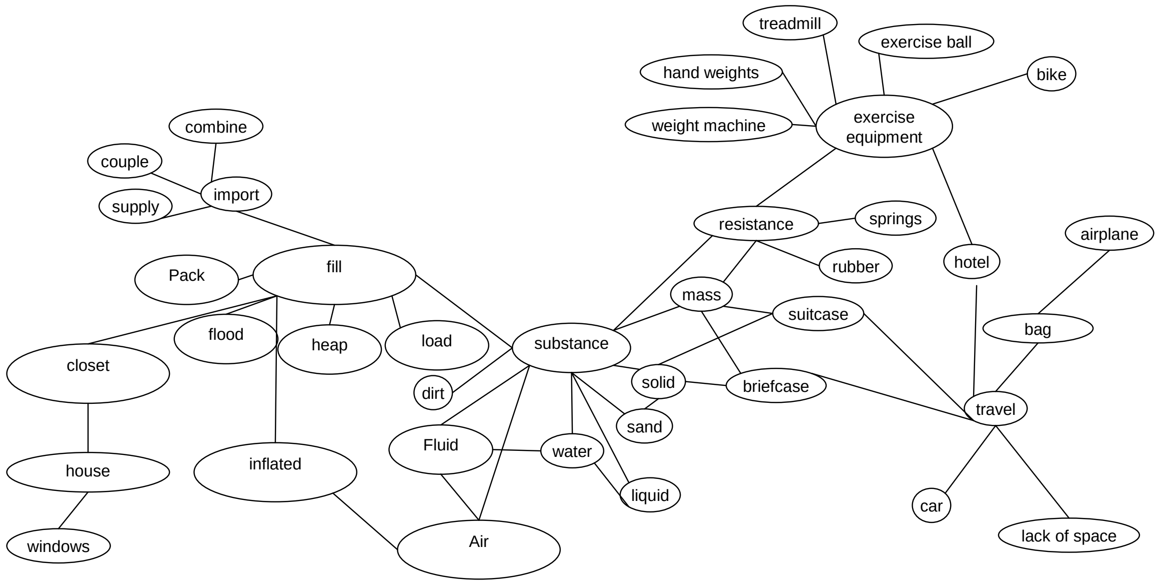


Figure 14: Example Semantic Network.

Principles of Memory: General Easier to Retrieve

Prior research in analogical reasoning found the encoded representation of a source analogy can ease retrieval if it is entered into memory in such a way that the key relationships apply in both the source and target problem domains (Clement, 1994; Clement, Mawby and Giles, 1994). This work shows that the internal representations in memory play a key role in retrieval. The analogies and problems used in these experiments were not specific to any domain of expertise and used fantasy problems relying on strictly linguistic descriptions. Little work has been carried out based on a strong psychological understanding of analogical reasoning combined with the design knowledge of analogies for high-quality designs. This dissertation takes a distinctive interdisciplinary route to combine these threads of research to develop a more complete understanding of the use of analogy in engineering design and to provide the basis for formal method development.

METRICS FOR EVALUATION

Previous sections explore the prior research on idea generation methods including design-by-analogy and clearly highlighted the need for more evaluation especially within the context of design. The prior research has used a number of different metrics to attempt to quantify the effects of the various techniques. A critical aspect of an experiment and its validity is the quality of the measurements used. Experiments with design methods are no different, but measurement techniques are not as well developed for understanding important aspects of engineering processes.

A number of different metrics for design problems in areas outside engineering have been used to evaluate idea generation techniques, including quantity of ideas, number of good ideas, practicality, novelty and variety (Bouchard, 1969; Parnes and Meadow, 1959, Gryskiewicz, 1988; Van der Lugt, 2002). Commonly used metrics are the quantity of non-redundant ideas and quality rating (Mullen, Johnson and Salas, 1991). Shah, *et al.* (2003) developed a set of metrics specifically for the evaluation of engineering idea generation techniques including quantity, quality, novelty and variety of ideas.

Metrics need to meet more stringent requirements than they appear to quantify the desired attributes. Any measure of human behavior or cognition needs to be reliable and valid (Aiken, 1997 pg. 145). Reliability is a necessary but not sufficient condition for validity (Aiken, 1997). Any measure must be independent of the administrator; this requires at a minimum, inter-rater correlation and agreement. Validity addresses if the measure evaluates the desired characteristic or not. Validity can be shown in many forms including content validity, whether the measure appears to evaluate the appropriate quantity, and predictive validity. Shah, *et al.* (2003) demonstrate theoretical foundations and content validity for their recommended metrics of engineering idea generation. These are the initial steps of illustrating the validity of a measure and this effort surpasses others in the field of design.

Shah, *et al.* (2003) excel at defining the characteristic of conceptual design to be measured but lack in effective techniques to produce reliable measures between evaluators and across different labs. The procedures outlined by Shah, *et al.* tend to have design problem specific, arbitrary choices built into them and also contain a bias toward particular views. Overall their metrics are biased toward a functional view of design which is not necessarily a shortcoming, but could pose limitations to the usefulness of the metrics. For example, their measure for novelty evaluations the frequency of a solution for a particular function within a device and then includes a weighting factor for each function of a given design problem. This causes a few issues. First the weighting factors are completely arbitrary; therefore two researchers could obtain completely different experimental results simply due to the use of different weighting factors. Secondly, what constitutes sufficiently similar solutions to be considered the same idea is not explained or defined. The basis for the variety of a set of ideas is a hierarchical tree formed around the differences in the physical principle, working principle, embodiment or the details for the design. This variety metric is not validated against human perception (expert opinion) of design similarity and is based on a particular view of difference.

Over time, measures for human behavior become standardized. Netemeyer, *et al.* (2003, pg. 2) list conditions for a standardized measure as (1) rules for measurement are well defined, (2) not demanding for the respondent or administrator, and (3) results do not depend on measure administer. The prior discussion highlights the fact that metrics for conceptual design have yet to become standardized. The variety metric defined by Shah, *et al.*, (2003), is very time consuming for a data evaluator to measure and results for the novelty measure are influenced by how the functional weighting factors are determined. Novelty, variety, quality and quantity of ideas are important constructs to be measured. Due to the limitations in reliability, biases within the metrics, and the time burdens of some of the measurement procedures, this dissertation seeks improved approaches for measuring the quantity, quality, novelty and variety of ideas resulting from conceptual design.

CONCLUSION

Prior work in psychology derives experimental evidence and guiding models that give direction for understanding design-by-analogy but also leave numerous research questions to be answered. A multitude of idea generation techniques have been created but limited empirical evaluation exists. Current literature gives little guidance for which group idea generation techniques are appropriate for a particular design situation. Few formal approaches for engineers seeking innovative analogies exist. The subsequent chapters begin by seeking answers to some of the questions critical to creating a design-by-analogy method and then use the results to develop a new design-by-analogy method which formally guides the engineer in the innovation process. This method is empirically evaluated and conclusions are drawn, especially with respect to the literature reviewed in this chapter.

Chapter 3: Experimental Evaluation of Representation and Group Idea Generation Methods

Engineering design occurs in a team-based environment. Group-based idea generation is common. Engineers represent information with internal cognitive representation and use external representations as support tools for their cognitive processes and as communication with their teammates. Prior work evaluating the effectiveness of Osborn's Brainstorming and similar techniques, which mainly use spoken verbal representations, show generally consistent but dismal results (Lewis, Sadosky and Connolly, 1975; Mullen, Johnson and Salas, 1991). Teams are less effective, in general, than the combined results of the same number of individuals working alone. A few promising studies with brainwriting techniques, including 6-3-5 and C-Sketch, highlight the potential for these approaches to be efficient means of team idea generation. Osborn's Brainstorming is also a verbally-based technique whereas engineers frequently use sketches to to support their cognitive processes (Goel, 1995; Römer, Weißhahn and Hacker, 2001). Some of the brainwriting techniques, including 6-3-5, directly incorporate sketching in the process. The experimental data available for techniques very similar to Osborn's Brainstorming is immense with hundreds of studies available (Mullen, Johnson and Salas, 1991). In contrast, there is little experimental data available for brainwriting type approaches. To more deeply understand the effects of representation in the team environment and to provide more guidance for the development of a design-by-analogy method, a factorial experiment was designed to explore the parameters influencing group idea generation.

POTENTIAL INFLUENCE OF THE COMPONENTS OF IDEA GENERATION METHODS

Much of the variation in formal group idea generation methods is likely attributed to two main parameters: the representation used for communication and how ideas are exchanged, Table 1. Many other parameters of group idea methods exist. Any problem representation highlights certain information while reducing access to other information (Markman, 1999). The *theory of embodied cognition* highlights the importance of external representations in cognition. Due to our limited working memory capacity, we use our environment to reduce our cognitive load. In addition, the *theory of perceptual symbols* suggests that representations in memory are perceptually based rather than a language-like, amodal representation that are arbitrary and bear no resemblance to the concepts they convey (Prinz and Barsolou, 2002). Sketches, as external representations, more closely resemble internal perceptions. Designers use a number of different external representations in the design process to support internal cognitive processes (Goel, 1995; Römer, Weißhahn and Hacker, 2001; Wilson, 2002). These representations include sketches, various forms of diagrams, and sentential annotations. Some diagrammatic representations are very specific in application, such as force flow diagrams for reducing system components, while others such as the "house of quality," are more generally applicable (Otto and Wood, 2001; Greer, Jensen and Wood, 2004). Designers know these varying forms of representation affect their thinking and therefore the final product (Goel, 1995).

Table 1: Summary of Formal Idea Generation Techniques.

Formal technique	**Form of external representation**	**How ideas are exchanged**
Osborn's Brainstorming	Spoken Word	All are viewed at the same time
6-3-5	Written Word	Rotational View
C-Sketch	Sketches Only	Rotational View
Gallery	Sketches & Written Word followed by Spoken Word	All are viewed at the same time
Brainsketching	Sketches & Written Word	Rotational View

In contrast, many idea generation techniques currently available emphasize communication through sentential description because they were developed for less visually-oriented applications such as business. The importance of sketches in design is clear (Goel, 1995; Römer, Weißhahn and Hacker, 2001), highlighted by a recent issue of *Design Studies* focusing on sketching (September, 2006). Sketches support transformation of ideas and help prevent premature fixation (Goel, 1995). Designers also use their sketches to perceive and mentally simulate the function of their design, thereby supporting revision and refinement (Suwa and Tversky, 1996; Suwa, and Tversky, 1997).

A key component of group idea generation is the communication of ideas and is influenced by both the representation (i.e. written, sketched or combination) and how ideas are exchanged (i.e. gallery viewing or rotational viewing). Shah (Shah, 1998) contends a potential benefit of limiting individuals in a group to sketches without verbal annotations is the increased potential for misinterpretations and an enhancement of the novelty and variety of solutions. The viewing conditions also influence the amount of visual stimulus available, evaluation, and how teams provide feedback to the individual members. In rotational viewing there is no feedback, whereas in gallery viewing, the individuals can see how their ideas are added to and changed. Prior research shows that available visual stimuli impacts the ideas generated (Goldschmidt and Smolkov, 2006).

POTENTIAL FOR VERBALLY-BASED TECHNIQUES TO SUPPRESS PERCEPTUAL MEMORY

Many cognitive models of memory theorize two types of knowledge being stored: perceptual (non-verbal) and conceptual (verbal) (Loftus and Kallman, 1979; Barrlett, Till and Leavy, 1980; Mandler, 1980; Paivio, 1986). The verbalization of perceptual information can interfere with the retrieval of perceptual information from memory (Schooler, Fiore and Brandimonte, 1997). This effect is known as *verbal overshadowing*. Prior studies have evaluated an individual's ability to recall a number of different types of complex perceptual information including memory of faces. The general format of these experiments is participants are asked to study a series of faces and then either asked to verbally describe the faces or not. Finally participants' recognition of the faces is tested. These experiments consistently show the interference between the verbalization of perceptual information and memory retrieval of perceptual information. Verbal idea generation techniques may suppress some of the perceptual information in memory, thus giving sketching-based techniques a possible advantage, or at least a complementary capability.

EXPERIMENTAL APPROACH AND RESEARCH QUESTIONS

Engineers need a robust idea generation method for predictably producing a large quantity of high quality, novel concepts. Prior research does not provide a singular approach that meets all criteria, nor is it clear which idea generation method parameters are responsible for improving outcomes. Using a factorial design of experiments, this study explores the influence of the representation used to communicate ideas and how ideas are displayed to individuals. The study seeks to answer the following research questions:

- Question 1: Do the techniques being tested in this experiment vary in the quantity of ideas generated, their novelty or variety? Which idea generation method produces the largest quantity of ideas, highest quality, most high quality concepts largest variety and greatest novelty
- Question 2: Does the representation method of ideas interplay with the display method, or are they independent?
- Question 3: Are certain representations better for producing or improving the quality of solutions? Do certain representations cause bias towards certain types of ideas?
- Question 4: Do time periods exist where team members do not add anything? Previous literature frequently refers to this phenomenon as social loafing. Does this occur less frequently for certain methods? If social loafing does occur in this experiment, does it support the hypothesis of this being one of the reasons for reduced productivity in brainstorming groups? Does the team members' behavior appear consistent with the social loafing hypothesis?

These four research questions are addressed systematically in the following sections. I discuss the experimental method, metrics for evaluation, data analysis approach and a summary of the results. In addition, I discuss secondary issues such as: Does building off teammate's ideas improve the quality of the idea? How does adding small modifications to a design compare with more drastic links from one concept to a new concept?

EXPERIMENTAL METHOD

A factorial experiment is conducted to explore the effects of key factors on the creative outcomes of group idea generation. The first factor controls how participants view the ideas, either all ideas are posted via gallery (on the wall), or sets of ideas are rotated between participants. The second factor controls how participants represent their ideas. Participants either use written words only, sketches only, or a combination of written words and sketches to communicate their ideas to their teammates. A *2* (Display of ideas: gallery or rotational view) X *3* (Representation: words only, sketches only, words combined with sketches) factorial experimental design is used (Table 2). No discussion is allowed during the session; all communication is written. This approach produces methods similar to 6-3-5 (Pahl and Beitz, 1996), C-Sketch (Shah, 1998), Brainsketching (VanGundy, 1988), Gallery Method (Pahl and Beitz, 1996) or Electronic Gallery (Aiken, Vanjani and Paolillo, 1996), Table 3.

Table 2: Summary of Experimental Conditions.

	Factor 2: Representation		
	Words Only	Sketches Only	Words & Sketches
Factor 1: Display			
Gallery View	1	3	5
Rotational View	2	4	6

Table 3: Experimental Conditions and Similar Formal Method.

Experimental Condition	**Similar Formal Idea Generation Method**
1	Electronic Gallery (Aiken, Vanjani and Paolillo, 1996)
2	6-3-5
3	
4	C-Sketch
5	Gallery
6	Brainsketching

The group factorial experiment was conducted over a two week period. Participants were asked to sign a confidentiality agreement to minimize participants hearing about the problem and confounding the experiment. Additionally, a post-experiment survey asks participants if they had heard about the problem and if they had tried to generate ideas prior to the session.

Participants

The participants are students from a mechanical engineering senior design methods course at the University of Texas at Austin. Students range in age from 20 to 35, with 21-24 being typical. Student teams are chosen because it provides a large sample of equally sized groups with experience working as a team. Students at this level have exposure to the majority of mechanical engineering theory and have some experience in the design process through class work and internships. More experienced designers will have a greater database of knowledge to draw from, and therefore it will influence the ideas they generate. Choosing students at the same level of education will minimize the prior experience variability across groups. The quantity of experience is expected to be independent of the parameters under study in this experiment.

The participants were told they would receive extra credit for their participation based on the number, quality, novelty and variety of solutions they develop. In the design methods course, students work throughout the semester in teams of 4-6 members. The course assigns teams based on a strategy for improved team dynamics based on Myers-Briggs personality types, 6-hats, and analytical/fabrication skills (Jensen, Murphy and Wood, 1998; Jensen, Bowe, 1999; Jensen, Feland, Bowe and Self, 2000; Jensen and Wood, 2000; Wood, Jensen, Bezdek, and Otto, 2001). This team formation strategy is not expected to influence the results of the experiment, especially in the context of the factors chosen, but is noted to show that the teams were not randomly formed. For the factorial experiment, fourteen of a possible fifteen teams chose to take part in the experiment and participated with their assigned teams. Participants are required to sign-up as a complete team, and each team participated in the experiment only once.

Students learn a series of idea generation techniques including Brainstorming, TIPS, information gathering, patent searching, analogies and a hybrid version of 6-3-5/C-Sketch that emphasizes sketching with short annotations (Otto and Wood, 2001). These methods are taught in a series of four, one-hour lectures with class attendance being required. None of the students in the experiments missed more than one lecture. The experiment took place after these methods had been taught in class. Students have minimal practice with any one of these techniques; therefore this exposure is not expected to cause a bias in the results.

Description of the Design Problem

The design problem is to design a device to quickly shell peanuts for use in places like Haiti and West African countries and is based on a real-world problem posted on ThinkCycle ("ThinkSpace: Peanut Sheller," 2004). Participants are told no electrical energy sources are available and given customer needs along with corresponding main functions (Figure 15). The problem is read to the participants with no further clarification given. This problem is chosen because it is a need-based, real world problem that a mechanical engineer would be able to solve and has a diverse set of available solutions. It is very unlikely that any of the participants would have extensive prior experience in solving this problem, yet shelling a peanut is a task all of the participants would have experienced or at least observed.

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

Figure 15: Design Problem Description.

Procedure for All Group Conditions

All conditions are randomly assigned and conducted with existing teams of five participants. For teams with six members, one person is randomly assigned to work alone (as a control), and their ideas are not included in the team totals. The single four member team also worked individually as a control. During one session, only four of the five members were present; thus their results will not be considered as part of the study. Sessions are scheduled at the team's convenience throughout the day and week. All sessions take place in the same room, a windowed conference room in the mechanical engineering building.

Participants are each given a unique set of five colored markers and are seated next to each other facing the same direction. The variety of colors makes it difficult for other participants to identify the originator of an idea while at the same time allowing identification by the experimenter. Previous work shows more ideas are generated when they are anonymous, but ideas must be identifiable to the experimenter to reduce social loafing (Diehl and Stroebe, 1987). Participants are told they could use the various colors any way they desire, but three examples of how color could be useful are given to encourage the use of multiple colors (Figure 16). These examples include using color to show different components of a design, variations on an idea, and to help explain ideas such as coloring water blue. These examples are intentionally unrelated to the design problem and included a sketch of a box with two different styles of holes and a facet. An additional effect of the markers is the equalization of drawing abilities. Sketches from participants with greater sketch ability look essentially the same as sketches from participants with less ability. There is no drastic difference in sketch quality across the participants.

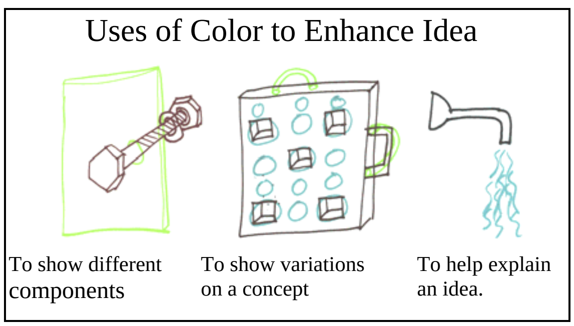


Figure 16: Participants were given examples of how to use the assortment of colored markers.

The experimenter (the same individual for all conditions) reads a set of scripted instructions and posts the ideas on the wall or rotationally exchanges ideas between participants. The instructions include a description of the problem, the basic idea generation rules (Osborn, 1957) of seeking a large quantity of ideas along with encouraging diversity ("wild," eccentric, or non-standard ideas), a reminder that criticism is not allowed, and a statement that the session is to test a new idea generation method. The experimenter tells the participants how to represent their ideas (words only, sketches only, or a combination of words and sketches) and then describes the prescribed idea generation method (“gallery view” or “rotational view”). The session lasts approximately 50 minutes with 40 minutes for idea generation, followed by a post-session questionnaire.

Factor 1: Display of Ideas

The first experimental factor determines how the participants view the ideas generated by their teammates. From previous research, it is not clear how the ideas should be displayed to the participants, all at once or only a subset. The first level of this factor, “Gallery View”, posts all ideas the team generates in a gallery style (on the wall) so all participants can see all of the ideas at the same time. This approach results in a method similar to Gallery Method or Brainsketching dependeing on the representation factor (VanGundy, 1988; Pahl and Beitz, 1996). The second level, “Rotational View,” is similar to 6-3-5 or C-Sketch (Pahl and Beitz, 1996; Shah, J. J., 1998; Otto and Wood, 2001). For rotational viewing, sets of ideas are passed around the table such that each participant focuses on a particular set and reviews it only once.

Gallery View Condition- Similar to Brainsketching or Gallery Method

For the first 10 minute period, each participant is given a number of paper sheets and told to write down at least two ideas on separate sheets of paper. Sheets are collected as participants finish but are not displayed until the end of the period. The time period length is based on the available time and literature recommendations, which vary from five to 15 minutes (VanGundy, 1988; Baxter, 1995; Shah, Kulkarni and Vargas-Hernández, 2000). The ideal time periods for the methods under evaluation are not known and are not one of the experimental parameters. At the end of the first period, all sheets are numbered and posted gallery style on the wall. In the four subsequent periods, each 7.5 minutes, ideas are posted as they occur and participants are told to execute one of the following options (Figure 17):

1. Add new ideas to one of the posted drawings. Participants can request a drawing by writing down its number on a small sheet of paper.

2. Make a separate drawing that is related to the ideas that are already posted, and write the number of the linked idea on the new sheet.

3. Start a completely new sheet.

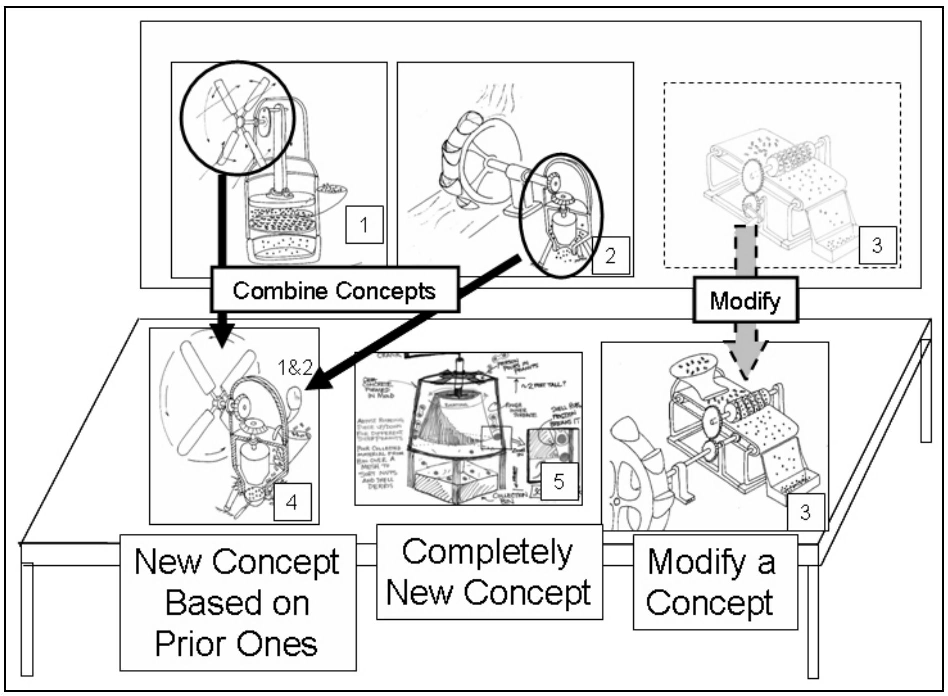


Figure 17: Options for building from others' ideas.

Rotational View Condition- Similar to 6-3-5 or C-Sketch

For the first 10 minute period, each participant is given a number of paper sheets and told to write down at least two ideas on separate sheets of paper (similar to the "Gallery View" condition). At the end of the period, the experimenter collects all sheets and systematically redistributed them such that each participant views each set of papers once. Participants can not identify which one of their teammates had the sheets previously. In the four subsequent periods, lasting 7.5 minutes each, participants have the same options as in the gallery view condition: to add ideas to an existing sheet, to create a new concept linked to another sheet or to start a completely new concept. The exception here is that participants focus on the specific set of papers given to them at a particular instance in time.

Factor 2: Representation

The second experimental factor prescribes how the participants communicate their ideas to other participants (words only, sketches only with no words, or a combination of words and sketches). At the end of the sessions, and after completion of the surveys, participants in either of the sketches-only conditions labeled their sketches with brief descriptions to facilitate evaluation. American mechanical engineers are typically not taught to free-hand draw, and therefore their sketches are usually difficult to interpret without annotations.

METRICS FOR EVALUATION

A critical aspect of an experiment is the quality of the measurements used. Experiments with design methods are no different, but measurement techniques are not as well developed for understanding important aspects of the conceptual design processes. A number of different metrics, for design problems in fields outside engineering, have been used to evaluate idea generation techniques, including quantity of ideas, number of good ideas, practicality, novelty and variety (Parnes and Meadow, 1959; Bouchard, 1969;

Gryskiewicz, 1988; Shah, Vargas-Hernández, Summers and Kulkarni, 2001; Van der Lugt, 2002). Commonly used metrics are the quantity of non-redundant ideas and quality rating (Mullen, Johnson and Salas, 1991). Shah, *et al*. (2003) developed a set of metrics specifically for the evaluation of engineering idea generation techniques including quantity, quality, novelty and variety of ideas. This study likewise measures the quantity, quality, novelty and variety of concepts and the quantity of ideas.

Three existing solutions for shelling peanuts were sketched and added to the participants' results to benchmark and add additional validity to the metrics. Two solutions are aimed at third world countries (DelHagen, *et al*., 2003; Full Belly Project", 2006), and the third solution is aimed at large-scale industrial application ("American Peanut Council," 2006).

Method for Measuring the Quantity of Ideas and Concepts

The literature demonstrates that the quantity of unique (or non-redundant) ideas is important for insuring the successful development of a product (Ulrich and Eppinger, 2004). A single concept is defined as all the ideas contained on a single page unless participants made a clear indication that the concept is continued onto another page. A single idea is more difficult to define. A critical element for measuring the quantity of ideas is a precise definition of what constitutes a single idea. Is a single idea an off-the shelf component or piece-part, a single noun phrase, an item that meets any function, or something else? This question is particularly difficult when the data are in the form of sketches because sketches frequently contain many vague details. Figures 18 and 19 show examples of a single concept for "words only" and "sketches only" conditions. Figure 19 also lists the ideas that are contained within the figure.

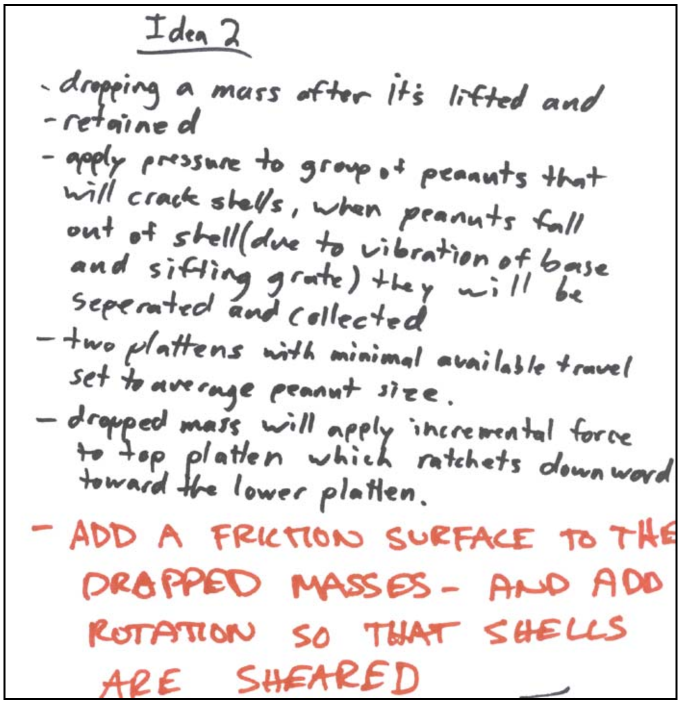
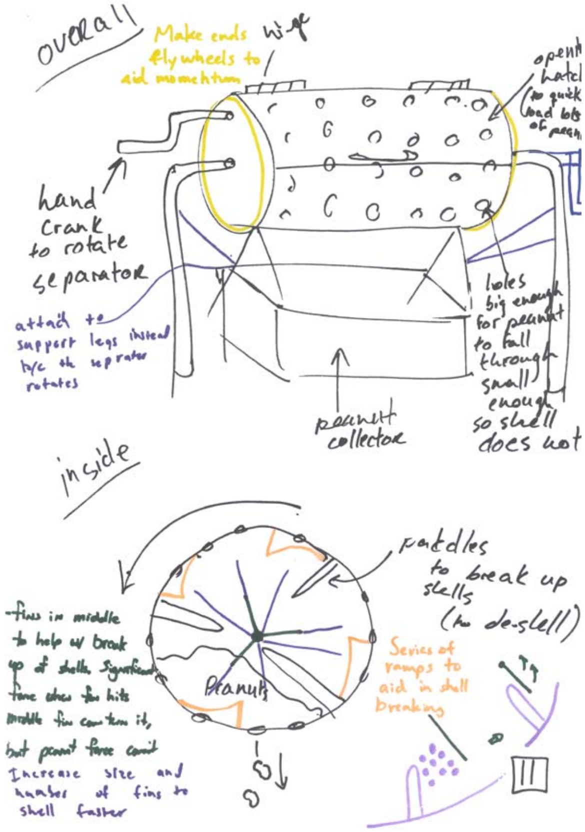


Figure 18: An example of one concept from the words only condition**.**

Building from the procedure developed by Shah, *et al*. (2000), a set of procedural rules are defined for what constitutes a single idea, see Linsey, *et al*. (2005) for more detailed examples. The basic definition for an idea used by this study is something that solves one or more of the functions of the design as defined by the functional basis, a clearly defined and tested language for expressing design functions (Hirtz, Stone and McAdams, 2002). A second definition of what constitutes an idea is developed for when participants create ideas based on a more abstract view of the problem, or "reframe" the problem. This situation occurs more frequently when participants are restricted to only words for description. These solutions are clearly ideas, but they do not fit defined functions of the functional basis for the stated problem. For example, ideas in this category range from genetically engineered peanuts to training squirrels that shell the peanuts. A third refinement is made for function sharing ideas, features that perform two or more functions. Function sharing ideas count as single ideas. This choice is made because it provides greater consistency between judges, leaving less room for interpretation of the intended function. Clearly, function sharing is good design practice, but identifying intentional function sharing is difficult due to the vagueness of sketches or word descriptions. This quantity metric is biased toward a functional view, but this definition combined with the definition for "reframing" ideas covers virtually every solution encountered. This method for measuring the quantity of ideas allows for a high degree of inter-rater agreement and a robust metric, as demonstrated by tests during the experiment.

Three judges independently counted the number of ideas based on the guidelines given above. Two judges were blind to the conditions of the experiment and the hypothesis, one of whom counted all of the data. The other two judges each counted a non-overlapping subset. Pearson's Correlation Coefficient (Clark-Carter, 1997) is 0.99 and 0.95 for the two sets of judges. This is a high level of correlation and indicates the guidelines are being consistently applied. Since the counting rules are being applied consistently, the analysis of the quantity data are completed using only comprehensive judge's results to minimize the variance due to using different judges.

Once ideas for each team are counted, the score for each individual is found by identifying the ideas' originator based on the marker color used to write or sketch it. Similarly, the time period the idea was conceived is determined. For gallery view conditions, the time each sketch is completed and the time of additions to it are recorded. The credit is evenly split between the participants when multiple participants thought of the same idea during the same time period. This situation occurs frequently for the rotational viewing condition and occasionally in the gallery view condition when two participants are writing down the same idea at the same time.



List of Ideas within the Concept
ramps
handle
door
fixed fins
rotating fins
rotating drum
container
filter holes
support legs
container hangers
flywheel
hinge
pivot
hand crank

Figure 19: Example of one sketched concept and the list of ideas contained within the concept.

Method for Measuring the Variety and Novelty of Ideas

To measure the variety and novelty of concepts generated, two independent raters sort the sheets into groups or bins of similar concepts, where a given rater chooses what constitutes “similar.” One rater was blind to the conditions of the experiment and the hypotheses. The first evaluator formed 34 bins and the second created 28 bins. The variety score for a team is measured by the percentage of total bins that the team’s concepts occupy. For example, if a team produces concepts that are sorted into 6 bins by rater 1, that group would receive a variety rating of 6/34 or 17.6%. Pearson’s Correlation (Clark-Carter, 1997) between the raters is high (r= 0.82). This indicates the metric is reliable.

The novelty score for each concept is a function of the number of similar concepts (i.e. number of concepts in that particular bin) relative to the total number of concepts. Specifically, novelty is equal to one minus the frequency an idea occurs and has been used previously (Jansson and Smith, 1991), Eq. (1). This metric fails if a team develops one very novel concept and then creates numerous variations on it. None of the teams in this study did this. A high correlation between raters is achieved (r=0.80).

$$novelty = 1 - frequency\ of\ idea = 1 - \frac{number\ of\ very\ similar\ concepts}{total\ number\ of\ concepts} \quad (1)$$

Method for Measuring the Quality

Quality, as defined by Shah *et al*. (2003), is a measure of a concept’s feasibility and how well it meets design specifications. In this study, quality is measured on a three-point rating scale (Figure 20) independently by two judges, one of whom was blind to the conditions of the experiment and the hypothesis. Each concept generated by a team received a quality scores. After initial data evaluation by both judges, Cohen’s Kappa (Clark-Carter, 1997) showed a fair level of inter-rater agreement (0.42). All differences were readily resolved through discussion. As expected, the benchmark solutions designed for third world countries scores a two and the industrial benchmark solution is rated at a one, Figure 21. A coarse (three-point) highly defined rating scale is used rather than an unanchored rating scale since prior work showed difficulties in applying an unanchored scale (low correlation between raters) (Kurtoglu, Campbell and Linsey, in review). An unanchored rating scale has an expert evaluator rate a concept on a spectrum, for example one to seven with one corresponding to lowest quality and seven to highest quality, without specifically defining each point on the scale. Figure 20 is a more highly defined rating scale since each point on the scale has a specific definition.

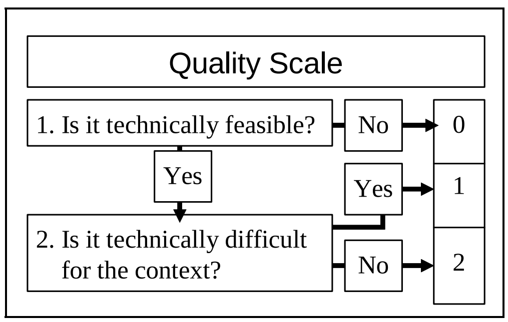


Figure 20: Quality Scale.

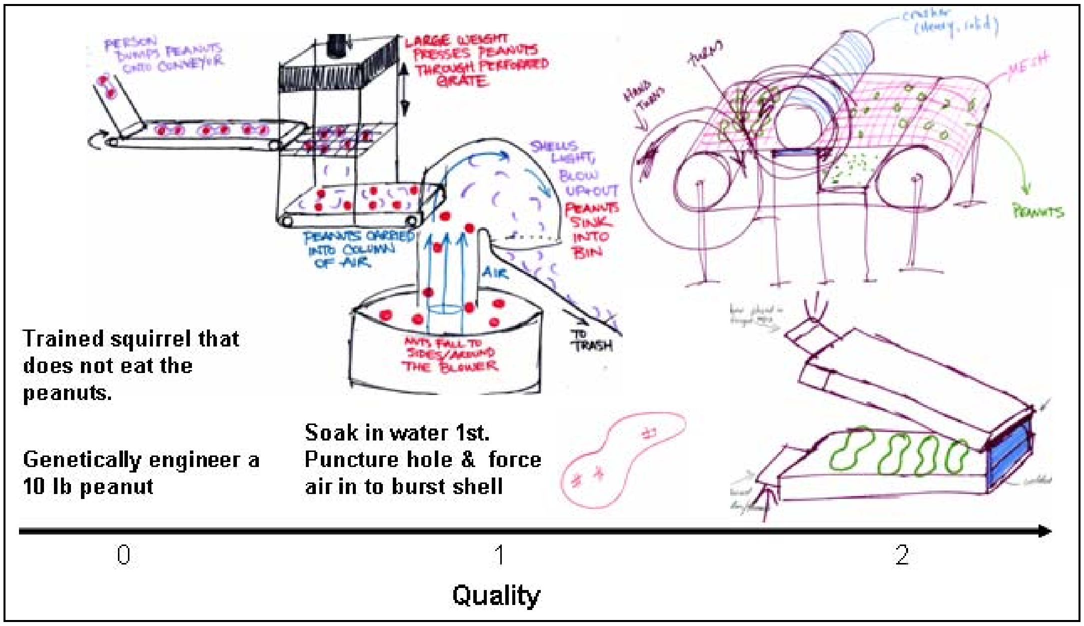


Figure 21: Examples of concepts at each quality level.

RESULTS

The following sections present results that further illuminate the research questions posed previously and describe the significance and implications of these results, according to each metric. Table 4 highlights the aggregate results for the experimental conditions, and Figure 22 presents example concepts. As shown in Table 4, the concepts generated by the participants have a high aggregate quantity, novelty and quality. Participants obviously commit their time seriously to a real-world problem that seeks an innovative solution. On the post-experiment survey, one participant in experimental condition 4 did note that they had heard about the experimental problem ahead of time and thought about the problem. This team's data were reviewed, and no significant or noticeable bias existed in the team's or individual's results.

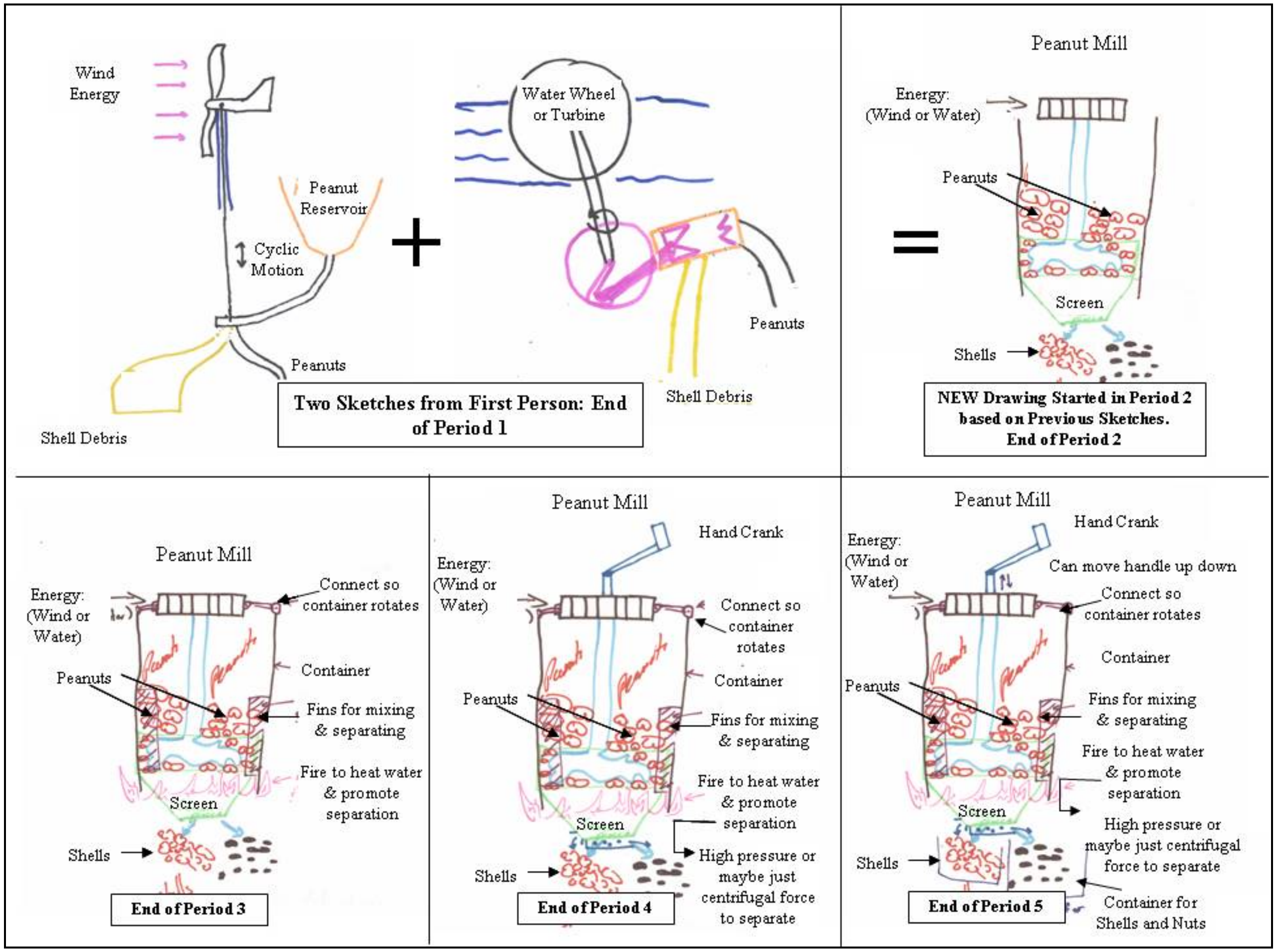


Figure 22: Example interesting results from a Words & Sketches combined with rotational viewing session. The quality of the concept increases as ideas are added.

Table 4: Averages for Each Metric by Condition.

Condition	Representation	Viewing Approach	Quantity of Ideas per Person (SD)	# of Concepts (SD)	Ave. Quality (SD)	# of High Quality Concepts (SD)	Variety (SD)	Ave. Novelty (SD)
1	Words Only	Gallery	12.1 (5.5)	25.5 (10.6)	1.36 (0.82)	11 (7.1)	43% (0.20)	0.94 (0.03)
2	Words Only	Rotational	17.5 (4)	18.5 (0.7)	1.19 (0.11)	6.5 (0.7)	38% (0.02)	0.93 (0.03)
3	Sketches Only	Gallery	17.6 (5.4)	23.0 (0.0)	1.74 (0.07)	17.5 (2.1)	35% (0.03)	0.92 (0.006)
4	Sketches Only	Rotational	14.4 (4.9)	19.0 (7.1)	1.86 (0.01)	16 (5.7)	33% (0.04)	0.92 (0.01)
5	Words & Sketches	Gallery	16.7 (4.1)	22.0(2.8)	1.60 (0.14)	14 (5.7)	32% (0.05)	0.92 (0.02)
6	Words & Sketches	Rotational	19.3 (4.9)	15.0 (2.8)	1.42 (0.16)	6.5 (2.1)	33% (0.04)	0.94 (0.01)
Average			16.3	20.5	1.53	11.9	36%	0.93

QUANTITY

The quantity of ideas is measured for each team and also for each individual. Since each participant uses a unique set of colors, their individual contributions are easily discerned. The quantity of ideas increases by 50% due to the variation in experimental conditions, Figure 23. Patterns in the team data mirrored the individual data with individual data having a larger sample size and therefore higher statistical significance. There are strong interaction effects between the representation and the viewing conditions, Figure 23 and Figure 25 (Display: $F(1,54)=1.65$, $p>0.2$, Representation: $F(2,54)=2.24$, $p>0.1$, Interaction: $F(2,54)=4.12$, $p<0.03$ and $MS_{error}=23.32$) The information in parentheses gives sufficient data to produce the ANOVA Table 5, see (Clark-Carter, 1997) for more details. Evaluating the ANOVA for the total group scores show a similar pattern of results but with lower significance levels due to the smaller sample size, Figure 23 (Display: $F(1,6)=1.21$, Representation: $F(2,6)=1.71$, Interaction: $F(2,6)=3.13$, $p=0.12$ and $MS_{error}=158.33$) In the “words only” and “words combined with sketches” conditions, the interaction follows the same pattern such that rotational viewing increases the number of ideas, Figure 25. For the “sketches only” condition, rotational viewing decreases the number of ideas.

Three 2 X 2 ANOVAs are compared to further understand the source of the interactions and highlight hidden effects. ANOVAs for the “words only” and “sketches only” conditions {Display: $F(1, 36)=0.48$, $p>0.5$, Representation: $F(1,36)=0.58$, $p>0.5$, Interaction: $F(1,36)=0.7.46$, $p<0.01$ and $MS_{error}=24.80$} and the “words & sketches” and “sketches only” conditions {Display: $F(1, 36)=0.038$, $p>0.5$, Representation: $F(1,36)=1.71$, $p>0.15$, Interaction: $F(2,6)=3.59$, $p<0.0.7$ and $MS_{error}=23.40$} shows that an interaction effect is due only to the “sketches only” conditions. This result suggests that others factors may be influencing the "sketches only" condition. Observations of the participants' sketching ability shows it is generally poor, and it is hypothesized that they may be frustrated by the difficulty in communication when limited to sketches.

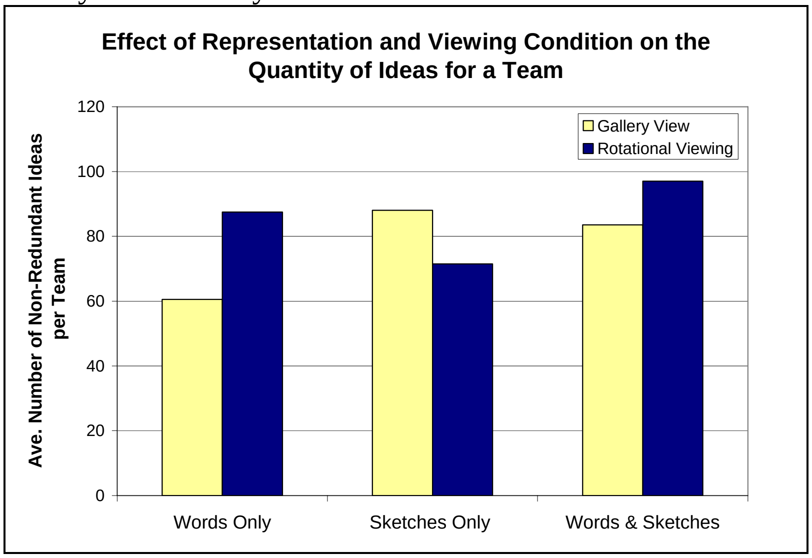


Figure 23: There is a significant interaction between representation and viewing conditions.

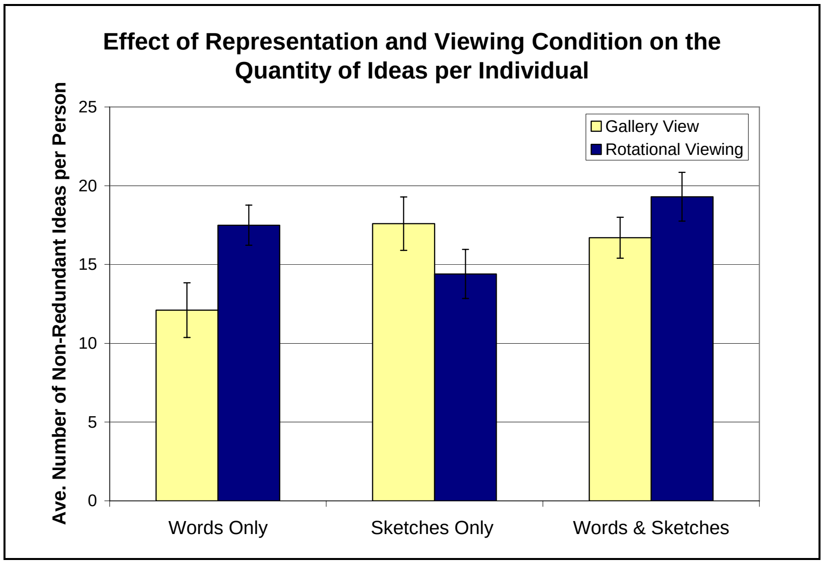


Figure 24: Results for each individual mirror the team results. A significant interaction between viewing condition and representation exists. Error bars are one standard error.

Table 5: Quantity 3X2 ANOVA Results, Quantity of Ideas per Individual.

	Sum of Square	**Degrees of Freedom**	**Mean Square**	**F**
Display	38.4	1	38.40	1.65
Representation	104.5	2	52.27	2.24
Interaction	192.4	2	96.20	4.12**
Error	1259.4	54	23.32	
Total	1594.7	59		

**statically significant results at the 0.03 level

The “sketches only” data follow a different pattern of results than the other two representation conditions. A comparison of the “rotational view” condition versus the “gallery view” condition shows statistical significance at the 0.01 level after removal of the “sketches only” effect, Table 6, {Display: $F(1, 36)=7.35$, $p<0.01$, Representation: $F(1,36)=4.70$, $p<0.05$, Interaction: $F(1,36)=0.9$, $p>0.5$, and $MS_{error}=21.77$}. This trend corresponds to an approximately 30% increase in the number of ideas for the five person team. A 30% increase in the number of ideas over a 40 minute time period is important. This result is significant and intriguing. The use of sketches and words increases the total number of ideas by about 20% compared to only words for the five person team and is statistically significant at the 0.05 level.

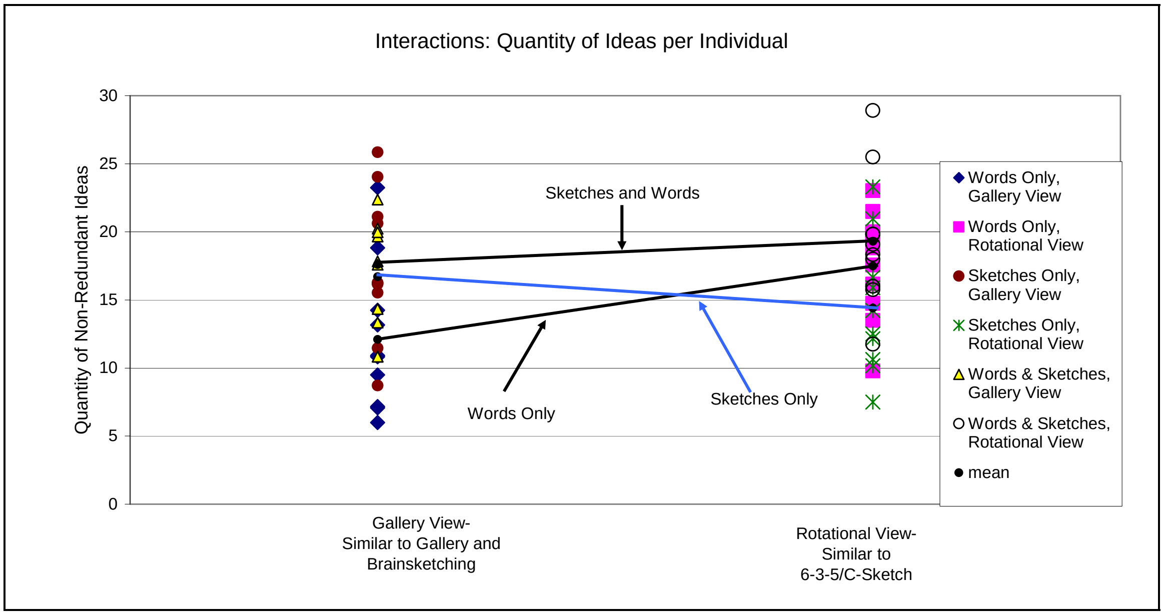


Figure 25: There is an interaction between the representation and how the ideas are displayed.

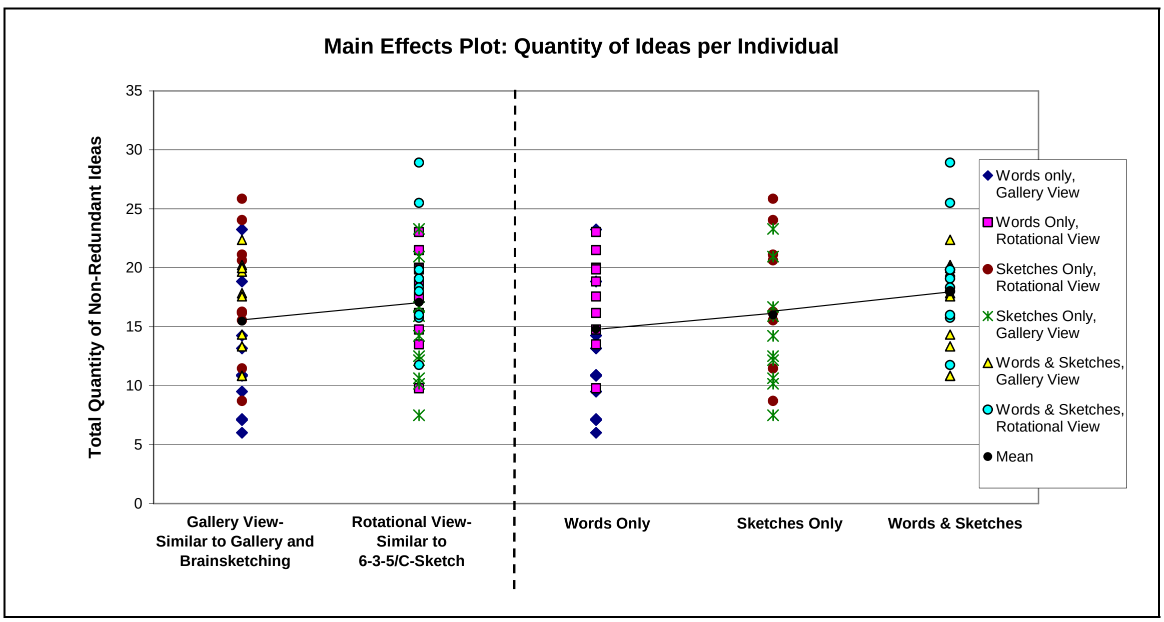


Figure 26: Main effects for representation and how the ideas are displayed. Number of ideas for each individual is shown.

Table 6: Quantity 2X2 ANOVA Results, Words Only and Sketches & Words Conditions.

	Sum of Squares	**Degrees of Freedom**	**Mean Square**	**F**
Display	160	1	160	7.35**
Representation	102	1	102	4.70*
Interaction	19	1	20	0.90
Error	784	36	22	
Total	1066	39		

**statistically significant result at the 0.01 level

*statistically significant result at the 0.05 level

Quantity of ideas over time

Figure 27 shows the quantity of ideas as they are incrementally added during the idea generation process. As expected, groups develop more non-redundant ideas during the initial time period, but a virtually equal and substantial number of ideas continue to be generated throughout the session (Figure 27). This result is significant and supports the concept that team members are piggy-backing on other members' ideas. In addition the number of ideas generated in time periods 2-5 remains constant indicting the teams had not run out of ideas and may have continued to generate more.

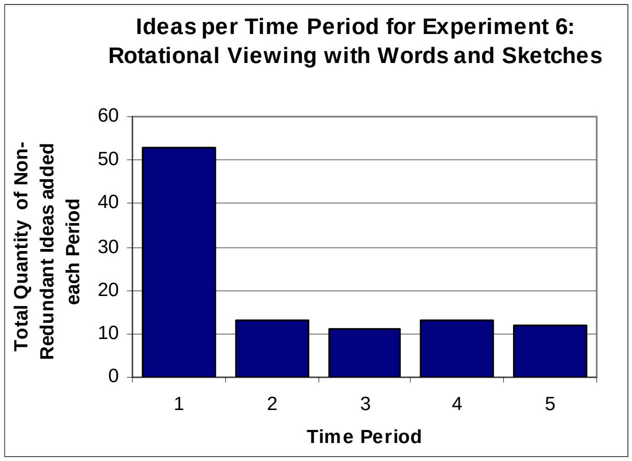


Figure 27: Quantity of non-redundant ideas added each time period.

As shown in Figure 28, a large number of ideas are gained during the first time period when individuals work alone and also through collaboration with other team members. However, building from others' ideas produces a nearly equal number of ideas as the individuals working alone. This result is a clear contribution and insight from this experiment, and is consistent throughout the experimental conditions.

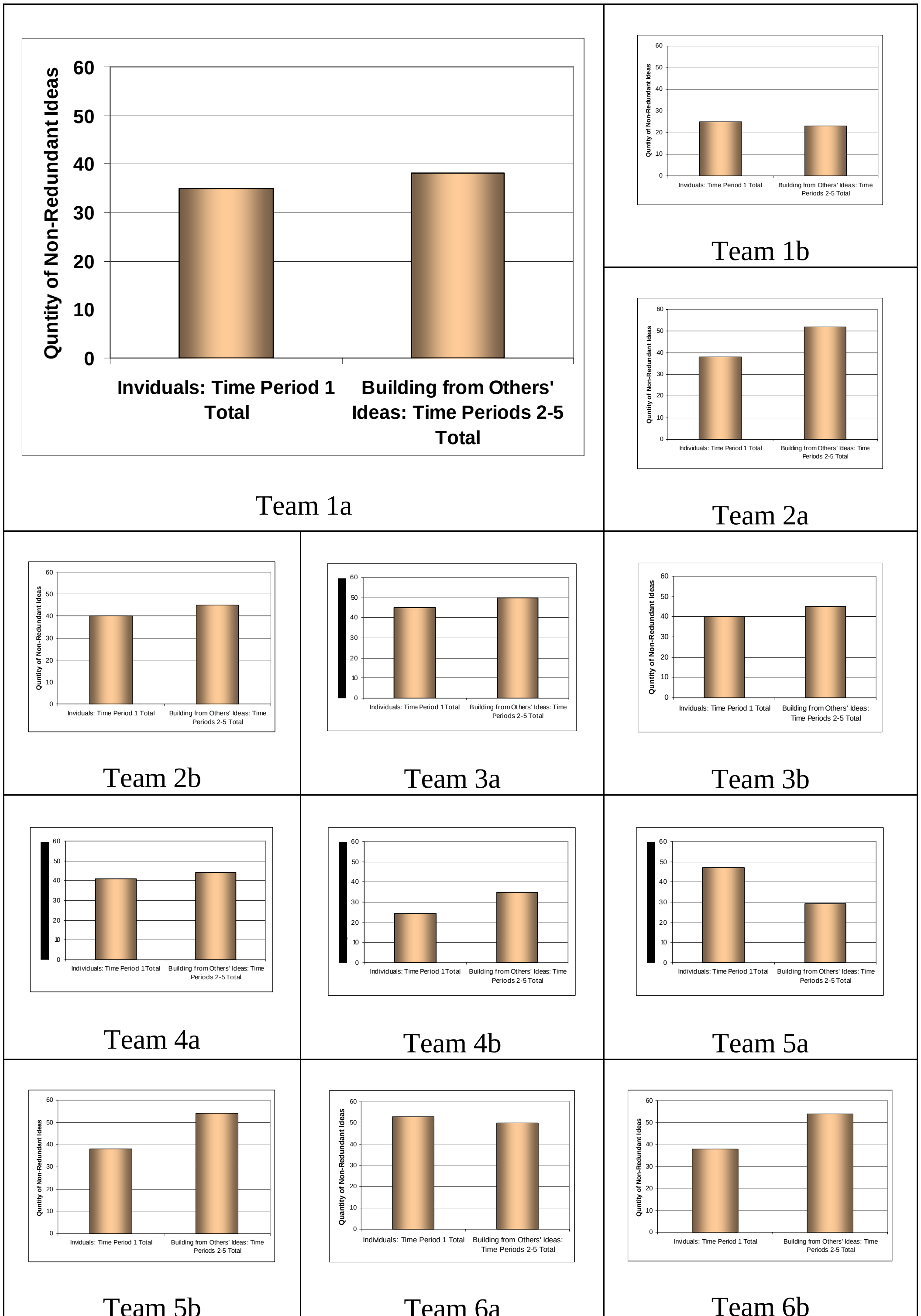


Figure 28: Teams gain a significant number of ideas through collaboration.

Investigating the Productivity of Individual Team Member: Quanity of Ideas Over Time by an Individual

Prior research on Osborn's Brainstorming shows that one of the possible reasons why group idea generation fails to produce more ideas than the combined non-redundant efforts of an equal number of individuals working alone is certain individuals do not contribute and "socially loaf" (Diehl and Stroebe, 1987). Time periods of non-contribution are observed in this data set also (Table 7, Figures 29 and 30). During a number of time periods certain individuals did not add any ideas. Many times participants appeared to be thinking or reviewing other peoples' ideas during these time periods. The occurrence of social loafing is most frequent in the "Gallery" conditions and distributed fairly evenly across the various representations. The rotational exchange of concepts reduces these occurrences.

Table 7: Number of individuals who during one or more time periods did not add any ideas.

	At least one time period	**Two or more time periods**
Factor 1: Display		
Gallery	14	3
Rotational	2	0
Factor 2: Representation		
Words	9	2
Sketches	4	0
Words & Sketches	3	1

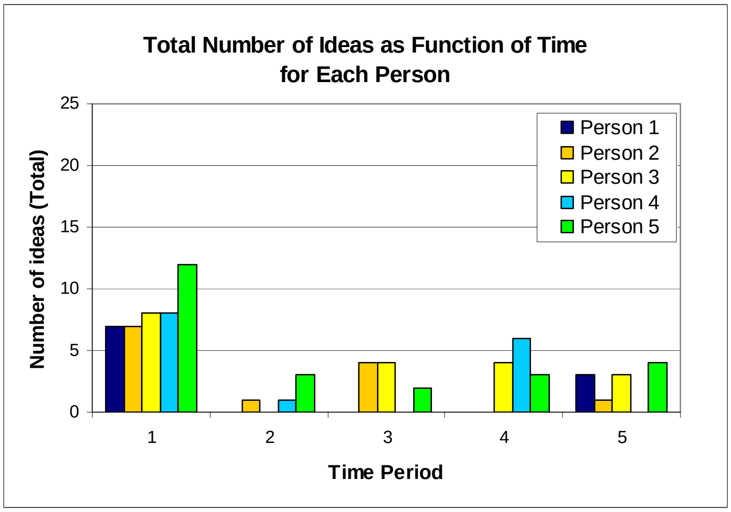


Figure 29: Team 1b (Galley View with Words Only) Many Instances of Social Loafing.

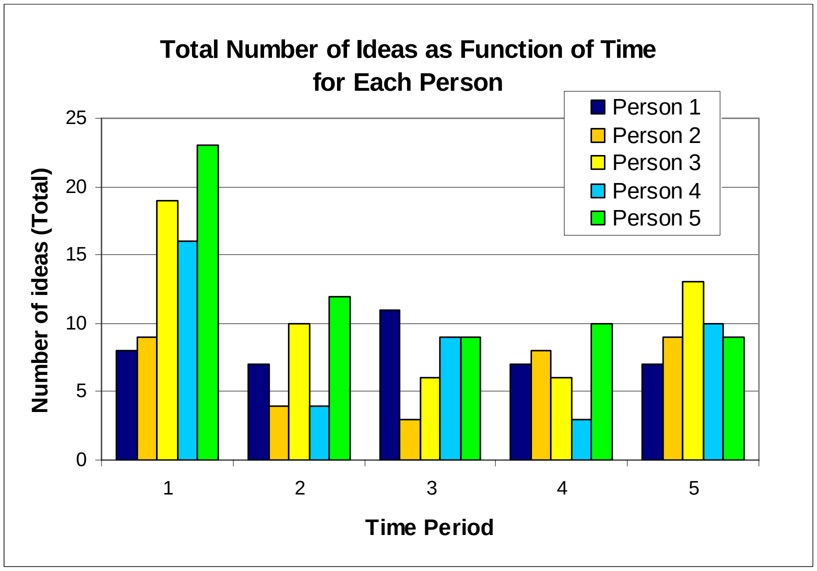


Figure 30: Team 3b (Rotational View with Words & Sketches) No Social Loafing.

Novelty

The novelty of the results did not vary across the conditions, Table 4. Participants found a number of very unusual solutions to the design problem. For one rater, nineteen of the concept bins contained only one or two concepts, indicting that the concepts are very unique. All conditions produce essentially equal levels of novel concepts, with ANOVA results showing no main effects for either representation or viewing conditions nor any interaction (Display: $F(1,6)=0.37$, $p>0.5$, Representation: $F(2,6)=0.27$, $p>0.5$, Interaction: $F(2,6)=0.71$, $p>0.5$ and $MS_{error}= 0.00032389$).

Table 8: Novelty ANOVA Results.

	Sum of Squares	Degrees of Freedom	Mean Square	F
Display	0.00012	1	0.00012	0.36
Representation	0.00011	2	0.00005	0.18
Interaction	0.00034	2	0.00017	0.52
Error	0.0019	6	0.00032	
Total	0.0025	11		

Variety

The variety for each team's results is not influenced by the experimental conditions, Table 4. The teams explored only a segment of the total design space. This result is of particular concern since the variety metric is a measure relative to all the solution generated by the twelve groups of participants and not all theoretically possible solutions to this problem. Most teams evaluated possible solutions in less than half of the design space, Figure 31. One team did explore significantly more of the design space showing that a greater breath of solutions is possible in the time allowed. ANOVA results show no significant differences for either the main or interaction effects (Display: $F(1,6)=0.08$, $p>0.5$, Representation: $F(2,6)=0.75$, $p>0.5$, Interaction: $F(2,6)=0.23$, $p>0.5$ and $MS_{error}=0.008$).

There is no difference in the total percent of the design space evaluated by each method, but there are differences in the average amount of the design space per concept. The viewing condition does affect the average amount of the design space covered by each concept, Figure 32. There is a significant main effect due to viewing condition, no effect for the representation or interaction (Display: $F(1,6)=6.06$, $p<0.05$, Representation: $F(2,6)=0.22$, $p>0.5$, Interaction: $F(2,6)=0.58$, $p>0.5$ and $MS_{error}=1.4768E\text{-}05$). Teams in the rotational conditions tended to use fewer concepts while covering the same total percent of the design space. This means there is greater distance in the design space between the concepts in the rotational viewing conditions. Rotational viewing tends to produce concepts with a greater average diversity, fewer concepts that cover the same amount of the design space as gallery view. The design concepts tend to be more different from each other. From these results, teams search only a fraction of the design space and additional idea generation methods are required to more fully explore the design space.

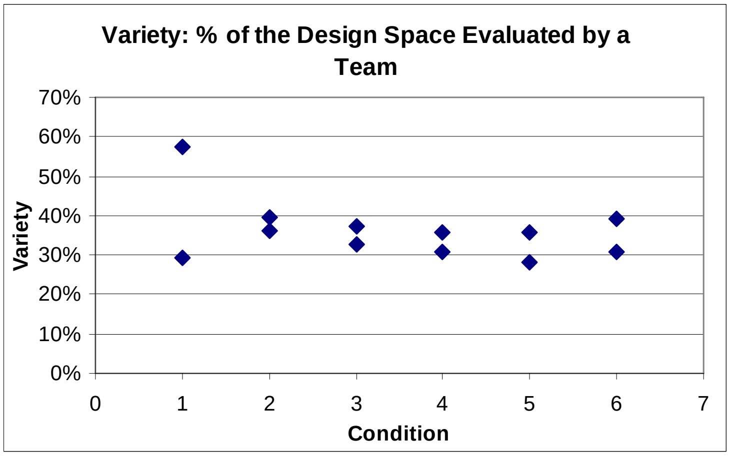


Figure 31: Most groups evaluated only a small fraction of the total design space.

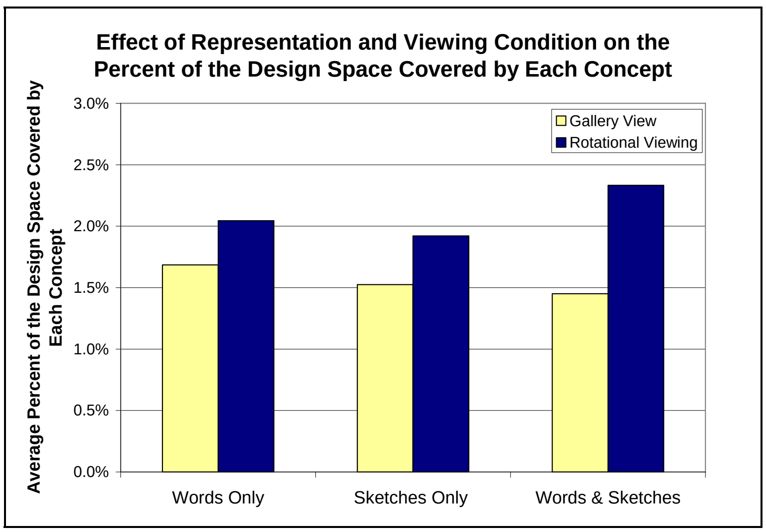


Figure 32: The average amount of the design space covered by each concept varies.

Quality

Each concept generated by a team receives a quality scores. The quality scores are then averaged over the team. This team average score is subjected to ANOVA analysis. The average quality of a concept is not influenced by the experimental factors, Figure 33. Overall the quality of the concepts is very high with an average of 1.5. This result means the average concept is at least technically feasible and not quite practical for the context. This is a very high level of quality for these participants considering their inexperience with the problem domain. The average quality of concept did not vary significantly across the factors; ANOVA results show no significance for either the main or interaction effects, Figure 33 (Display: $F(1,6)=0.15$, $p>0.5$, Representation: $F(2,6)=2.31$, $p>0.15$, Interaction: $F(2,6)=0.24$, $p>0.5$ and $MS_{error}=0.12$). The set of idea generation methods evaluated in this experiment is clearly useful for finding high quality, practical solutions to a given design problem. From the quality results, it is also apparent the participants commit themselves to seriously attempting to solve this problem and exert a high level of effort.

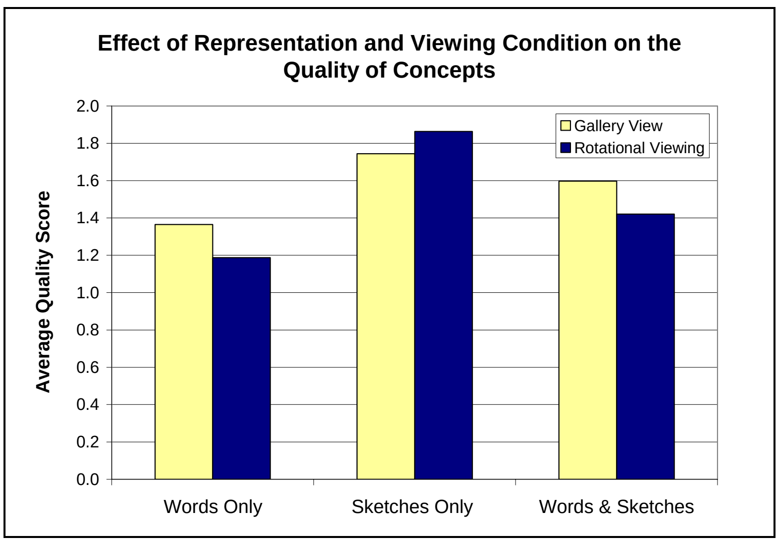


Figure 33: Average Quality of a Concept.

Table 9: Average Quality ANOVA Results.

	Sum of Squares	Degrees of Freedom	Mean Square	F
Display	0.02	1	0.02	0.15
Representation	0.56	2	0.28	2.31
Interaction	0.06	2	0.03	0.24
Error	0.73	6	0.12	
Total	1.36	11		

The distribution of the scores and the number of high quality concepts (a score of 2) provides additional insights into the various techniques being evaluated in this study, Figures 34 and 35. One group in condition 1 (words only, gallery view) generated an unusually high number of technically infeasible solutions. In contrast, almost no technically infeasible solutions are generated by groups communicating with either only sketches or a combination of sketches and words. Groups in the sketches only condition created significantly more high quality concepts than the other two representations, Figure 35. ANOVA results show a main effect for representation and a close to significant result for viewing condition, (Display: $F(1,6)=2.95$, $p=0.14$, Representation: $F(2,6)=3.51$, $p<0.1$, Interaction: $F(2,6)=0.44$, $p>0.5$ and $MS_{error}=20.58$, Table 2). Comparing the means of the "words only" and "words combined with sketches" conditions to the "sketches only" condition using a linear contrast (Howell, 2002) shows the "sketches only" condition results in more high quality concepts ($F(1,6)=6.8$, $p<0.05$).

Table 10: Quantity 2X3 ANOVA Results.

	Sum of Squares	Degrees of Freedom	Mean Square	F
Display	38	1	38	1.65
Representation	104	2	52	2.24
Interaction	192	2	96	4.12*
Error	1259	54	23	
Total	1594	59		

*statistically significant at 0.02 level

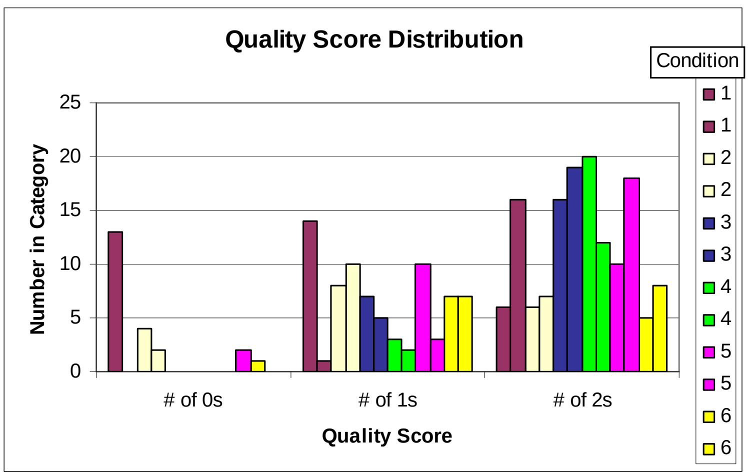


Figure 34: Distribution of Quality Scores.

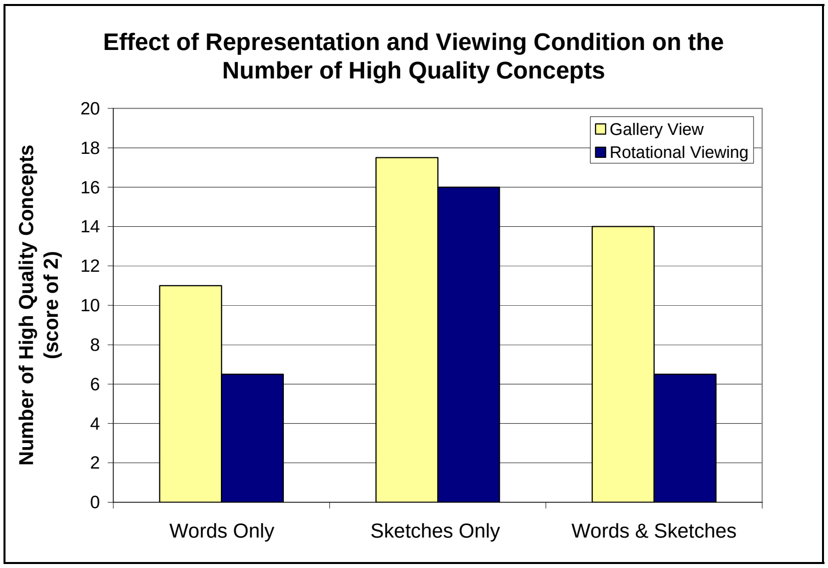


Figure 35: Number High Quality Concepts for Each Condition.

Change in Quality over Time

The quality of a concept frequently changes as team members add their ideas. An example of this result is shown in Figure 22. The concept begins as a large-scale machine powered by a wind or water mill. As ideas are added, it became a hand-powered, more complete and feasible system. In this experiment, two methods are available for the teams to build off each others' ideas and change the quality of the concept. They can add their ideas directly onto the same sheet (embellish) or start a new sheet and include a cross-reference or "link" to a previous concept number. A few concepts are both embellished and cross-linked. Concepts which are embellished tend to be higher quality concepts, Table 11. When teams crosslink a concept, the resulting concept is usually of equal quality and occasionally of higher quality, Figure 36 and Table 12.

As individuals add ideas, the overall concept can drastically improve. For example, Figure 22 shows the successive additions made to one sketch. The initial idea is interesting, but probably a bit impractical to import energy to the system. During the fourth time period, importing human energy through a hand crank is added. This change is intriguing because the physical size of the system using a wind or water turbine is drastically different from the size of the system using a hand crank. The lack of dimensions in the sketch promotes improvements to the concept. Each time period results in more solutions to the required functions and overall a more complete concept. This high quality concept is very similar to a solution currently used for shelling peanuts in third world countries ("Full Belly Project", 2006).

Table 11: Quality of Concept Added or Linked to.

	Percent of Concepts for a Given Quality Score		
	0	**1**	**2**
Linked to	14%	7%	10%
Added to at least once	23%	44%	43%
Not linked or added to	64%	47%	54%

Table 12: High Quality Concepts are Linked to Most Often.

	Initial Linked Concept Quality Score		
	0	**1**	**2**
Number of Concepts	3	8	29

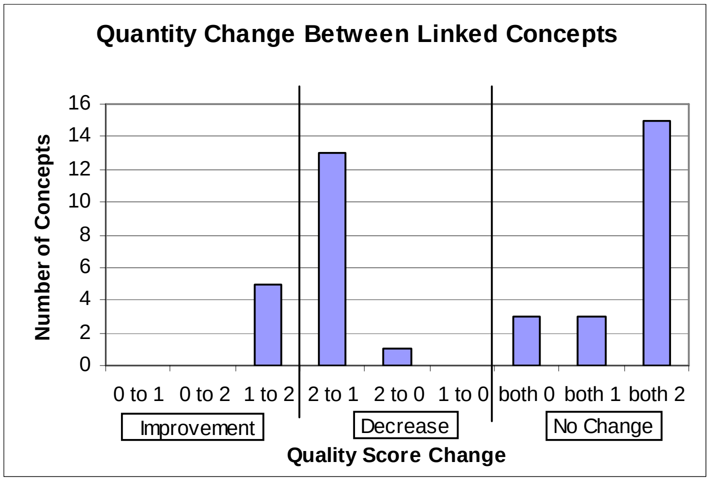


Figure 36: Quality Change from the Initial Linked Concept to the New Concept.

Correlation between Quality and Quantity

A strong correlation is found between the number of concepts generated by a team and the number of high quality concepts they produced (quality score of 2), Figure 37. This result is consistent with the anecdotal evidence stating that quantity increases quality (Ullman, 1997; Ulrich and Eppinger, 2004) and with other brainstorming studies (Parnes and Meadow, 1959; Briggs, *et al*., 1997). The Pearson's Correlation Coefficient is 0.76 ($p<0.01$) when one outlier is not included in the analysis, Figure 37. The outlier team produced a large number of concepts but few high quality ones. The quantity of ideas does not correlate with the number of high quality concepts ($r = -0.2$).

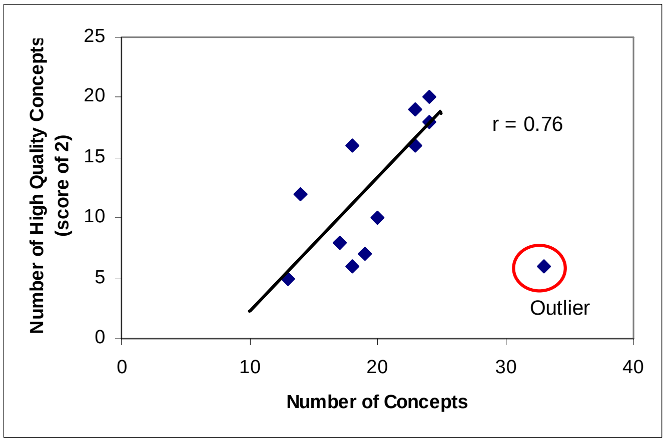


Figure 37: A greater number of concepts results in more high quality ones.

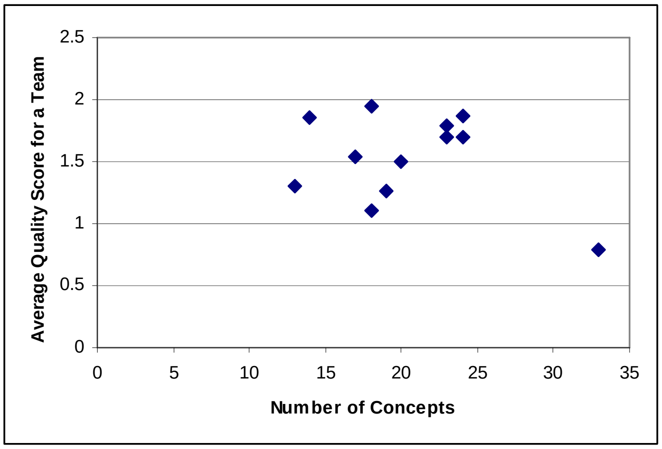


Figure 38: The average quality is not correlated with the number of concepts.

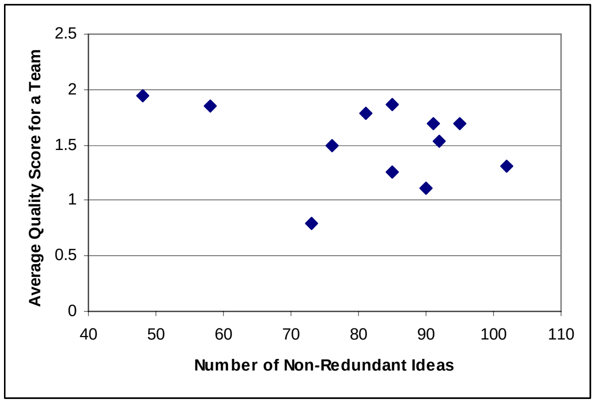


Figure 39: The average quality score for each group is not correlated with the number of non-redundant ideas.

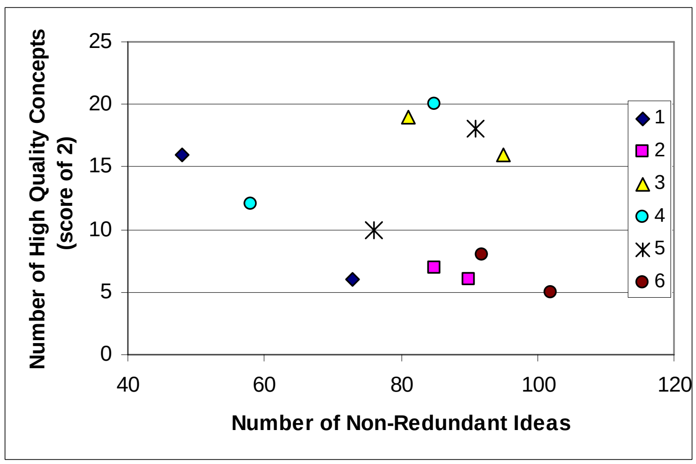


Figure 40: The number of high quality concepts for each group is not correlated with the number of non-redundant ideas.

Survey Results

A survey is used to provide further insights into the group idea generation process, Tables 12 and 13. Two questions were taken from previous brainstorming research (Dennis and Valacich, 1993). From the survey, a number of insights are possible. The majority of the participants enjoy generating ideas. They also like using multiple colors and felt it enhances the idea generation process. The effects of using multiple colors in the idea generation process are not evaluated quantitatively, but this participant preference presents an opportunity for further enhancements and research. Participants did feel they had contributed to the solution. Consistent with the design outcome data, participants worked hard on the problem, felt motivated, enjoyed the idea generation session and found the problem to be interesting. Participants are split regarding if they had enough time during the idea generation session.

From an open-ended question on the survey that stated, "Please make any comments you would like to about the idea generation session," numerous participant comments showed a strong dislike of being restricted to either words or sketches only. This result may have been influenced by the idea generation methods taught in the participants' design methods class. In their class they were introduced to a hybrid 6-3-5/C-Sketch method that combines the use of sketches with brief annotations (Otto and Wood, 2001).

Table 13: Select semantic differential scale survey results from all conditions combined

What participants thought of the idea generation session						
Fun	22%	45%	26%	8%	0%	Boring
Not an interesting problem	0%	6%	17%	42%	35%	Interesting Problem
Easy	5%	14%	34%	37%	11%	Difficult
Had enough time	14%	29%	14%	29%	14%	Did not have enough time
How the participants felt they performed during the idea generation session						
Word hard	41%	47%	11%	2%	0%	Did the minimum
Felt motivated	38%	45%	12%	5%	0%	Not at all motivated

Table 14: Select likert scale survey results from all conditions combined

Question	Strongly Disagree	Disagree	Neutral	Agree	Strongly Agree
I enjoy generating ideas.	1.5%	1.5%	12.3%	60.0%	24.6%
I helped contribute to the solution of this problem.	0.0%	0.0%	24.6%	60.0%	15.4%
I liked using the multiple colors.	1.5%	3.1%	18.5%	47.7%	29.2%
The extra colors did not enhance the idea generation process.	24.6%	41.5%	12.3%	20.0%	1.5%

ADDRESSING THE RESEARCH QUESTIONS

The data provides significant insights into the effects of the two critical factors on the idea generation process and gives guidance for the approaches engineering design teams should use. The following discussion provides further insights based on the results.

Question 1: Do the techniques being tested in this experiment vary in the quantity of ideas generated, their novelty or variety?

Words combined with sketches and rotational viewing produces the largest number of ideas. A combination of words and sketches produces about 20% more ideas than words alone. Also, “sketches only” produced more ideas than “words only”. Ward's path of least resistance model, for how new ideas are structured by information in memory (Ward, 1998), applies to this question. As people begin to categorize a problem in a particular way (for example by seeing other people’s ideas), their memory of existing products or physical systems will affect the new designs and fewer ideas will be generated. Gallery viewing provides more concepts and therefore teams may more quickly categorize the problem in a similar manner. This result could explain why gallery viewing produces fewer ideas than rotational viewing.

The effects of adding sketches may be underestimated because the current method does not take into account the geometry, layout or overall configuration of the sketch. This type of information is frequently included in sketches but rarely in verbal descriptions. In addition, as engineers sketch, they tend to add many details that they may not include if they give a verbal description of a device. For example, if an individual describes the use of a motor and gear train to power a system, the drawing will frequently include parts like shafts, bearings and supports, but when only a verbal description is used, these ideas are not included.

All conditions in this experiment are virtually equal in terms of variety and novelty. Some very novel concepts were produced, but there is more potential in this area. Overall teams explored only a fraction of the design space. Other idea generation methods need to be sought in order to improve the variety and novelty of the solutions.

In this experiment, all members of the team generated ideas without communicating during the first time period. This independent step may have led the teams to develop a similar variety of concepts regardless of the later communication modes resulting in an equal level of variety and novelty for all conditions. If this idea generation session had been compared with other idea generation techniques, such as Osborn's brainstorming, the results may be different.

Gallery viewing produces more concepts and more high quality concepts but overall fewer single function ideas. McKoy, *et al*. (McKoy, Vargas-Hernández, Summers and Shah, 2001) also found that sketches result in higher quality concepts than sentential descriptions. In contrast, rotational viewing produces fewer concepts, less high quality concepts, but an overall greater number of ideas. The difference in number of high quality concepts is close to the statistical significance of the experiment at $p=0.14$. The rotational conditions use a smaller number of concepts to span the same fraction of the design space as the gallery conditions, where the average diversity for each concept is greater. This result suggests that an improved process for concept generation consists of first using a gallery communication method to generate a large number of high quality concepts and then moving to a rotational viewing method using words and sketches to develop the details of the concepts and a large number of ideas.

Question 2: Does the representation method of ideas interplay with the display method or are they virtually independent?

Representation and the viewing method cause interaction for the quantity of ideas but not for the other metrics. This interaction is caused by the "sketches only" conditions following a different pattern of results as compared to the other conditions. For conditions containing words, rotational viewing produced a greater quantity of results, but for sketches there are fewer ideas. One hypothesis is regardless of representation, rotational viewing encourages the participants to spend more time processing other teammate's ideas. The results of this effort vary based on representation. In the sketches only conditions, this process has a detrimental effect because the sketches without any verbal descriptions are difficult to interpret and therefore more effort is applied to understanding what is in front of participant rather than on generating more ideas. In general engineers are not taught to draw, and their skill in sketching may be poor. In contrast, the other two representations are relatively straight-forward to interpret and much easier for the engineers to communicate, and thus more ideas are produced.

Another reason why the "sketches only" conditions could be different from those conditions in which subjects use words is that sketches tend to contain less general, abstract concepts. Sketches may be viewed as being more detailed and concrete, therefore placing constraints on what the participants perceived to be allowable changes. If so, then sketches may bias participants toward making less radical changes to the concepts than are made to concepts described in words. Another possible reason for the differences is sketches may lead to abstract interpretations, i.e., unintended interpretations because of how a participant views and visually assesses another's sketches. This type of abstraction will obviously be different than words abstractions. When participates have both representations, they may bias their abstractions toward information provided by the verbal descriptions rather than the sketches. These hypotheses require further analysis of the data or further experimentation to reach conclusive interpretations.

Question 3: Are certain representations better for producing or improving the quality of solutions? Do certain representations cause bias towards certain types of ideas?

The average quality is similar across conditions, but the "sketches only" conditions results in a greater number of high quality concepts. One possible reason why the "sketches only" condition produces more high quality concepts is there are certain categories of ideas that are difficult to draw. Participants may have thought of these ideas then did not attempt to draw them, refocusing their attention on concepts they could sketch. For this particular problem, these difficult to draw ideas tend to be lower quality, including ideas such as using chemicals to dissolve the shells and genetically modifying the peanuts. The "sketching only" condition acts to filter out these low quality solutions by virtue of the difficulty in embodying them.

Some information, particularly abstract concepts, is easier to convey in words, whereas other information such as geometry and configuration tends to be easier to convey with drawings. Most design problems involve a combination of these two types of information. In addition, verbal overshadowing suggests conditions using written words may have a disadvantage as compared to using only sketches. The verbalization of perceptual information can interfere with the retrieval of perceptual information from memory. The verbal over-showing effect has the potential to make it difficult to retrieve information on how a device moves and related pieces of highly visual information that is difficult to verbalize.

Question 4: Do time periods exist where team members do not add anything? Previous literature frequently refers to this phenomenon as social loafing. Does this occur less frequently for certain methods? If social loafing does occur in this experiment, does it support the hypotheses of this being one of the reasons for reduced productivity in brainstorming groups? Does the team members' behavior appear consistent with the social loafing hypothesis?

Time periods do exist in this data set where individuals are not adding anything to the set of ideas (Figures 29 and 30). This phenomenon occurrs more frequently for teams in the gallery view conditions and these conditions also produce fewer ideas. Results from this experiment do support the hypotheses that the "social loafing" phenomenon is a cause of the reduced productivity of groups. The behavior of the participants during the experiment does not support the fact that they are loafing. During the time periods when the participants do not add ideas, when the data would suggest they are “socially loafing”, individuals appear to be thinking or trying to understand their teammates’ ideas. This suggests that the individuals are not loafing but instead the lack of additional ideas is caused by something else. In addition, for both viewing conditions in this experiment, ideas are equally identifiable so no difference in social loafing is expected.

DISCUSSION OF ADDITIONAL RESULTS

Does building off teammate’s ideas improve the quality of the idea? How does adding modifications to a design compare with more drastic links from one concept to the next?

Concepts that are added to, tend to be better concepts. As ideas are added there is potential for significant improvement in a concept’s overall completeness and quality (Figure 22 and Figure 36). When a completely new concept is built from a previous one, this usually produces new concepts that are equal in quality to the old concept. High quality concepts are linked much more frequently than lower quality ones, showing that as teams build from others’ ideas, there is an implicit evaluation taking place.

How do the contributions of the individuals before the ideas are shared with the group compare with the number of ideas the group generates by building from these initial ideas?

A large number of ideas are developed when individuals work alone. Teams are likewise able to develop a significant number of ideas by sharing ideas (Figure 28). Therefore both individual and group work is important in the idea generation process.

The number of ideas teams produced during time period 5 is equal to time periods 2-4, indicating the participants' ideas are not exhausted by time period 5 (Figure 27). Open questions include: what are the reasons engineering teams choose to stop, at what point and for what reasons would these participant teams have chosen to end the idea generation session? What criteria do engineering teams use when deciding to stop developing concepts? Is it when a feasible concept is found or due to time constraints? These questions are the topics for future investigations. Further work needs to be completed to determine how long individuals should work alone prior to sharing their ideas.

Seeking a large quantity of concepts to achieves high quality

Teams with a greater number of concepts tend to produce more high quality concepts. The guideline to produce a large quantity of concepts in order to achieve high quality is supported by these data. Anecdotal evidence in engineering design also strongly suggests the two are correlated (Ullman, 1997; Ulrich and Eppinger, 2004). Early brainstorming studies also find this to be true (Parnes and Meadow, 1959). More recent work with electronic brainstorming agrees with this but cautions that quality may not always track quantity (Briggs, *et al.,* 1997).

Teams only explore a fraction of the design space: New methods are needed

Design teams need to be able to have confidence that they have found very good and innovative solutions to their design problem. An encompassing exploration of the design space increases the probability of this outcome. The techniques evaluated in this study do not completely satisfy this goal. In general, teams explore only a segment of the total design space, and none of the methods tested encourage greater breath. One team did evaluate a greater diversity of concepts, showing that it is possible given the short time period of the experiment. Concept generation methods need to be developed that support finding a larger variety of solutions.

CONCLUSION

Creation and innovation are significant and driving factors in engineering design. These factors draw many individuals to the profession. To support this area, we must continually seek improved methods to understand and express human creativity. This chapter addresses important elements of creativity and the concept generation process. While past research in psychology, engineering design and other fields has included human studies in idea creation, a vast void remains in understanding the underlying factors of many of the popular concept generation techniques. A number of anecdotes exist about the advantages and disadvantages of the techniques, and some quantitative results also exist that address the aggregate methods in a group setting. By using a systematic approach, the key factors that differentiate the methods are identified. This may be exploited more fully to create more effective techniques.

This study uncovered a number of important insights. The choice of group idea generation method significantly impacts the total quantity of ideas generation and number of high quality ideas. Over the 40 minute session, 50% more ideas are generated using rotational viewing combined with ideas being described with words and sketches as compared to using only words and displaying them gallery style. The rotational viewing combined with sketches annotated with words condition corresponds to a hybrid 6-3-5/C-Sketch method. In contrast, more high quality ideas result when all concepts are displayed on the wall, gallery viewing, and represented using only sketches. These results suggest an improved process for concept generation consists of first using a gallery communication method to generate a large number of high quality concepts and then moving to a rotational viewing method using words and sketches to develop the details of the concepts and a large number of ideas.

This study also shows that both individual and group interactions are important in the idea generation process. As group members add ideas, the overall concept becomes more complete and improves. This study should be replicated with professional, more experienced engineers to add futher validity. This study used teams of undergraduates with a short time period to solve the problem which posely possible limitations. In addition addition design problem should be evaluatined since the results could be problem depenedent.

Participants do not simply create their own concepts in isolation. An equal or greater number of new ideas are developed that build upon or are directly influenced by other group members. Visualizing others' ideas produces even more ideas is not just an anecdote. The data show that group member's ideas "spark" other members to a greater level of productivity.

Chapter 4: Effects of Memory Representation on Analogy Use

Analogy, and therefore analogical reasoning, is a frequently used approach in design (Casakin and Goldschmidt, 1999; Leclercq and Heylighen, 2002; Christensen and Schunn, 2007). A detail and accurate model of the human cognitive process for reasoning by analogy will facilitate the creation of improved conceptual design methods for analogical design. This chapter focuses on the first two of three experiments aimed at increasing the understanding of reasoning by analogy within the design process. The first two experiments focused on evaluating the effects of the representation of an analogy in a designers' memory on future use. The third experiment also evaluates the effects of the problem representation. Prior research in analogical reasoning found the encoded representation of a source analogy can ease retrieval if it is remembered such that the key relationships apply in both the source and target problem domains (Clement, 1994; Clement, Mawby and Giles, 1994). The analogies and problems used in these experiments were not specific to any domain of expertise and used fantasy problems relying on strictly verbal descriptions. The use of various representations, including visual and semantic, warrants further understanding for application of this result in design. The following experiments investigate visual and semantic representation effects on design-by-analogy and lead to a deeper understanding of how to enhance the design-by-analogy process.

EXPERIMENTAL APPROACH

To further explore the effects of representation on analogy use for real-world problems and to further understand how supporting methodologies should be created, a series of three experiments is implemented. This series of experiments controls how participants learn about a series of products and therefore also controlled how the products were represented in their memories. This allowed the predictions from psychological models of analogical reasoning and semantic memory to be evaluated. These models, along with additional knowledge gained from experimentation, will be used as a basis for methods development. The pilot experiment was conducted with graduate students in mechanical engineering. The first two experiments, Analogy Experiments 1 & 2, were conducted during two different semesters with senior mechanical engineers. A different professor taught the class each semester. This group of engineers had instruction in design methodology including idea generation. Each experiment contained a unique set of participants.

The first and second experiment explored the effects of the analogous product representation on a designer's ability to later use the product to solve a novel problem. A total of six design problems with corresponding analogous products were explored to more fully understand the influence of semantic representation and other factors in analogical design. The analogous solutions were semantically described using either domain specific or more general terms that applied across both the problem and the analogous product domains.

Overview of the Analogous Product Representation Analogy Experiments 1 & 2

A pilot study and two full experiments were run to more fully understand the effects of memory representation on future analogy use. All experiment materials for the pilot experiment and Analogy Experiment 1 are shown in Appendix B. Analogy Experiment 2 materials are shown in Appendix C. The experiments consisted of two tasks: *Memorize the Analogous Products and Solve the Design Problems* with a week in between for most participants. Normally when faced with a design problem, a useful analogous product has not been seen immediately beforehand, but the analogous product is stored in a person's long term memory. A week was chosen as a relevant time because any analogies retrieved will be taken from long-term memory, and this time frame has been used previously (Thompson, Gentner and Loewenstein, 2000). Instead of a week break, the pilot experiment had a distracter task of evaluating some design concepts between the two parts of the experiment. The break task, for the pilot experiment, required about 15 minutes and was long enough for the participants to not make a connection between the tasks. Multiple solutions were encouraged for all parts of the experiment. Participants were told the experiment evaluated various skills in the design process.

The two analogous product representation experiments were virtually identical with the exception of the design problems and analogous products being evaluated. The second experiment also contained questions at the end asking the participants which features they mapped from the analogy to the solution. Results from Analogy Experiment 1 left many unanswered questions and showed some short-comings in the analogies that were chosen (Linsey, *et al*., 2006). To further understand design-by-analogy, a second set of analogies were evaluated in Experiment 2. For Experiment 1, the football to the raft analogy required the mapping of visual rather than semantic information and the sketches of the flour sifter device were difficult to interpret. For Experiment 2, two innovative products found in the literature were used. The first, a kayak with a hydrofoil could have been based on an analogy to an airplane wing (Regenold, 2006). The second, a set of dirt bike racer goggles was based an analogy to film in a camera (Kelley and Littman, 2001).

Procedure for Experiments 1 & 2

For the first task, *Memorize the Analogous Products*, participants were given five short functional descriptions of products along with a picture (example in Table 15 and see Appendices B and C for complete descriptions) and asked to spend thirty minutes memorizing the descriptions. The products were functionally described in a few short sentences either with a more general description that applied in both the source analogy and target design problem domains, or with a domain-specific description. An example of the descriptions used for the film in a camera is shown in Table 15. The product descriptions and the design problems included meaningful pictures. For the pilot experiment only, participants in the 'General' group also had to draw function structures for the devices (see reference Otto and Wood, 2001; Stone and Wood, 2000; and Hirtz, Stone and McAdams, 2002 for more details on function structure concepts). The semantic descriptions of the devices were varied but the pictures were identical for both conditions. The focus of these experiments was on the linguistic representations of the devices, but visual information was also present.

Both 'Domain Specific' and 'General' groups were then given up to fifteen minutes to answer a quiz, requiring them to write out the memorized descriptions. Finally the groups spent up to ten minutes to evaluate their results. Three of the products acted as source analogies for the design problems in the second task, *Solve the Design Problems*, and three were distracter products that shared surface similarities with the design problems (Figures 41 and 42).

Table 15: An example of the domain specific and general device descriptions given to participants for task 1.

Sentence / General (G) or Domain (D) Specific							
1	**G**	Two reels	move	a surface	in the path of	incoming substance.	
	D	Two reels	feed	the film	in front of	the stream of light.	
2	**G**	The surface	collects	the substance	and then a new	unchanged surface	is moved into place.
	D	The film	captures	the image	and then a new	unexposed section of film	is moved into place.

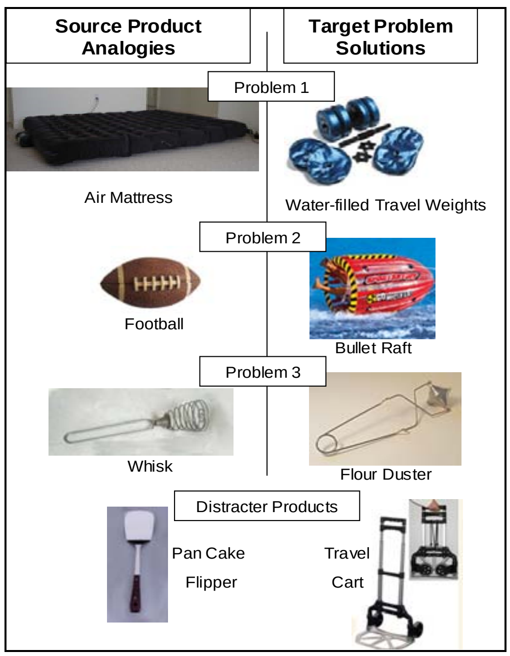


Figure 41: Source products analogies, corresponding target problem solution and the distracter products for Experiment 1.

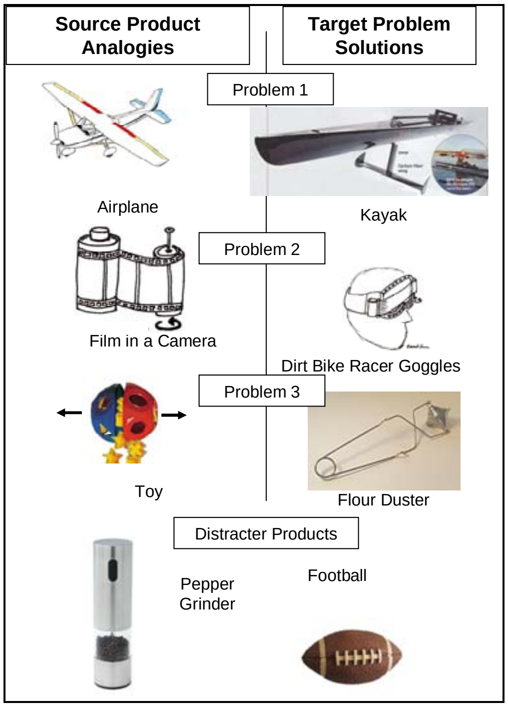


Figure 42: Source products analogies, corresponding target problem solution and the distracter products for Experiment 2.

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

Time limitations for Analogy Experiments 1 & 2 were based on a pilot experiment with graduate students with no time limits. Time limits were set to be longer than the amount of time required by most participants in the pilot experiment. For certain tasks and phases, it was clear participants were not spending enough time on the task, so the time limits were actually extended well beyond the time required in the pilot experiment.

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

Phase 1: Open-ended design problems, few constraints

Phase 2: Highly constrained design problems

Phase 3: Identify analogies and try using analogies

Phase 4: Informed task 1 products are analogous

Phase 5: Target analogous product is given and participants find the solution

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

In phase 1, the problems were initially presented with few constraints. Participants received eleven minutes to generate ideas for the open-ended design problems and then eleven additional minutes for the same problem with additional constraints. The additional constraints limited the design space increasing the chance the desired source analogy would be retrieved. Next they had a five minute break.

In phase 3, participants spent fifteen minutes listing any analogies they had used and also used analogies to develop additional solutions. In phase 4, the participants were told that products from the first task were analogous, to mark their solutions that used the analogy and to generate additional solutions using the products from the first task (*Memorize the Products*). The concept of design-by-analogy had been taught with examples in the design methods class and a verbal example of an analogy was given during the experiment. Finally, participants were given the target analogy for each problem, asked to place a check where they had used it and asked to generate more ideas if they had not used the described analogy. This final phase serves as a control to verify that the analogies being used are sensible, are useful for these particular design problems and to facilitate data evaluation. At each phase, participants used a different color of pen, thus identifying the phase. A short survey at the conclusion of the experiment evaluated English language experience, work experience, if the participant had heard about the experiment ahead of time, functional modeling experience, if they felt they had enough time and prior exposure to the design problem solutions. For Experiment 2, the survey also included a question asking the participants to write down a list of features they used from the targeted analogous product from task 1 to find their solution to the design problem. For the sketches that were difficult to interpret, the additional survey questions for the Analogy Experiment 2, assisted in evaluating if the appropriate features from the analogous product had been used to solve the design problem. Results from the first task were matched to the second task. The entire experiment required about three hours.

Metrics

Each analogy produces a set of solutions, not a single solution. Participants also created a large number of solutions which were not based on the analogies provided. The primary interest was in the phase of the study at which participants produced a solution to the constrained design problem based on the targeted analogy and also the phase at which they identified the analogy that they used. People often show evidence of being influenced by an analogous product without explicitly recognizing where the idea came from. This factor is discussed in detail in section, *Analogy identification and implications for naturalistic analogy research*. Two evaluators coded the data independently, recording when the analogous solution was found and when the target analogy was labeled. Initial agreement was approximately 80% across the experiments and disagreements were readily resolved through discussion. The most common reason for the initial differences was the participant cross-referenced solutions appearing on different pages of the results.

PILOT RESULTS AND DISCUSSION

The pilot results show that representation is likely to influence the design-by-analogy process. The pilot results show a trend of the more general description group resulting in a greater probability of using the analogy for design problems 2 and 3 (Figures 43 and 44). The graphs show when participants both found a solution and then also label it with the target analogy. This result is in contrast to the full experiment results which will show only when participants found a solution. About 80% of the participants in both groups remembered seeing the solution to design problem 1, which was presented in their graduate design class. Therefore the two groups used the analogy at similar rates, and it was not a valid test since most participants had seen the solution prior to the experiment.

The pilot experiment was set up to test whether a change in an analogous product's representation could affect how easily it was used to finding a new solution.

Therefore the two conditions were created to maximize the expected difference in results in order to verify whether a larger sample size experiment was justified. The experimental group, “General Description Group”, was given both a more general verbal description and also told to draw function structures. This creates a confounded factor since it is not clear if the results are primarily due to the verbal descriptions or the functional structures, but this will be investigated later.

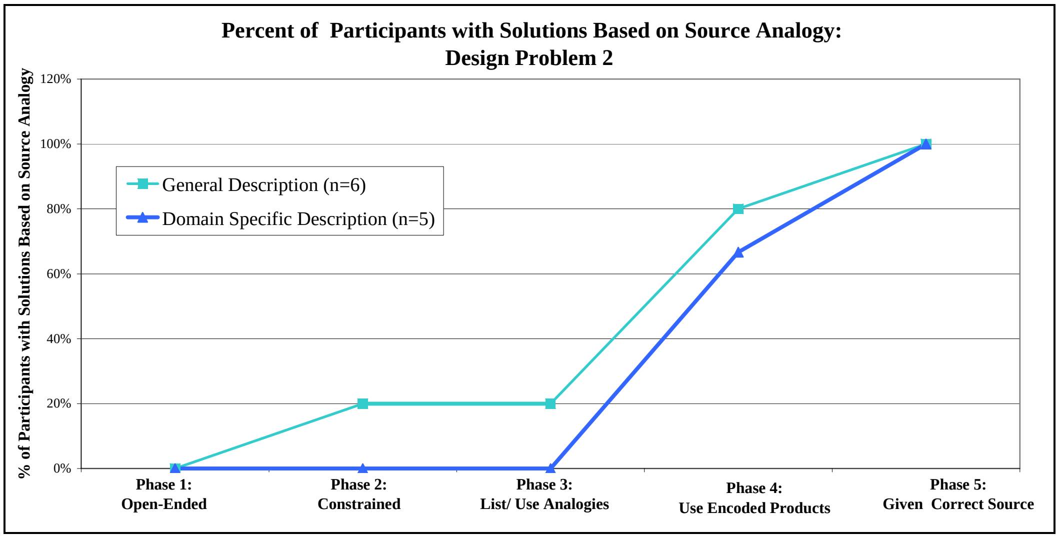


Figure 43: Pilot data shows a trend of the general product description increasing the probably of analogy.

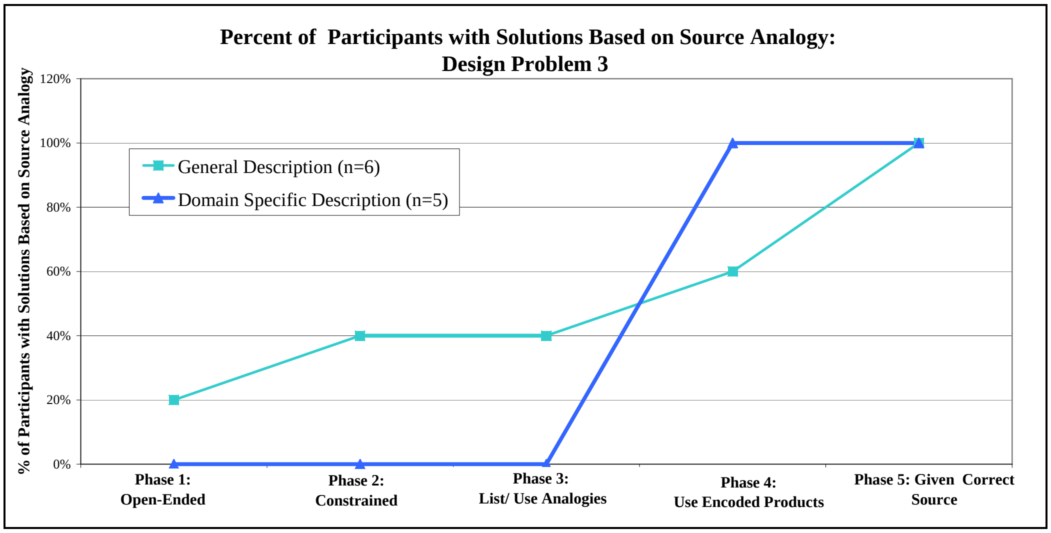


Figure 44: Pilot data shows a trend of the general product description increasing the probably of analogy.

RESULTS AND DISCUSSION: ANALOGOUS PRODUCT REPRESENTATION EXPERIMENTS 1 & 2

Example solutions are shown in Figures 45 and 46. Figures 47-52 show the cumulative percentage of participants who found a valid solution to the constrained design problems based on the appropriate analogous product. The analyses excluded participants who remembered seeing the expected solution prior to the experiment. The expected solutions are actual products so it is possible for the participants to have seen the products prior to the experiment. In addition, a verbal description without a picture of the water weight example is given in the textbook used in the participants' design methods class but the section is in the optional readings for the class. It is unlikely that any of the students read this section of the book prior to the experiment.

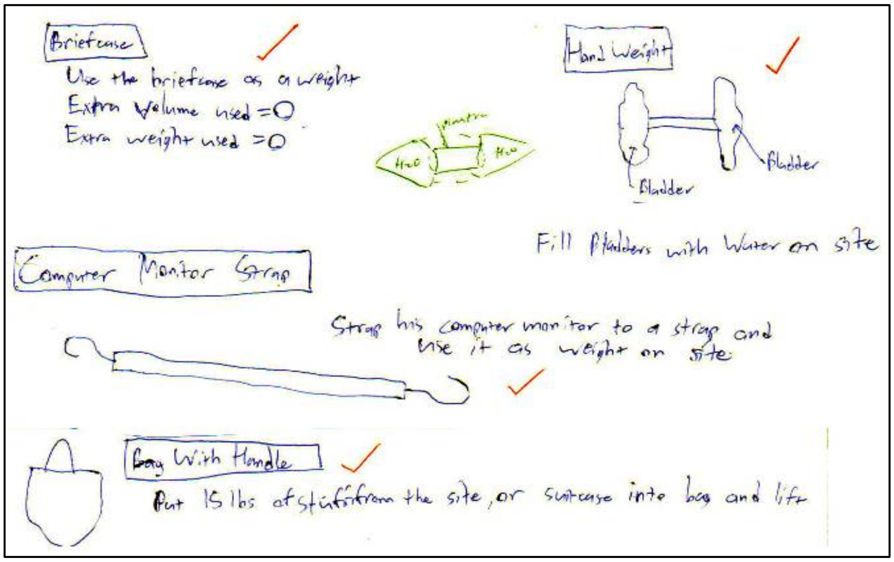


Figure 45: Example solutions for problem 1, Experiment 1, based on the analogy to an air mattress.

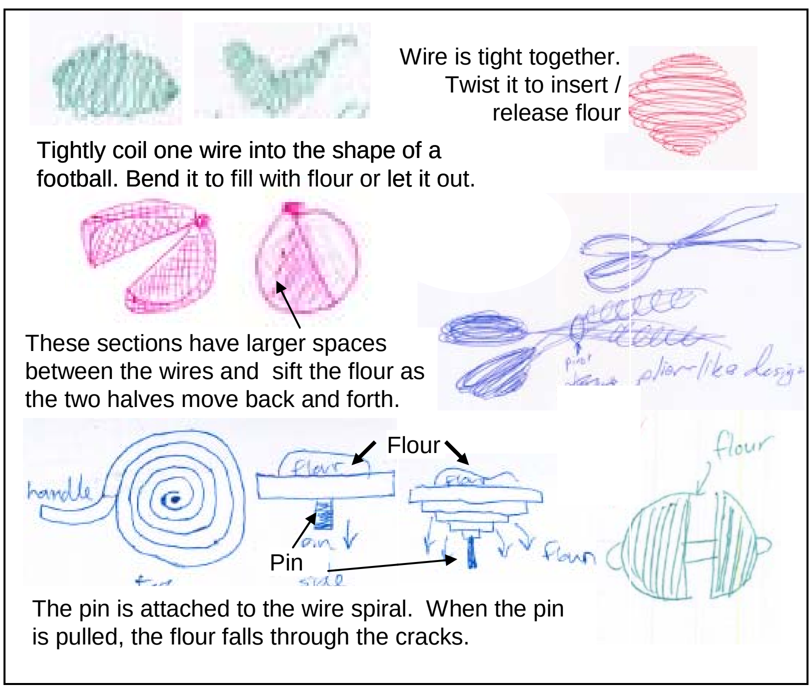


Figure 46: Examples of flour sifter solutions found by the participant based on the analogy to the toy, Experiment 2.

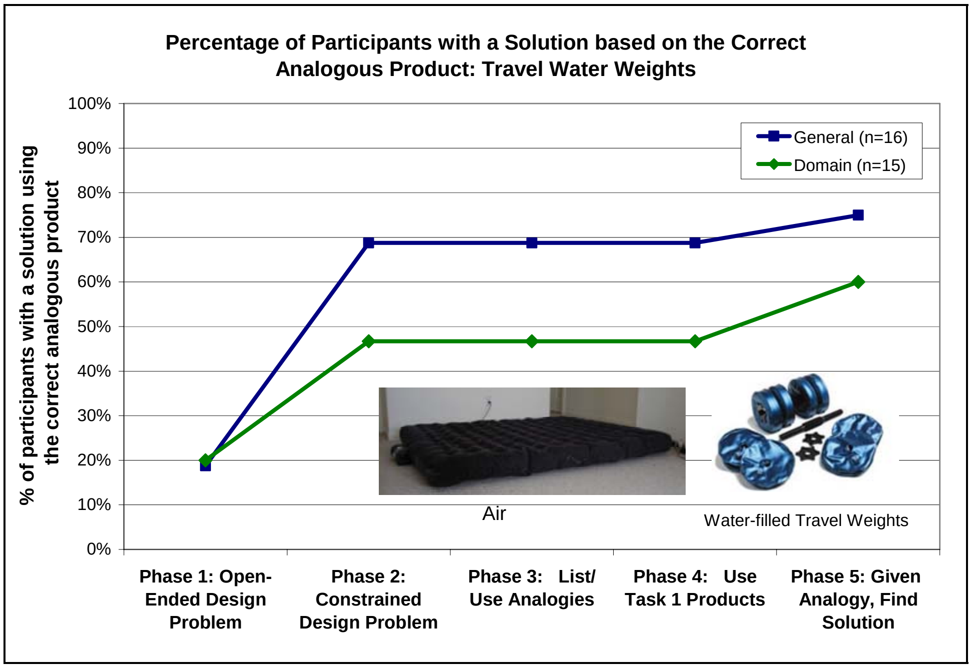


Figure 47: Design Problem 1, Experiment 1. A general description facilitated retrieval and use of the analogous product to solve a novel design problem.

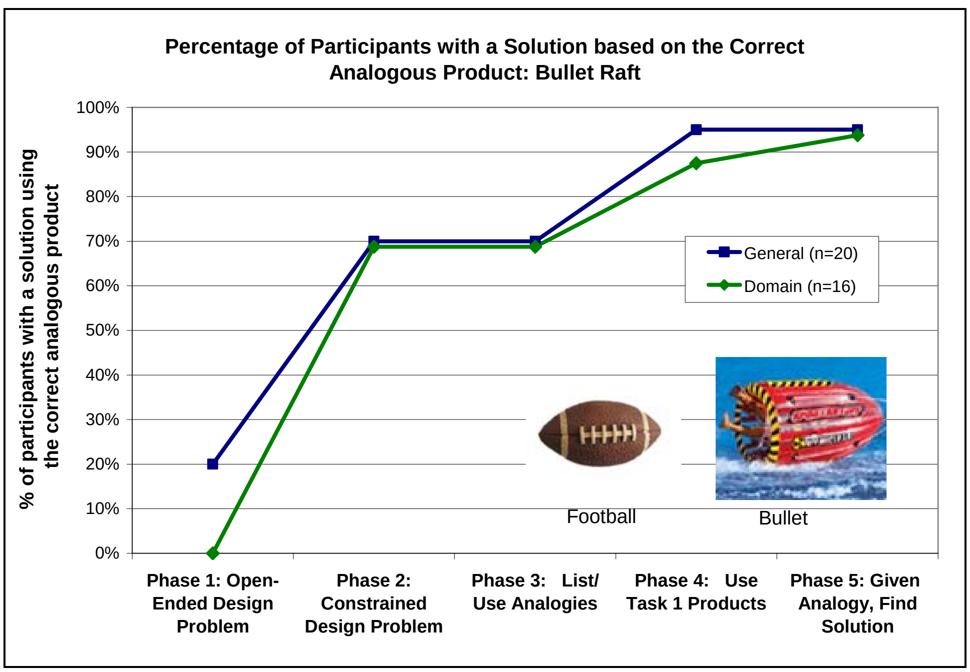


Figure 48: Results Design Problem 2, Experiment 1.

The representation of the analogies in the participants' long-term memory affects the probability the analogous product would be used to solve an appropriate design problem under certain conditions (Figure 47 and 52). Appropriate representations can improve the success rate in design-by-analogy. For two of the design problems, participants who received general descriptions of the analogous products had statistically higher probabilities of success. The results for phase 4, are statistically significant for design problem 1 Experiment 1 and design problem 3 Experiment 2 (Figure 47 and 52). Using a binomial probability distribution (Devore, 1999), the probability that the domain specific description group is from the same distribution as the general description group is almost zero.

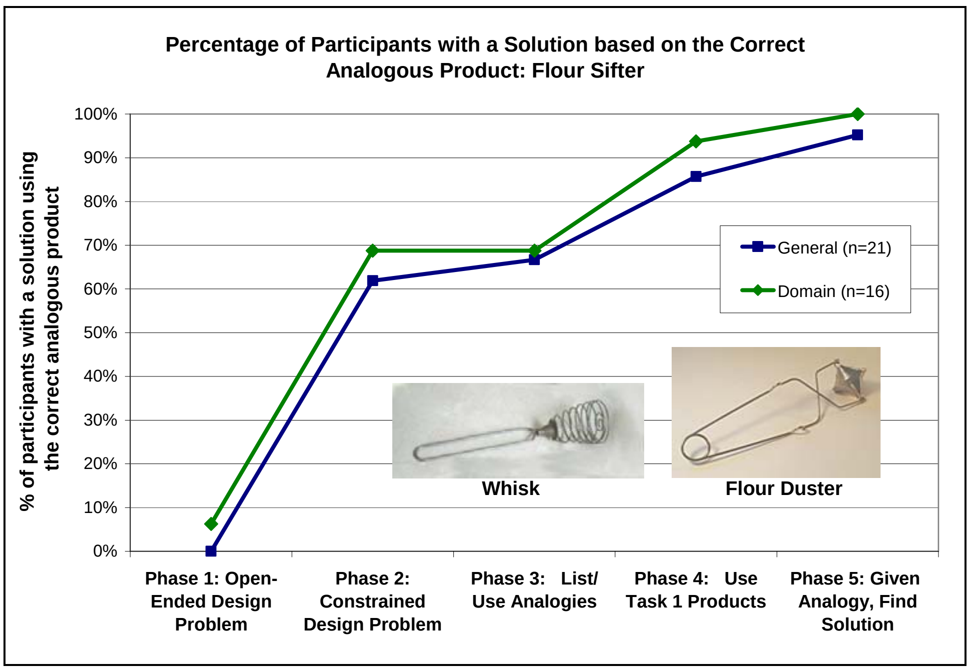


Figure 49: Design Problem 3, Experiment 1. The semantic representation did not influence analogy use for this problem.

It is noted that the data from Experiment 1 was reported in a prior paper (Linsey, *et al*., 2006), though it was analyzed differently. In the previous paper, data was presented showing when the participants both used the analogous solution and when they explicitly mentioned the analogy they had used. Looking more carefully at the data, participants frequently find the analogous solution without realizing the source of the idea. This issue is discussed in detail in Chapter 5, *Analogy identification and implications for naturalistic analogy research*.

The semantic representation has an impact on analogy retrieval but other factors also influence the process. The key features to be mapped in Experiment 1, problems 2 and 3 were visual information, the shape of the football and the varying spacing of the wires in the whisk. The semantic representation may dominate the analogical reasoning process when the information that must be accessed and mapped is stored verbally instead of visually. This proposal is consistent with the observation that nearly all prior studies of analogical reasoning involve semantic materials (typically written stories) (Clement, 1994; Clement, Mawby and Giles, 1994). Visual and verbal information are two distinct types of knowledge stored in long-term memory (Schooler, Fiore, and Brandimonte, 1997).

For Experiment 1 design problems 2 and 3, it was also much more difficult to evaluate the appropriateness of the solution and to isolate the features that had been mapped. This would lead to more inaccurately mapped solutions being counted and erroneous results. This issue was corrected in Experiment 2.

Again in Experiment 2 additional factors which influence the design-by-analogy process were observed. In Figure 50, the participants who received the domain specific descriptions had a higher success rate in solving the design problem. This result was not the hypothesized. The kayak problem, design problem 2, required domain knowledge of fluid mechanics to select and map the appropriate characteristics of the airplane onto the kayak. All participate were expected to have the required domain knowledge but it is clear that some did not. The domain knowledge influence dominated this design problem. It also appears it was easier for participants to retrieve the required domain knowledge when the analogous product was described in domain specific terms (for example, the word "airplane") than when it was described generally (Figure 50).

For the dirt bike racer design problem, a retrospective evaluation of the domain description and the problem revealed that the word "film" is readily retrieved for the design problem. This likely caused there to be no influence for the analogous product description (Figure 51). It was as easy for participants in the domain condition to remember the appropriate analogy as it was for participants in the general condition.

Experiments 1 and 2 highlight the effects of sentential representations on the design-by-analogy process. Other factors that influence the design-by-analogy process are also alluded to by these experiments.

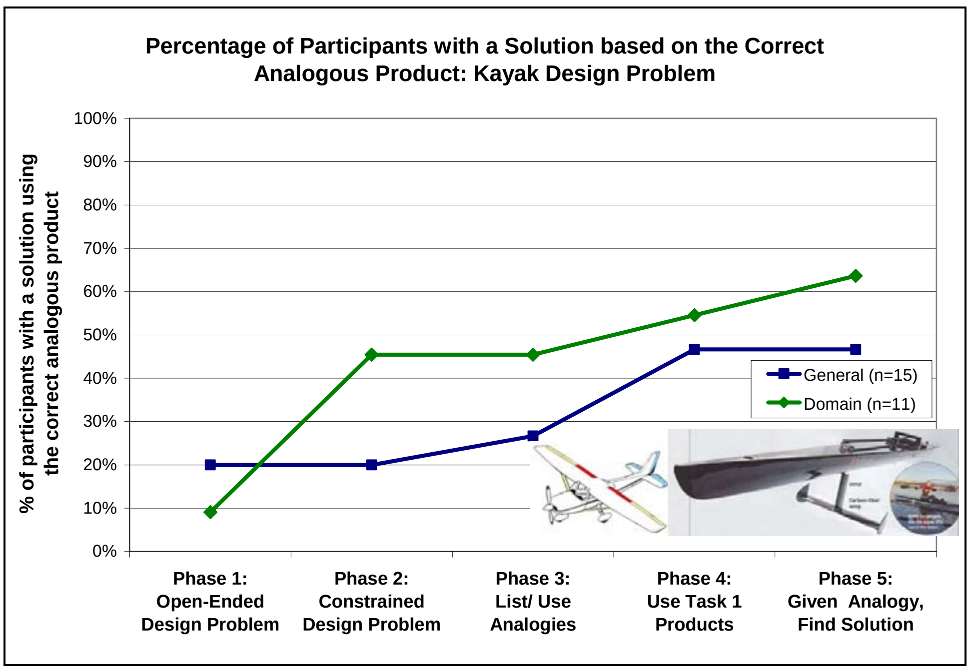


Figure 50: Design Problem 1, Experiment 2. This problem required participants to use their knowledge of fluid dynamics to appropriately choose the right characteristics from the analogy.

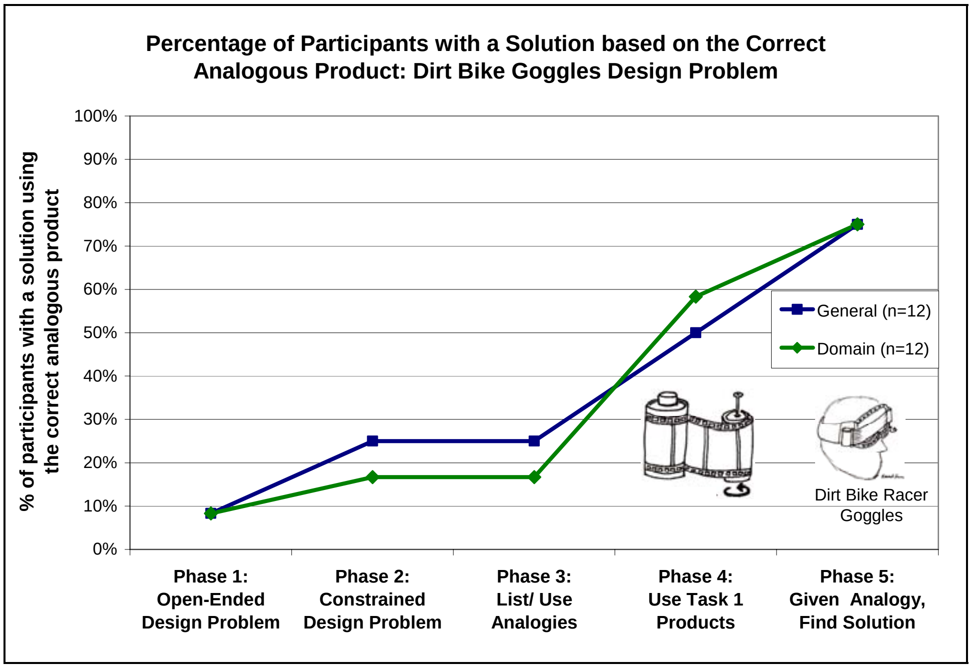


Figure 51: Design Problem 2, Experiment 2. The word "film" in the domain specific description also mapped well for the design problem.

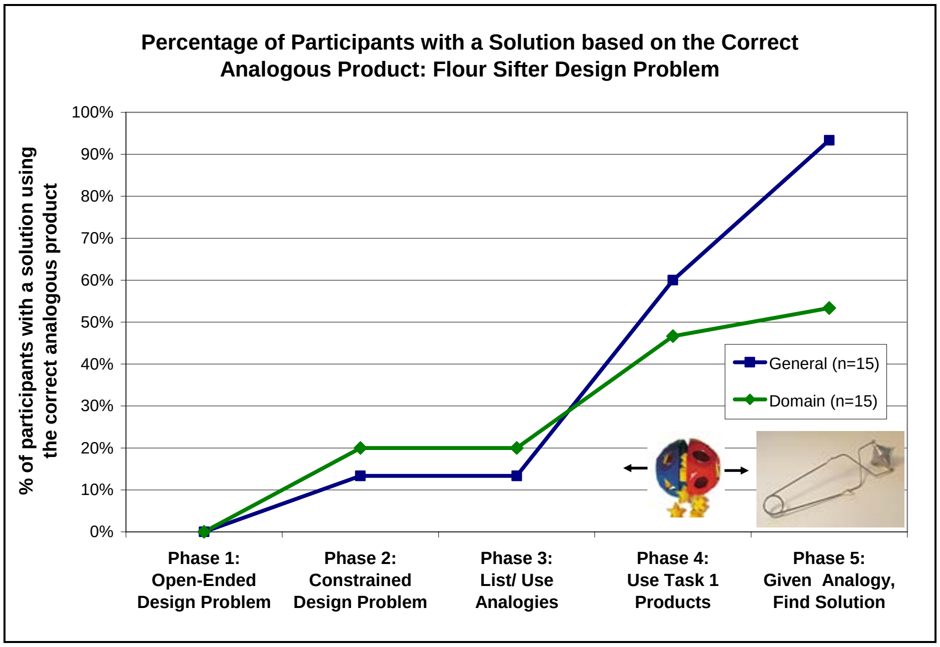


Figure 52: Design Problem 3, Experiment 2. A general description facilitated retrieval and use of the analogous product to solve a novel design problem.

Observations and Qualitative Results

Further insights were gained from the experiments. Not surprisingly, participants in Experiment 1 produced more concepts for the unconstrained problem than for the constrained design problems. This was not measured for the later experiments. Most participants used analogy without specific instructions to do so. Participants were familiar with the use of analogies for idea generation prior to the experiment. Participants tended to use analogies that shared many characteristics with the design problems and were in similar domains (Figure 53). This result is expected and also causes the distracter products to be used erroneously. Typically, participants found solutions with the distracter products that did not meet the constraints of the problem.

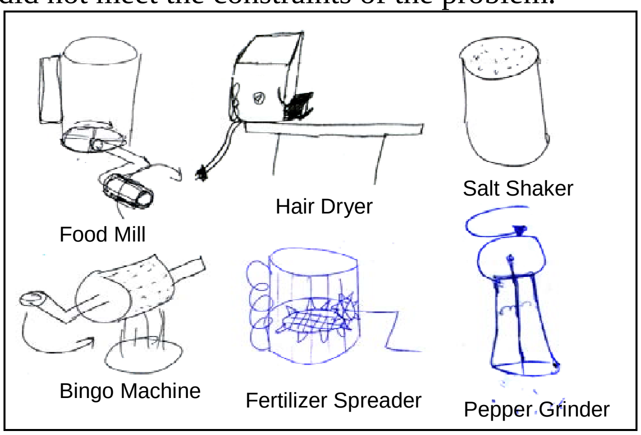


Figure 53: Other analogies used for design problem 3, device to sprinkle flour over a surface.

By using the target analogy for the constrained design problems, a few participants were able to find highly unique and unexpected solutions that meet the constraints (Figure 54). This result occurred rarely, but produced some rather novel solutions to the problems and raises a number of research questions for future experiments. In particular, how do we assist designers in training their thought processes to generate such solutions?

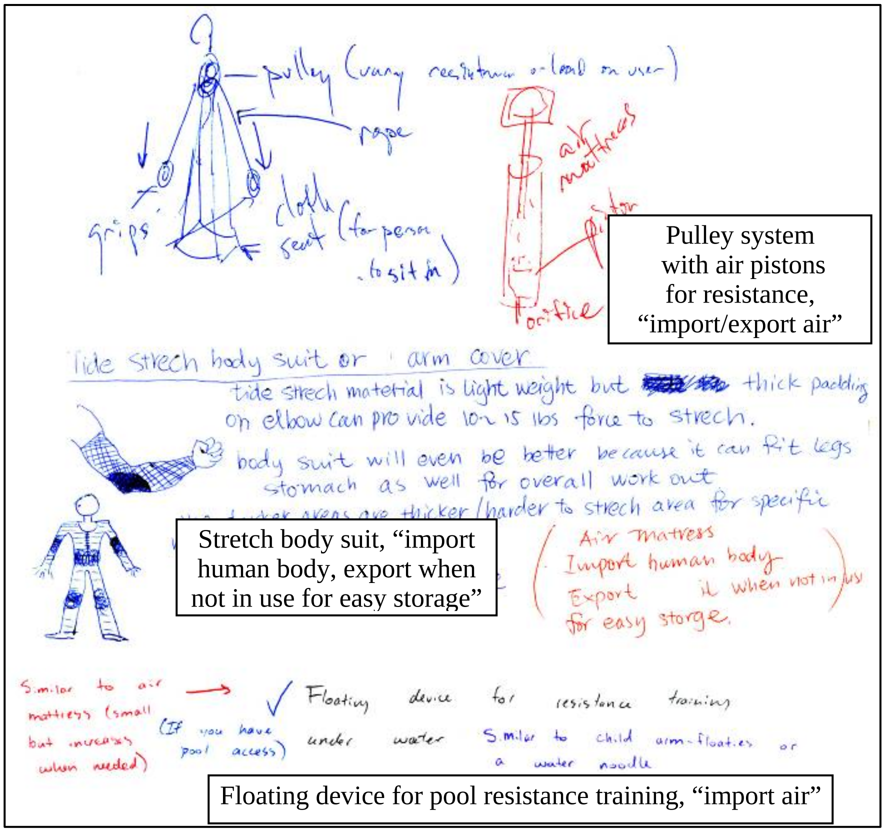


Figure 54: Unique solutions to constrained design problem 1.

DISCUSSION OF ADDITIONAL RESULTS AND OTHER IMPLICATIONS

The series of experiments provide results and implications beyond the research questions. These range from implications on research approaches to the development of new design methods and future research questions.

Design constraints guide the designers to search particular areas of the design space

Based on the experimental results shown here, it is hypothesized that the application of design constraints can lead designers to search particular regions of the design space. Systematically adding and removing constraints may assist the designer in thoroughly searching portions of the design space. This approach has potential as part of a design method. The experiments presented in this paper intentionally constrained the design space to areas where it was known that good solutions existed. The constraints required participants to search particular regions of the design space and thus increased their probability of finding the target solution.

Influences on the design by analogy process highlighted by the experiments

This series of experiments highlights the conclusion that there is some understanding of the influence semantic representation has on analogy use in design. This understanding will be used as a basis for method creation. The experiments also illustrate instances when the semantic representations may not dominate the design by analogy process. When the information to be mapped is visual rather than linguistic, the influence of the semantic representation is not observed. This result occurred for the analogy between the football and the bullet raft, Experiment 1, design problem 2. This proposal is consistent with the observation that nearly all prior studies of analogical reasoning involve semantic materials (typically written stories) (Clement, 1994; Clement, Mawby and Giles, 1994 and the fact that visual and verbal information are two distinct types of knowledge stored in long-term memory (Schooler, Fiore, and Brandimonte, 1997).

Domain expertise is sometimes required for successful design-by-analogy. The kayak problem, design problem 2, required domain knowledge of fluid mechanics to select and map the appropriate characteristics of the airplane onto the kayak. Some participants retrieved the appropriate analogy but then mapped the wrong characteristics resulting in a design that did not meet the problem requirements. The importance and effects, both positive and negative, of domain expertise should not be underestimated in conceptual design.

The solutions that are easily retrieved for a given problem are another factor. For the dirt bike racer design problem, a retrospective evaluation of the domain description and the problem revealed that the word "film" is readily retrieved for the design problem. It was as easy for participants in the domain condition to remember the appropriate analogy as it was for participants in the general condition.

Ideal characteristics of useful problems and analogies for experimentation

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

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

CONCLUSIONS FROM ANALOGY EXPERIMENTS 1&2

A deeper understanding of the mechanism behind analogical reasoning and their implications within design will guide the development of drastically improved design-by-analogy methods and tools for design innovation. Representation clearly matters and seeking improved representations will enhance the innovation process. A more general semantic description of a product allows for a greater chance of using a previously experienced product as a source analogy later. There are a number of other additional factors that influence the process including expertise, visual representations, individual ability and the easily retrieved solutions. The results and insights gained from the analogy in design experiments support the assertion that the form of concept representation is important in the cognitive analogy formation process.

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

Chapter 5: Analogy 3-Effects of Memory and Problem Representation on Design-by-Analogy

Designers need a predictable method for developing innovative solutions to difficult design problems. One approach for innovative design is by enhancing design-by-analogy. The first two analogy experiments, see Chapter 4, illustrate memory representation effects on a designers' ability to use an analogous product to solve a future design problem. These experiments highlight the impact and importance of representation. They also show that analogous products should be learned in more general representations. Ultimately, when faced with a novel problem, designers cannot modify the information in memory and its representation at that instance. Instead, only the representation of the design problem may be changed. Thus, it is crucial that the relationship between the representation of the design problem and the representation of analogous product descriptions in memory is understood.

EXPERIMENTAL APPROACH AND RESEARCH QUESTIONS

From the first two experiments, representation has a clear influence on the retrieval of a prior or "similar" solution. The ultimate purpose of this research is to define a method for increasing innovation, or at least increase the number of analogies, novelty of ideas and number of ideas a designer may develop compared to those based on their intuitive approaches. To reach this goal, a follow-up analogy experiment is designed to explore the factors that make previously seen analogous products easier to retrieve and use in solving a design problem. In this context, the answer to the following research questions is sought:

Question 1: Is prior product knowledge more likely to be retrieved and used in innovative design when it is described using domain-general or domain-specific language? Prior psychological literature (Clement, 1994; Clement, Mawby and Giles, 1994) and experimental results in Chapter 4 imply that the domain-general descriptions should be more likely to be retrieved. This result needs to be validated and explored in a more realistic design situation.

Question 2: How does the representation of the problem statement affect the ability of a designer to retrieve and use a relevant analogous product to expose a solution to a new design problem?

Question 3: Usually, when a designer is solving a novel problem, the representation of appropriate analogous products is not known to the designer. What are good approaches to representing a design problem in this situation and what implications does this have for a design-by-analogy method?

Question 4: Does the addition of functional models facilitate solving a novel design problem?

OVERVIEW OF THE EXPERIMENT

This third experiment controls the way in which a designer learns about an analogous product (represents it in memory) and also how a design problem is stated. This set-up allows the effects of representation in memory and of the design problem to be observed. The first two experiments only evaluated the represents in memory with both conditions being given identical problem statements. Throughout the experiment, participants employ a combination of sketching and words to reason and document ideas.

This experiment evaluates the effects of representation for both an analogous product and design problem. A 2 X 2 factorial experiment design is employed which results in four different experimental groups, Table 16. For both the analogous product and the problem description, two levels of participants are compared, a *"Domain Specific Description"* Group and a *"General Description"* Group. All experiments use a combination of visual and semantic information to represent the source design analogy.

Table 16: Overview of the Factorial Experiment Design.

		Factor 1: Analogous Product Representation	
Factor 2: Design Problem Representation		**General**	**Domain Specific**
	General	Group 1: General, General	Group 2: Domain, General
	Domain Specific	Group 3: General, Domain	Group 4: Domain, Domain

The experiment consists of two tasks: *Memorize the Analogous Products and Solve the Design Problems* with a week in between for most participants. Normally when faced with a design problem, a useful analogous product has not been seen immediately beforehand, but the analogous product is stored in a person's long term memory. A week is chosen as a relevant time period for the experiment because any analogies retrieved will clearly be taken from long-term memory. This time frame has been used in previous experiments (Thompson, Gentner and Loewenstein, 2000). In each task, participants receive linguistic representations using either domain specific wording or more general terms, Table 17. Results from the first task are matched to the second task. Participants are senior mechanical engineers with an instruction in design methodology including idea generation. The participants ranged in age from early twenties to early thirties with some industrial experience from co-ops and internships. The experiment was run over three semesters with students from two different senior design methods classes and two different professors. Multiple solutions were encouraged for all phases. Participants were told the experiment evaluated various skills used in the design process.

Table 17: An example of the domain specific and general device descriptions given to participants for task 1.

Sentence / **General (G) or Domain (D) Specific**								
1	**G**	The	device	is filled with	a substance	at the location	where it will be	used.
	D	The	air bed	is inflated with	air	in the home	where it will be	slept on.
2	**G**	The	substance	required to cause	the device	to function	is available at the location	
	D	The	air	required to cause	the air bed	to inflate	is available in the home	

Procedure

For the first task, *Memorize the Analogous Products*, participants were given five short functional descriptions of products along with a picture (Figure 55) and asked to spend thirty minutes memorizing the descriptions. All experiment materials are given in Appendix D. Both groups were then given up to fifteen minutes to answer a quiz, requiring them to write out the memorized descriptions. Finally the groups spent up to ten minutes to evaluate their results. Two of the products acted as source analogies for the design problems in the last task, *Solve the Design Problems*, and three were distracter products that shared surface similarities with the design problems. The products were functionally described in a few short sentences either with a more general description that applied in both the source analogy and target design problem domains, or with a domain-specific description. An example of the descriptions used for the air mattress is shown in Table 17, and all descriptions are in Appendix D. The product descriptions and the design problems included meaningful pictures. The semantic descriptions of the devices were varied, but the pictures were identical for both conditions. The focus of this experiment was on the linguistic representations of the devices, but visual information was also present. The problems used in these experiments have many viable solutions. The goal of the experiment is not to determine if the participant can find solutions to the design problem, but to explore the factors that affect the use of analogous solutions so that a method for design-by-analogy may result.

All time limitations throughout this experiment were based on a pilot experiment with graduate students where they were given no time limits. Time limits were set to be longer than the amount of time required by most participants in the pilot experiment. For certain tasks and phases, it was clear participants were not spending enough time on the task, so the time limits for the experiments were longer than the time required for the participants in the pilot experiment.

In the second task, *Solve the Design Problems,* participants were given two design problems to solve in a series of the following seven phases:

Phase 1: Open-ended design problems, few constraints (Table 16)

Phase 2: Highly constrained design problems

Phase 3: Identify analogies and try using analogies

Phase 4: Continue using analogies

Phase 5: Try to use a function structure to help you find a solution

Phase 6: Informed task 1 products are analogous

Phase 7: Correct analogous product is given

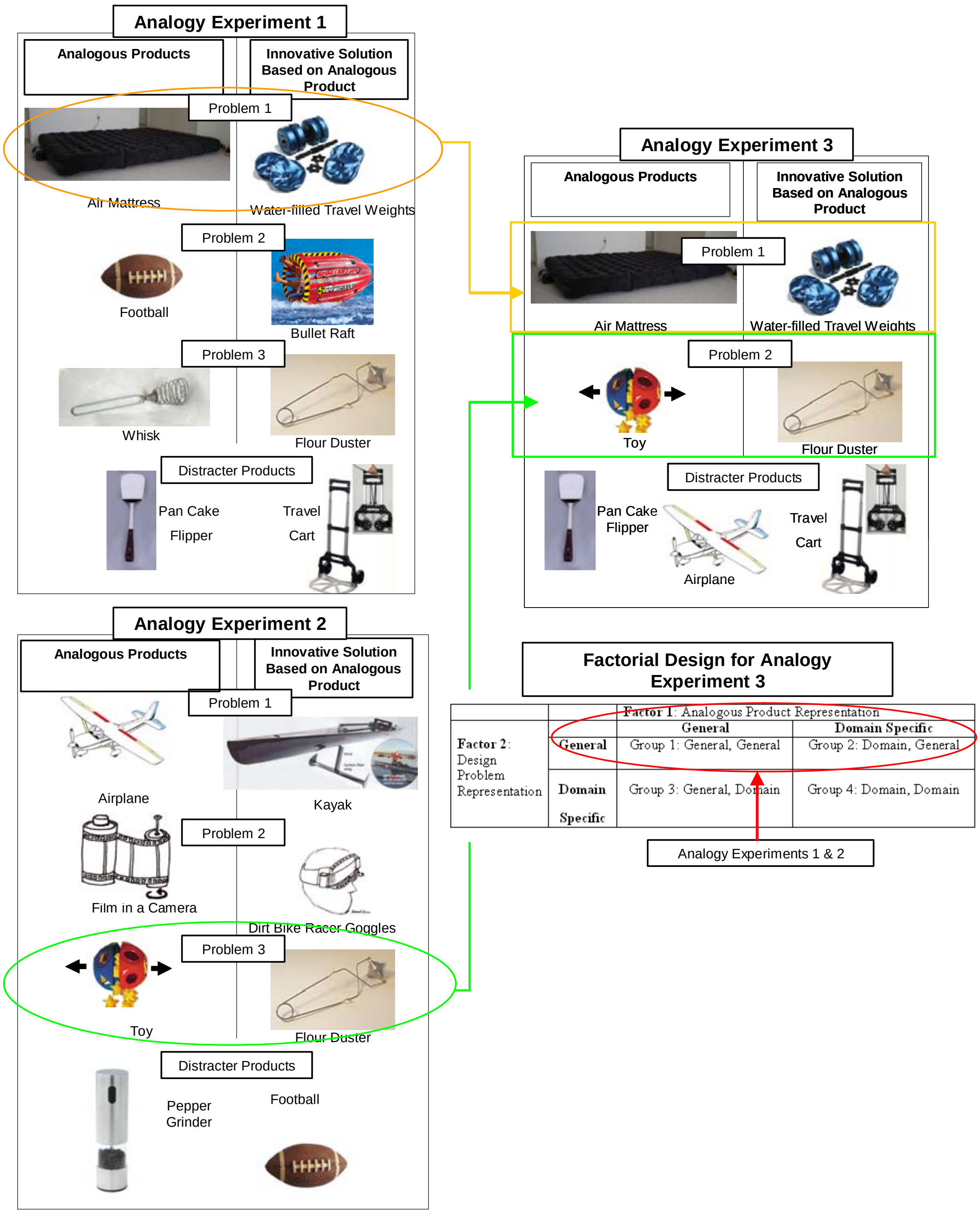


Figure 55: Overview of the three experiments and their relationship to each other. Analogous products and solutions based on the analogies.

Table 18: Domain Specific and General Problem Statements.

	Problem Statement for Design Problem 2
Domain Specific	Design a kitchen utensil to sprinkle flour over a counter.
General	Design a device to disperse a light coating of a powdered substance that forms clumps over a surface.

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

In phase 1, the problems were initially presented with few constraints. Participants were given eleven minutes to generate ideas for the open-ended design problems and then given eleven additional minutes to create more solutions to the same problem with additional constraints. The additional constraints limited the design space, thus increasing the chance the participants would retrieve the desired source analogy. Next they had a five minute break.

In phase 3, participants spent ten minutes, listing any analogies they had used and also using analogies to develop additional solutions. An open question from one of the prior experiments in Chapter 4 was if the participants were given more time to use analogies, would they be more likely to find the source analogy from task 1? Therefore, following the initial phase using analogies, participants were given ten additional minutes to continue to use analogies to create solutions.

Next participants were shown a series of six function structures and asked to develop more solutions to the constrained design problem (example in Figure 56 and a complete listing is in Appendix D). This phase provided a foundation for evaluating the effectiveness of function structures for generating novel design solutions. Function structures are representations used in engineering design (see Stone and Wood, 2000 or Otto and Wood, 2001 for more detail on function structures). When function structures are created for novel design problems, process choices must be made. The process choices for the function structures were made so that they are consistent with the solution based on the analogous product and were expected to improve participants' ability to generate a solution. This phase of the experiment addresses the issue: if given an appropriate functional representation will it assist in solving a difficult design problem? This experiment does not address how these particular functional representations with appropriate process choices can be developed.

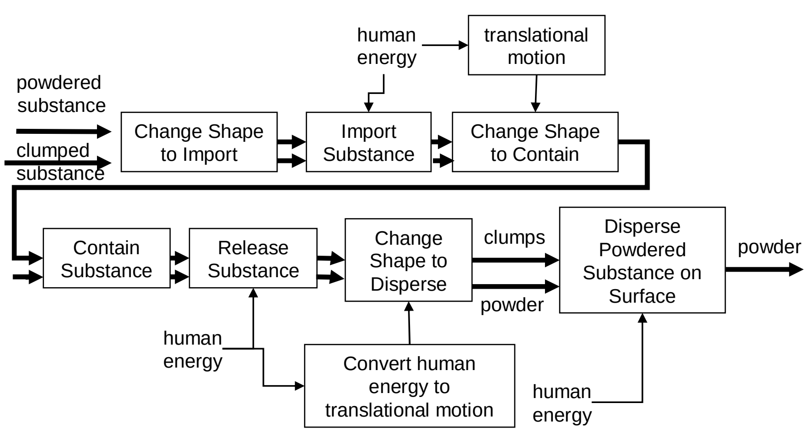


Figure 56: Functional model for design problem 2: flour sifter.

In phase 6, the participants were told that products from the first task were analogous, to mark their solutions that used the analogy and to generate additional solutions using analogies. Similar to the prior experiments the concept of design-by-analogy had been taught with examples in the design methods class and a verbal example of an analogy was given during the experiment. Finally, participants were given the correct analogy for each problem, asked to place a check where they had used it and asked to see if they could solve the design problem using the correct analogue if they had not used the described analogy. These final two phases serve as controls to verify that the analogies being used are sensible, are useful for these particular design problems and facilitate data evaluation. At each phase, participants used a different color of pen, thus identifying the phase. A short survey at the conclusion of the experiment evaluated English language experience, work experience, if the participant had heard about the experiment ahead of time, functional modeling experience, if they felt they had enough time and prior exposure to the design problem solutions. During one of session of task 2, a fire alarm occurred during phase 2. The data was reviewed and little impact was observed. These four participants were spread across the conditions and are included in the results. The entire experiment required about three hours, one hour for part 1 and two hours for part 2.

Metrics

Each analogy produces a set of solutions not a single solution. The main metric used for this experiment was when the participants produce a solution to the constrained design problem based on an analogy and when they then identify the correct analogy. The goal is to explore the factors that make previously seen analogous products easier to retrieve and use in solving the problem. The problems used in these experiments have many viable solutions. This experiment is design to explore the factors that improve analogical retrieval and not to determine if a participant can find solutions to a design problem. The solutions of interest for this experiment are the ones based on products presented in the first part of the experiment. These analogous products represent a useful source for finding solution to the design problems.

Two raters, one aware of the conditions and the other blind to the hypotheses of the experiment, scored the data for when a solution based on the analogous product was first drawn and when it was labeled with the analogy. Initial agreement was approximately 80% and disagreements were readily resolved through discussion. The most common reason for the initial small differences in scoring was resolving the participant references to solutions that appeared on different pages of the generated design solutions. Each concept was also scored for being a valid solution that meets the constraints of the design problem and if the correct characteristics were mapped from the corresponding analogous products. Occasionally, participants select the appropriate analogous product but do not map the correct characteristic from the analogous product to the design problem.

During part 1 of the experiment, participant are given a quiz measuring their memory of the analogous products and then asked to score their results. The scores were recorded and reviewed. One participant was removed from the dataset based on unusually low memory scores and difficulty following directions in the second part of the experiment. Participants who affirmed in the survey that they had seen the solution products for the design problems were not included in the results. One additional data point was removed from design problem 1 since the participant’s solution was virtually identical to the existing commercial product. This was done to remove a possible bias from the experiment. Participants who only completed one task of the experiment were also not included in the results.

RESULTS AND DISCUSSION

Figures 57a and 58a show the percentage of participants at each phase who were able to generate the solution to the design problems based on the analogous product. Figures 57b and 58b show when participants both generated the solution and then also explicitly referenced the analogous product from task 1. Both sets of graphs are based on the evaluators' indication of the solution being correctly mapped from the analogous product. Graphs showing participants' indication of the solution being based on the desired analogous product provide similar results and are shown in the following section. Examples of participants' solutions based on the analogous product are shown in Figure 59. Figure 59 also contains models of the participants' ideas built by the author for illustration and clarification. The analogous product representation and the problem representation had a clear influence on the designers' ability to use the analogy to generate a solution to the design problems. The trends are similar across the two design problems. Participants who had previously seen the solution to the design problems based on the analogous product were removed from the data set. This filtering included thirty-two participants for design problem 1 and five participants for design problem 2. Participants who memorized the analogous product in a general form had the highest rate of success. This result is shown by the top green line (general / domain) in the figures, where success rate increased by up to 40%.

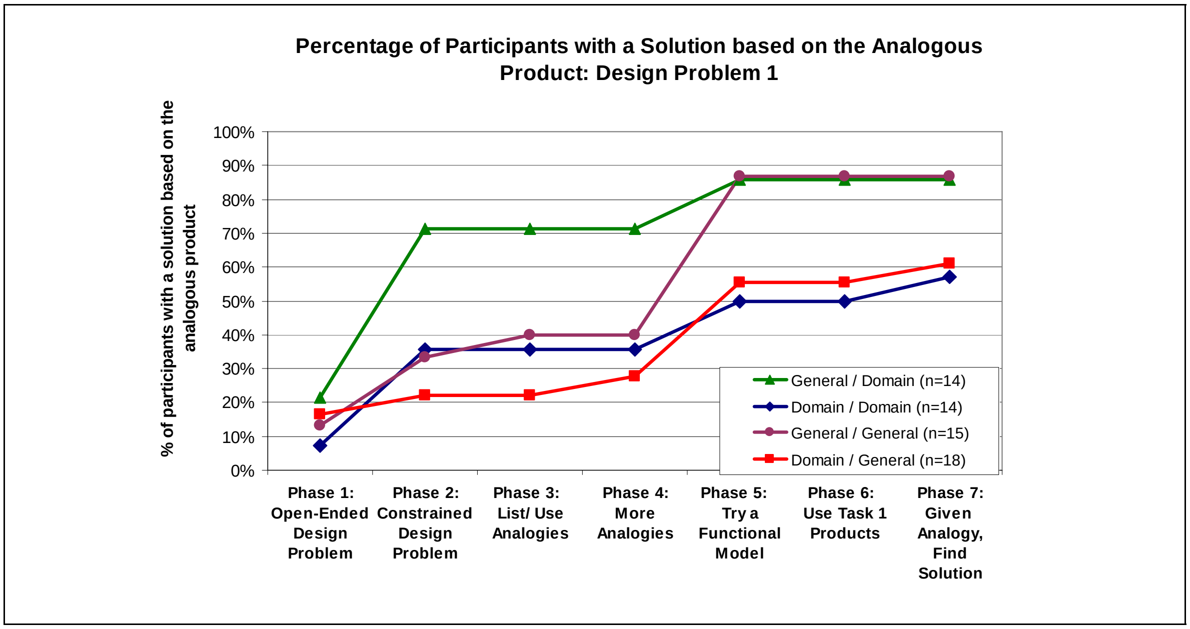


Figure 57a: The memory representation of an analogous product significantly influenced a designer's ability to remember and use the analogy to solve a design problem.

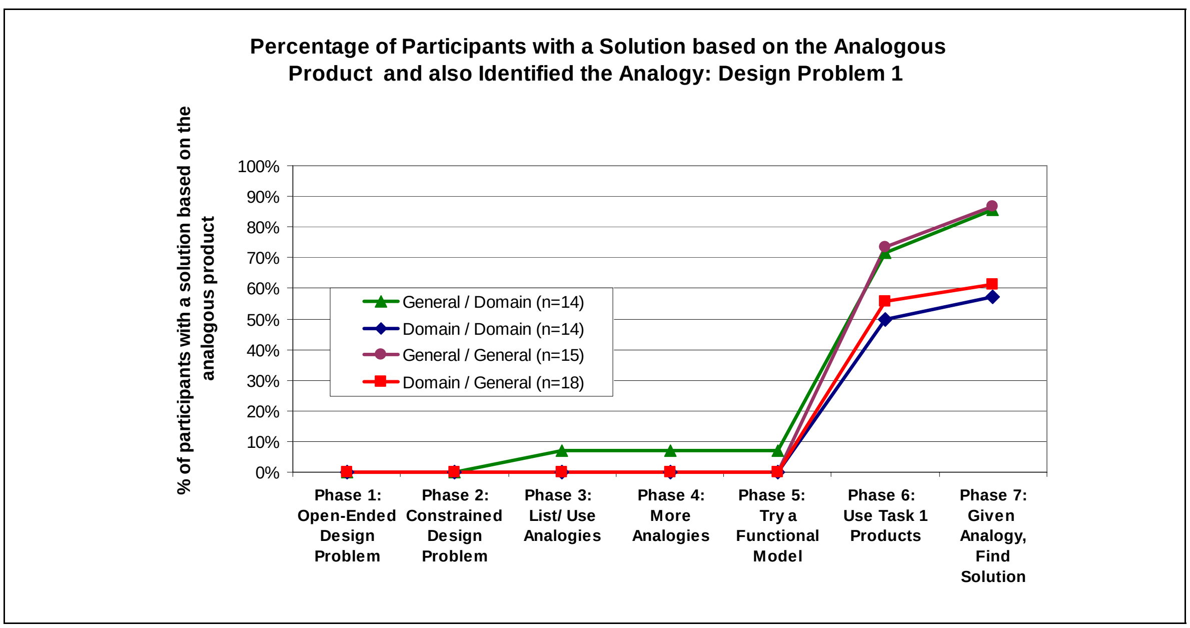


Figure 57b: Participants identify the source of their idea much later in the process.

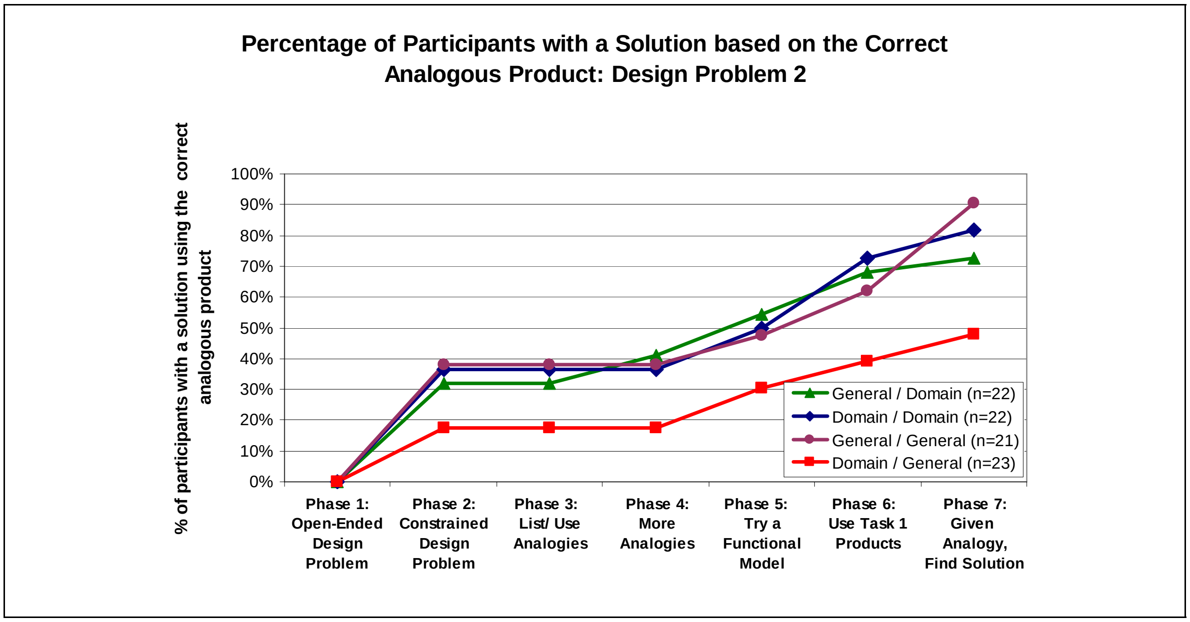


Figure 58a: The memory representation of an analogous product and the problem representation significantly influenced a designer's ability to remember and use the analogy to solve a design problem.

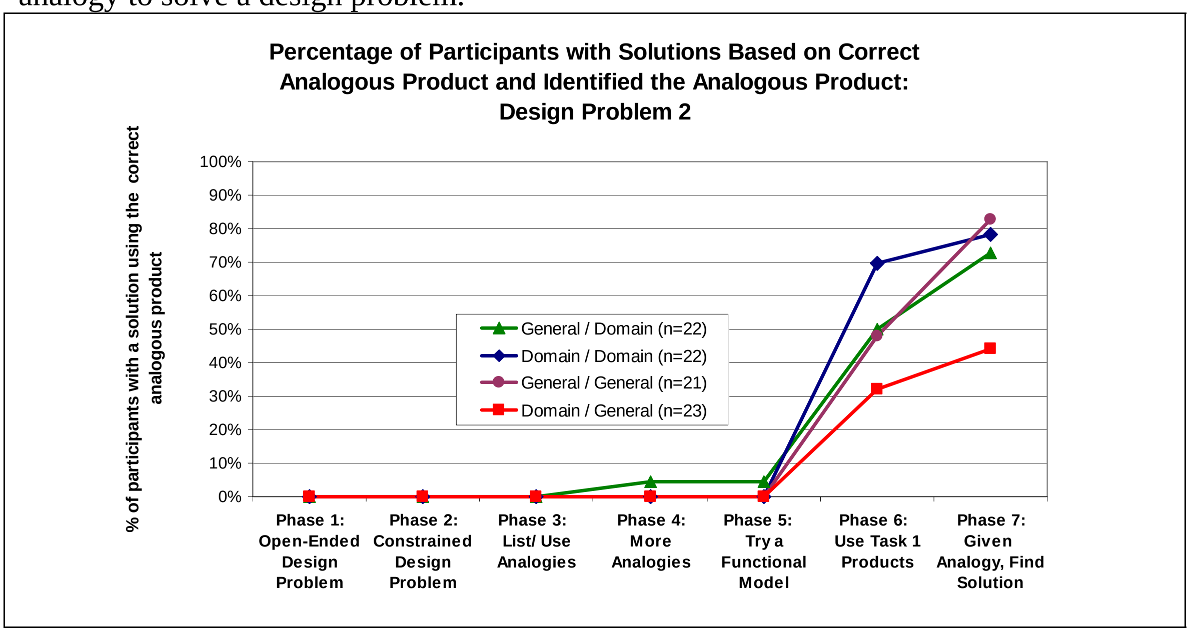


Figure 58b: Participants identify the source of their idea much later in the process.

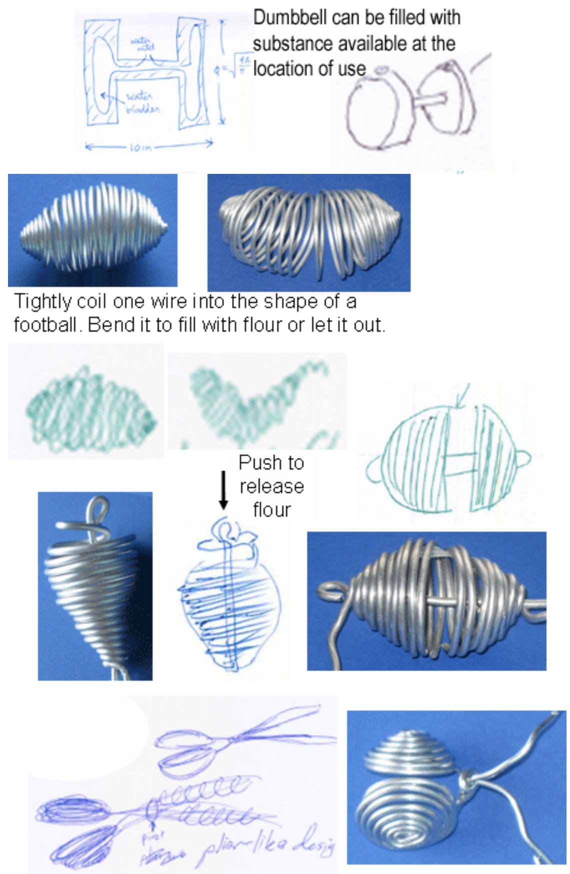


Figure 59: Example solutions found by the participant and models built by the author for illustration of the participants' ideas.

A Cox regression (Tabachnick and Fidell, 2001) was implemented to ascertain the statistical significance of the results. Cox regression is typically used for event analysis, and is a method that takes into account the effects across all seven phases. Cox regression is appropriate for binary outcomes that occur over time. For design problem 2, a Cox regression model with two predictors and the interaction terms shows a significant interaction effect for the memory representation and the problem representation (χ^2=4.2, $p<0.05$). There is also a main effect for memory representation (Wald=5.8, $p<0.02$). In other words, the effect of the problem representation depends on how the analogous product is represented in memory.

For design problem one, a Cox regression model with the two factors showed no significant interaction so the interaction term was removed from the model (χ^2=0.0, $p>0.9$). The representation of the design problem was also not significant (χ^2=0.12, $p>0.7$). The representation in memory was significant (χ^2=3.9, $p<0.05$). The Cox model accounts for the effects across all seven phases and if the effects are similar across the seven phases, Cox regression has more statistical power to detect differences. If the effects are not consistent across all phases then a logistic model at phases of interest is more appropriate. A two predictor logistic model (Kutner, Nachtsheim and Neter, 2005) at phase 3 shows a main effect due to the memory representation and the problem statement ($p<0.04$ and $p<0.08$ respectively) with a non-significant interaction term. At phase 4 a two predictor model shows only the memory representation to be significant ($p<0.07$).

The Cox regression model is showing that memory representation effects are statistically significant accounting for all phases of the experiment. The problem statement representation has a smaller effect size and thus is not significant in the Cox regression model. In addition, the Cox model assumes a constant rate of success for each time period with a different rate for each condition. For design problem 1, this assumption is likely causing a lower significance level to be observed. The logistic model at the end of phase 3 indicates that given a larger sample size, it is very likely that the problem statement may also be significant. The Cox model also assumes a constant rate of change across all time periods. This also may be reducing the statistical significance of the problem statement.

Results: Comparing Participate Scoring to Evaluator Scores

For this data set there are two measures for the use of an analogy to solve a design problem, the participants' indication of a solution being based on the analogous device and the raters' evaluation of appropriate features being mapped from the analogy (Figures 57a, 58a, 60 and 61). Generally the trends are the same using either measure with the participant evaluations showing higher scores. The rater evaluation generally show higher statistically significance. The participant evaluations likely have a greater amount of noise and individual differences in evaluations.

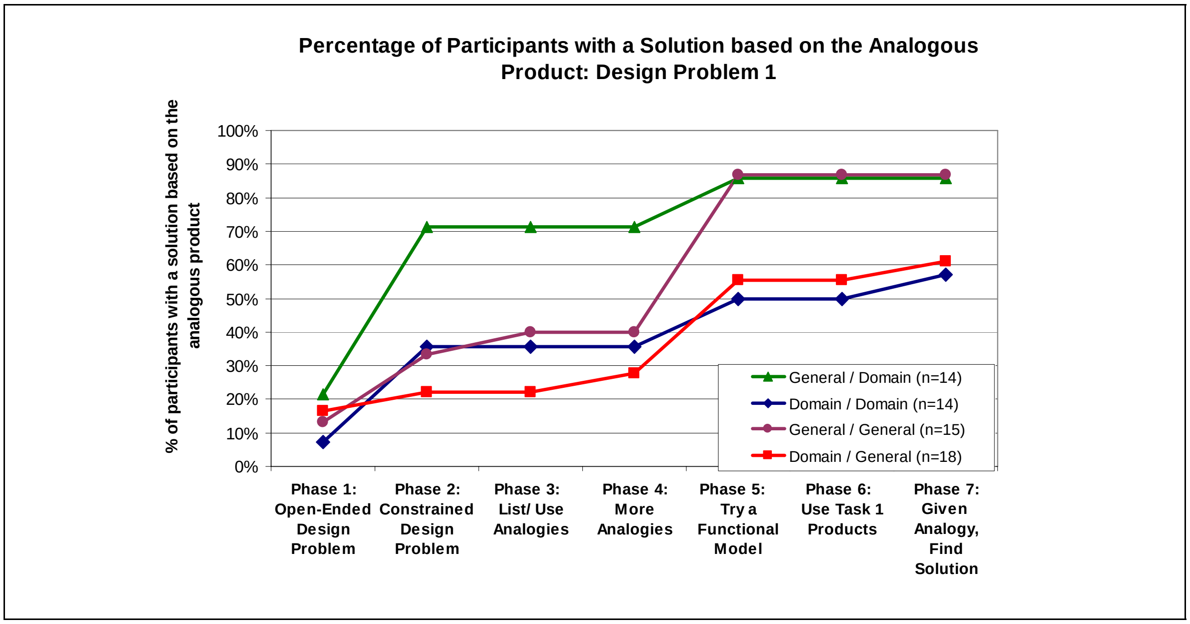


Figure 57a: Rater evaluation of success in finding a solution based on the analogous product. This figure is repeated for convenient comparison.

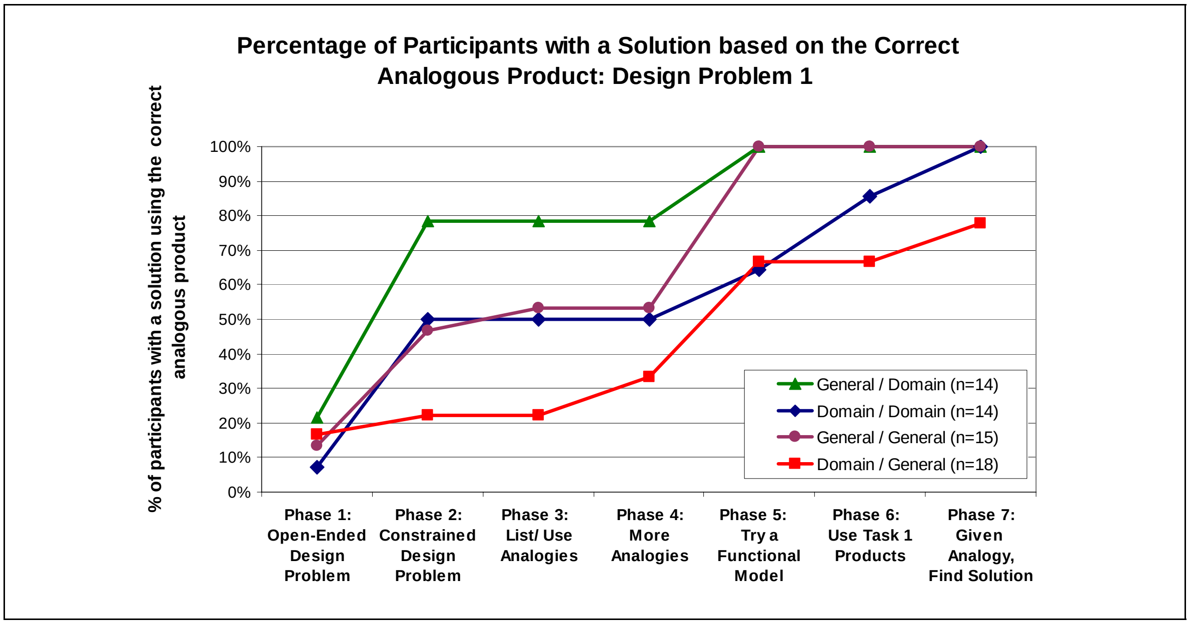


Figure 60: Participant indicated success in finding a solution based on the analogous product. Participant and rater evaluation show a similar pattern of results.

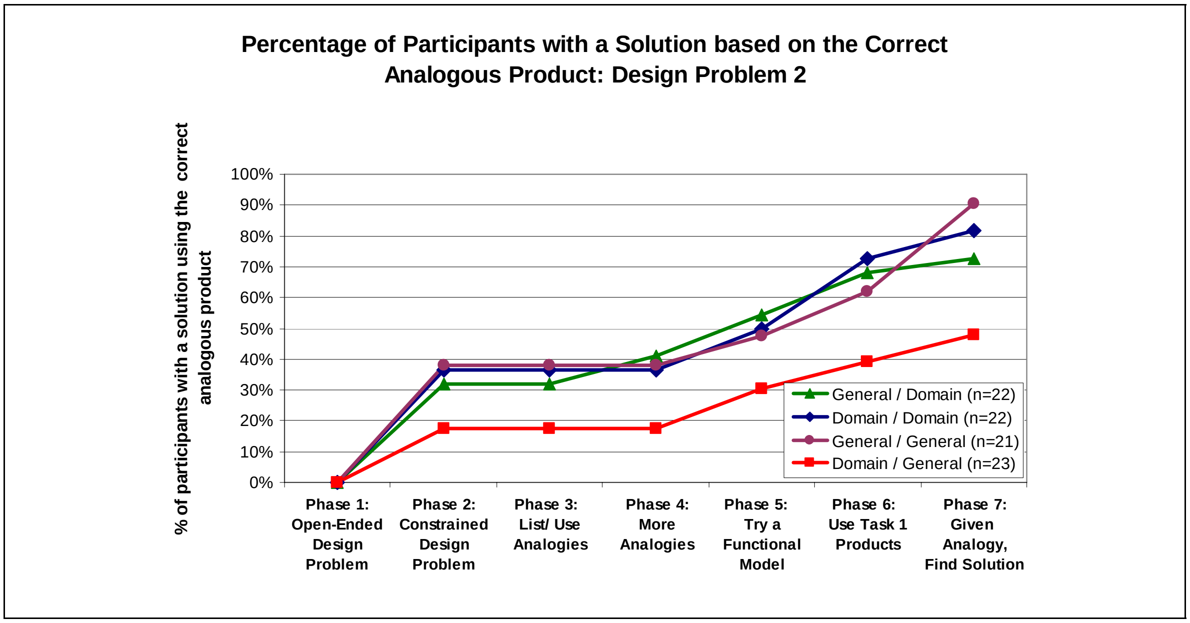


Figure 58a: Rater evaluation of success in finding a solution based on the analogous product. This figure is repeated for convenient comparison.

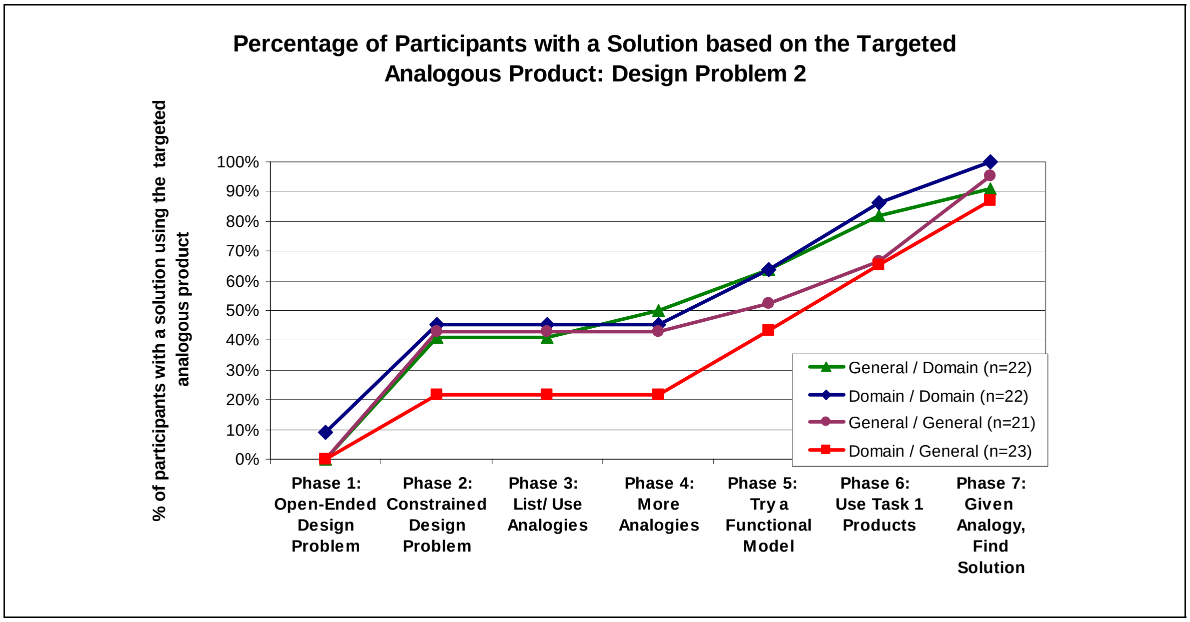


Figure 61: Participant indicated success in finding a solution based on the analogous product. Participant and rater evaluation show a similar pattern of results.

Effect of the Functional Models

Figure 62 shows the percentage increase with the addition of the functional models in the number of participants who had found the targeted solution to the design for Phase 4 to 5. The functional model has a similar effect across all conditions for design problem 1. For design problem 2 there is a greater increase for the general/general condition.

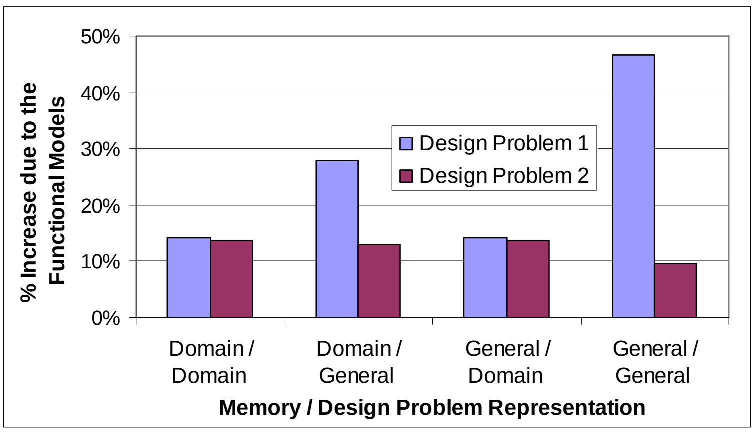


Figure 62: The functional models assisted the designers who had not been able to find the solution using the problem statement and trying to find analogies.

Evaluation of a Possible Limitation to the Experiment: Survey Results- Did participants have enough time?

The survey was mostly used to remove participants who had seen the solutions to the design problem and to verify that they had not heard about the details of the experiment prior to participants. Two survey questions evaluated a possible limitation of the experiment. To evaluate if the participants felt they had enough time, two Likert scale questions were asked. The questions asked participants to agree or disagree with the statements, “I ran out of time before I ran out of ideas,” and “I ran out of ideas before I ran out of time.” Over 75% of the participants felt they had plenty of time, and they ran out of ideas before they ran out of time (Figure 63).

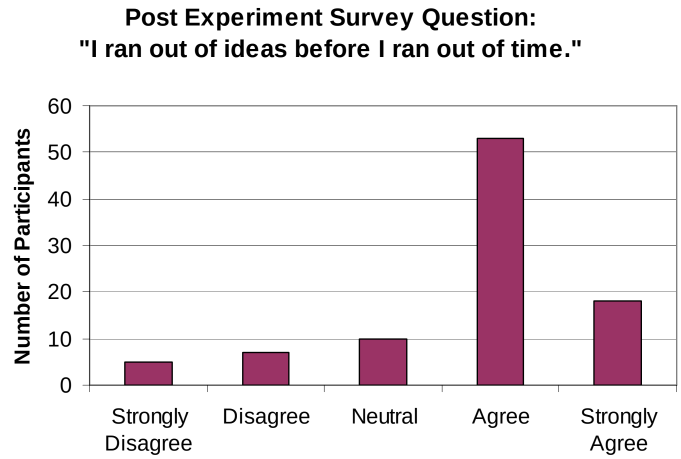


Figure 63: Almost all participants felt they had plenty of time and that they ran out of ideas.

The time periods for this experiment were based on a pilot experiment, but open questions from prior work were posed as: would the participants have a much greater chance of generating analogous solutions if they were given more time, and are the time periods adequate? To address these questions, participants received a survey at the end of the experiment asking them if they had run out of time or ideas first. An overwhelming majority of the participants, 76%, agreed that they ran out of ideas first, whereas a mere 14% disagreed. Clearly the vast majority of participants felt they had enough time (Figure 63). It is possible that even though participants felt they had enough time that they would actually have a greater likelihood of generating the analogous solutions if they spent more time ***engaged*** on the problem. To give insight into this issue, the time period for searching for solutions through analogies was doubled compared to the prior experiments described in Chapter 4 (Linsey et al., 2006) and split into two periods (phase four and five). During this second time period, only three additional participants found the solution for either of the two design problems. Simply spending more time attempting to use analogies has very little effect, at least within the experimental setup, process and conditions. The time periods were long enough for these basic yet novel problems. While the increased time period did not facilitate the retrieve of the analogous product from the first task, participants did continue to find additional analogies and solutions. Methods that help designers to spend more time searching for analogies by preventing designers from feeling they have run out of ideas will also enhance the process.

Analogy identification and implications for naturalistic research

Designers frequently use analogies to solve design problems without realizing the source of their idea. The participants used analogies, but did not mention that they were using analogies and/or did not realize that their solutions were analogous to previously experienced products until a later phase (Figures 60a-b and Figures 61a-b). If the designers realized the source of the idea, they would have listed the analogy at an earlier phase. Instructing participants to use analogies and list the analogies they had used caused little effect.

Our findings, in part, replicate the work of Schunn and Dunbar (1996), but for an independent data set and in the engineering domain. Schunn and Dunbar found that participants often used analogies to solve difficult insight problems, but the subjects did not realize they were doing so. One implication of this result is that analogies play an important role in problem solving, but do so, at least in part, outside awareness.

Another implication is that, in naturalistic observation studies, simply recording how often people say they are using analogies is likely to underestimate the true frequency. For example, imagine an investigator who seeks to determine how important analogies are in generating new designs. This researcher decides to observe expert designers at their workplace generating novel designs and counts the number of times the experts say “this is just like [some other product]”. Intuitively, this procedure seems reasonable, but the data suggest that it will underestimate the role of analogies. The results also indicate that designers frequently use analogy without recognizing it. This implies that design by analogy has an even greater impact on the design process than what is currently indicated by the anecdotal evidence.

ADDRESSING THE RESEARCH QUESTIONS

The data provide insights into the effects of the problem and analogous products representation for design-by-analogy. The following elaborates on these insights.

Question 1: How does the linguistic representation affect a designer’s ability to later use the analogous product to solve a novel design problem?

General linguistic representations, which apply both in the analogous product and design problem domain, increase the success rate more than ***domain specific*** representations. If a designer stores analogous products in memory in more general representations, they are more likely to be able to later use these analogies to solve novel design problems (Figures 60a-61a). This result has important implications for how design methods are strutted and teaching designers to think about and remember design solutions they encounter. If they seek representations that apply across more domains and in more general forms, they will be much more likely to be able to use the design in the future. For example, framing an air mattress as “a device that uses a substance from the environment it is used in”, rather than “a device that is filled with air” makes it much more likely to be used in future design problems that seek innovative solutions.

Question 2: How does the representation of the problem statement affect the ability of a designer to retrieve and use a relevant analogous product to find a solution to a new design problem?

The representation of design problems clearly influences a designer's ability to generate analogous solutions (Figures 60a-61a). The representation that will give the designer the highest probability of exposing or generating an analogous solution depends on how the analogous solution is stored in memory. If the analogous product is stored in a general form, then a domain specific representation is the most efficient means to retrieve it. Generally, it is not known in advance what representation is most likely to retrieve the desired information. This means that a good approach for seeking analogous solutions is to use multiple representations that vary across the range of domain specific or domain general and are domain-specific in multiple domains.

This experiment also provides a basic study of the potential for function structures (functional models), another representation of the problem statement, to enhance the design-by-analogy process. Participants were given function structures with process choices which are consistent with the analogous solutions. The function structures also included linguistic functional descriptions different from the given problem statements. This experiment does not address how the participants would develop these particular function structures. This experiment addresses the question that if given an appropriate function structure, does it increase the likelihood of generating an analogous solution? From the results, there is a clear increase at phase six when participant use the function structures to assist them. This result is exciting and a validation of anecdotal claims about an important role of functional modeling in design. Function structures are another potential representation to enhance the design process and should be included in the search for analogous solutions. Diagrammatic representations merit further investigation.

Question 3: What are good approaches to representing a design problem when the representation in memory is not known and what implication does this have for a design-by-analogy method?

For any design task, a number of representations should be created with a varying semantics. Typically it is not known how relevant analogies are represented in memory and which retrieval cues are required. Therefore a number of representations and therefore retrieval cues should be created to maximize the probability a useful analogy will be found. Design-by-analogy methods need to be created that systematically assists the design in developing multiple representations of their design problems. These should range from domain-general to domain-specific representations in analogous domains.

Question 4: Does the addition of functional models facilitate solving a novel design problem?

There is a clear increase in the number of participants who found a solution based on the analogy during phase five, when participants used the function structures to assist in generating solutions. This result is exciting and a validation of anecdotal claims about an important role of functional modeling in design. Function structures are another potential representation to enhance the design process and should be included in the search for analogous solutions. It is important to point out, however, that participants were given function structures with process choices that were consistent with the analogous solutions of interest in the experiment. These function structure also included linguistic functional descriptions that were different from the given problem statements. This experiment does not address how the participants would develop these particular function structures. Instead, it suggests that if designers create an appropriate function structure, it will increase the likelihood that they will generate the analogous solutions. Further research must explore the kinds of function structures that designers generate spontaneously and the influence of these function structures on the analogies retrieved.

CONCLUSIONS

Design-by-analogy is a powerful tool in a designer's toolbox, but few designers have the methods to harness its full capacity. Simply recognizing its potential and attempting to search mentally for analogies is not enough. Designers need methods and tools to support this process. They need approaches for when they feel they have run out of ideas. They need methods to represent the problem in a multitude of ways. The right representations have the potential to increase a designers' probability of success by up to 40%. These methods need to be built on a solid understanding of human capacity combined with design and applied scientific knowledge. This experiment demonstrates, at least foundationally, the impact the representation has on design-by-analogy.

Design-by-analogy is a common occurrence in the design process. Designers frequently use analogous products without recognizing the origin of the idea. Participants who have been exposed to the technique of design-by-analogy will spontaneously use it when asked to generate design solutions. Design-by-analogy is not limited to an elite few designers who learn to harness its power but it is commonplace. A deeper understanding of the mechanism behind analogical reasoning and their implications within design will guide the development of drastically improved design-by-analogy methods and tools for design innovation. Representation clearly matters and seeking improved representations has great potential for significantly enhancing the innovation process.

Chapter 6: WordTree Design-by-Analogy Method

The chapter begins by describing a new method, the WordTree Design-by-Analogy Method, to enhance an engineer's ability to find relevant analogies for a design problem. Prior chapters illustrate the importance of design-by-analogy and the influences on the design process. This previous work serves as the basis for the creation of the method. The method systematically guides the engineer to re-represent a design problem with multiple linguistic representations. After illustrating the method, the guiding principles, derived from the studies in this dissertation and other literature, are described while highlighting their implementation in the WordTree Method. The subsequent sections evaluate the WordTree Method through a case study, implementations in three Senior Design Industrial-Sponsored Projects, use for product redesign in the Senior Design Methods Class, and finally with a controlled experimental study.

WORDTREE DESIGN-BY-ANALOGY METHOD

The WordTree Design-by-Analogy Method systematically re-represents a design problem, assisting the designer in identifying analogies and analogous domains. Figure 64 overviews the method's steps. The method begins by identifying the problem descriptors which are the key functions and customer needs. These are then linguistically re-represented in a diagram know as a WordTree (Figure 65). Next potential analogies and analogous domains are identified. The potential analogies are researched and the analogous domains are used to find solutions in distant domains. New problem statements ranging from very domain specific in multiple domains to very general statements are 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 results into conceptual solutions to the design problem and provides additional inspiration for the designers. The following sections detail the WordTree method and illustrate it with the case study design problem of "developing a device to fold wash cloths, hand towels and small bath towels." The guidance from experimentation for the creation of this method is also described in parallel to explaining the method in detail.

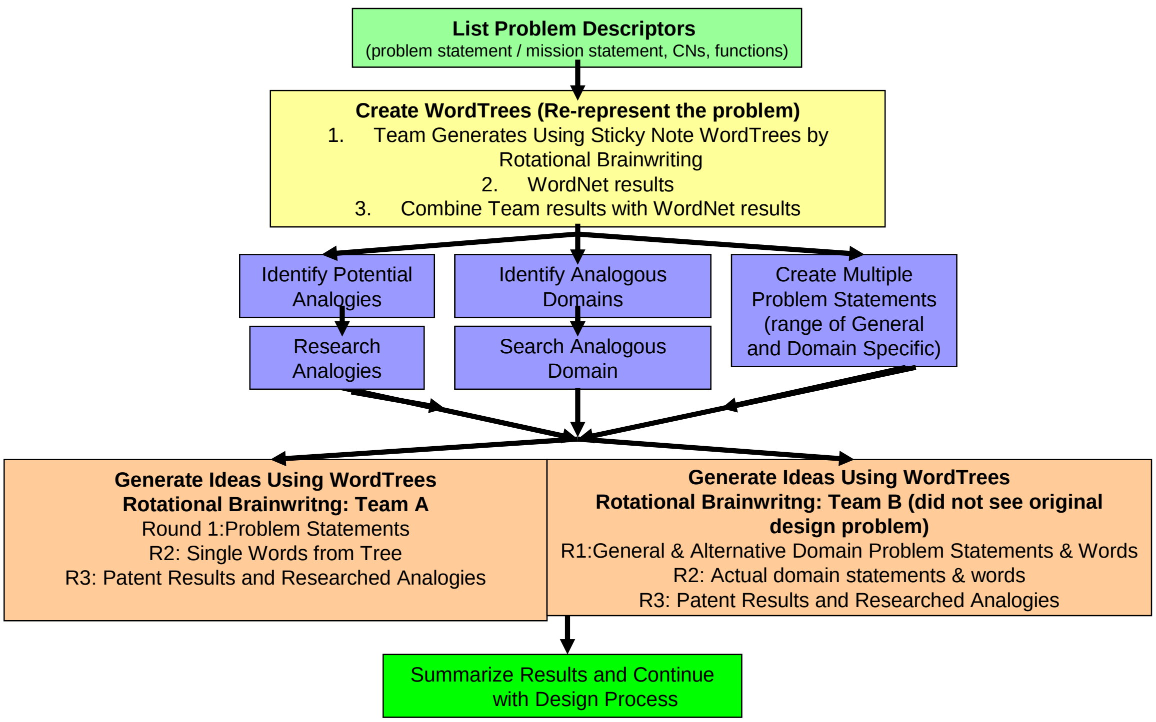


Figure 64: Overview of the WordTree Design-by-Analogy Method.

One of the main principles for enhancing analogical retrieval provided by the experiments in this dissertation is the design problems need to be represented in multiple ways, thereby providing a variety of retrieval cues. It is not possible to know *a priori* which representation will locate useful for analogies stored in memory. By creating a variety of retrieval cues, the chances of finding a relevant analogy are increased. The

WordTree method focuses on creating multiple linguistic representations of the design problem through numerous other representations are likely to be effective including functional models. TRIZ, with a different approach, also linguistically re-represents the design problem as the conflict between two generalized engineering parameters (Otto and Wood, 2001). Other possible re-representations and other linguistic approaches are possible.

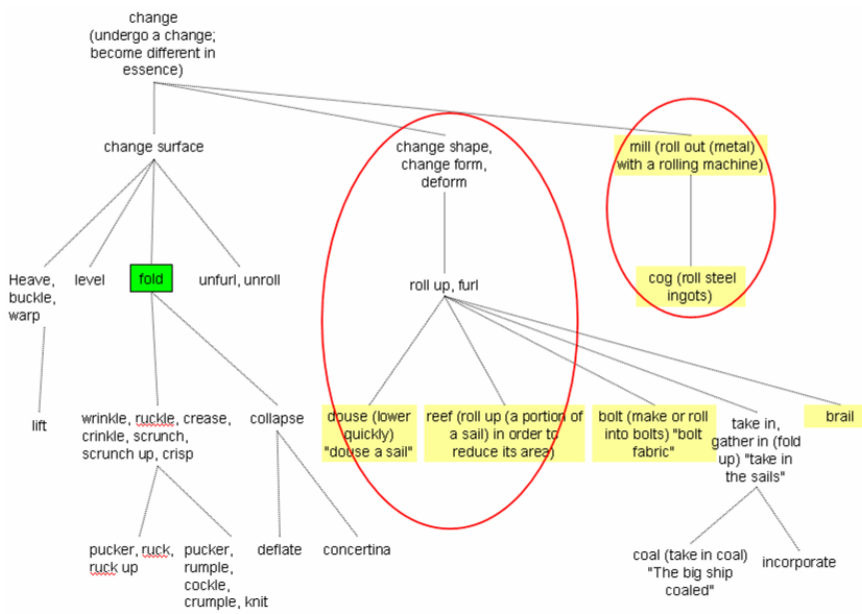


Figure 65: Partial WordTree for the function of “Fold”. Analogous domains for folding include sailing (douse a sail, reef a sail) and machining processes (cog: roll steel ingots).

This 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 the design problem. The Key Problem Descriptors are defined from the customer needs, mission statement, function structure and black box model. Key Problem Descriptors fall into a few categories. One set describes the overall function of the device with a single word. The next category is the critical or difficult functions to solve, and the final category is the 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 of "easy to repair" is "repair". Figures 66-68 illustrate the mission statement, partial functional model and black box model for a device to fold laundry (Ajetunmobi, *et al*., 2006). The laundry folding device is intended for students with very limited fine motor skills. Some of the customer needs for this device are to smooth the laundry, rugged, easy to use and portable. Some of the key problem descriptor for this device are fold, prepare [for storage], store and smooth.

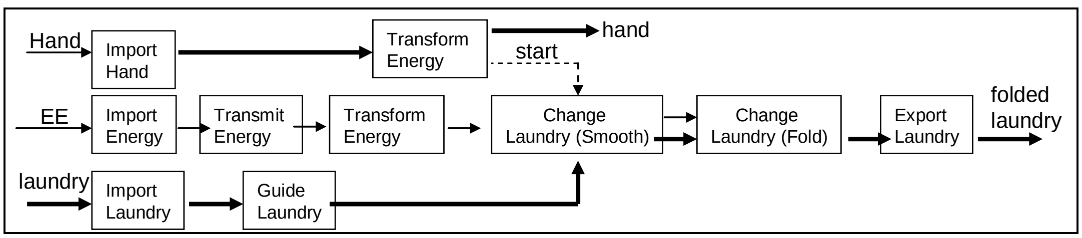


Figure 66: Partial Functional Model for the laundry folding device.

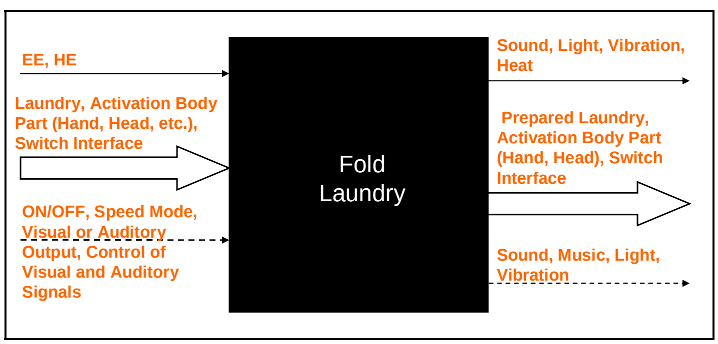


Figure 67: Black box model for the laundry folding device

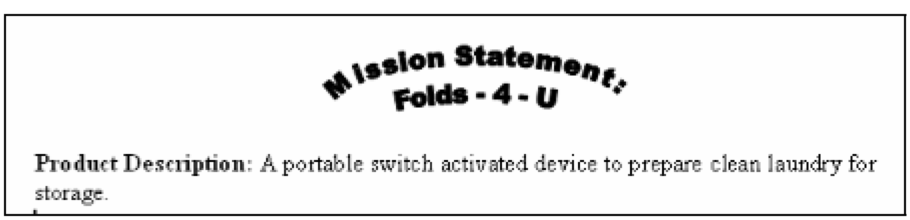


Figure 68: Partial Mission Statement for the laundry folding device.

The next step is to re-represent the key problem descriptors using WordTrees. This step facilitates the identification of analogies and analogous domains. The first the design team to use rotational brainstorming to create sticky note WordTrees (Figure 69). Rotational brainstorming is very similar to 6-3-5 except that each team member receives three separate sheets of paper and develops one WordTree on each sheet (Figure 70). A rotational brainwriting method was chosen since the Group Idea Generation experiment in Chapter 3 resulted in a greater number of ideas in this condition.

The set of key problem descriptors should be divided evenly between team members. Each person begins with a set of three different problem descriptors and spends ten minutes creating the WordTree. The WordTrees are rotated clockwise around the table and the next person spends five minutes adding to the WordTrees. 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 “wrinkle, tuck, ruffle, pleat and crease.” More general verbs are placed above and more specific are placed at lower levels (Figure 69).

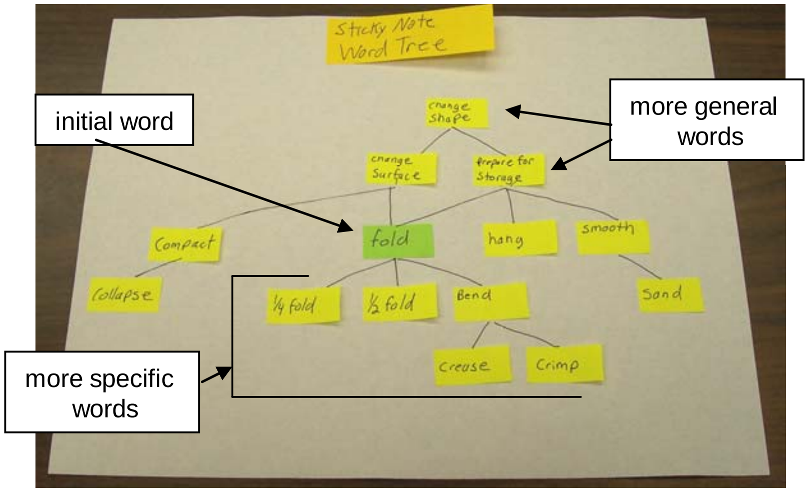


Figure 69: Sticky Note WordTree.

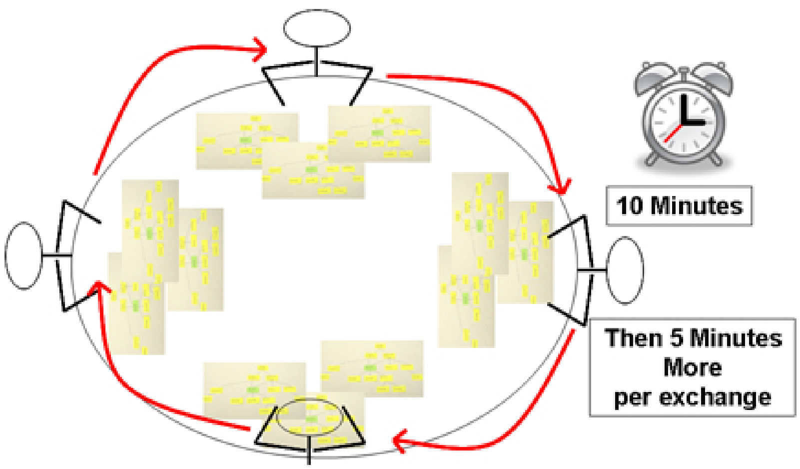


Figure 70: Rotational Brainwriting

After the team generates the sticky note WordTrees using rotational brainwriting, WordNet (http://wordnet.princeton.edu/perl/webwn) is used to find additional results. WordNet was originally developed as a database to support natural language processing and computational linguistics (Fellbaum, 1998). It is similar to a thesaurus since it gives synonyms for words, but it is far more sophisticated. WordNet structures words in the same manner in which they are used within the English language with some having very broad general meaning and others being much more domain specific. WordNet often gives brief usages and definitions for words, for example “douse a sail” (lower quickly). 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. The WordNet and sticky note WordTrees are combined (Figure 65).

Next the team reviews the WordTrees looking for potential analogies and analogous domains. Analogies can occur anywhere in the WordTree and many of the words will trigger new ideas. Analogies frequently occur as words that are both nouns and verbs. These are often unusual words whose meaning as verbs is unfamiliar, for example brail (Figure 65). Many of the analogies occur at the ends of the branches or on the “leaves of the tree.” Analogous domains frequently occur on parallel branches which contain multiple potential analogies. For example in Figure 65, “douse a sail” and “reef a sail” indicate that sailing is an analogous domain. The analogous domains and general terms are categorizes of possible solutions. The WordTree structure highlight the general terms.

After potential analogies and analogous domain have been identified, the analogies are researched along with searching for solutions in analogous domains. Google Image© is an effective and efficient tool for finding information about a potential analogy. Patents in analogous domains should be searched for also. Searching for analogies and patents in analogous domains can be completed prior to the teams attempting idea generation because it has been shown that uncommon solution, which is the type of solutions analogies should provide, tend to increase the number of ideas generated and not cause fixation (Dugosh and Paulus, 2005; Perttula and Sipila, 2007).

Finally teams use the results to generate more ideas. Ideally two separate teams of designers will base the idea generation session on the results from the WordTree Method. The first team is the original team who generated the WordTree and knows the details of the design problem. The second team is unfamiliar with the problem and is given the general and alternative domain problem statements along with general and alternative domain words. When using analogies, individuals tend to focus too much on the surface and unimportant features of the problem rather than the causal structure (Gentner & Landers, 1985; Gick & Holyoak, 1980). It is believed, the second team will be less likely to focus on unimportant features of the original design problem since they will be shown a series or analogous problems which will tend to focus them on the deep structure and not the surface information. After team idea generation, the results are summarized and the team continues with the design process.

RESEARCH QUESTIONS EVALUATING THE WORDTREE METHOD

The WordTree Method is founded on prior experimental results and theory. This basis does not guarantee an effective design approach. A series of evaluations is used to understand the outcomes of the WordTree Method and provide guidance for further refinement. This endeavor is focused through a set of research questions as follows:

- Question 1: Does the WordTree Method increase the number of analogies identified? Does the WordTree Method produce unexpected, useful analogies and solutions?
- Question 2: What are engineering designers' opinions of the method?
- Question 3: Does the WordTree Method change how designers search for solutions using databases?
- Question 4: Is there an increase in the novelty, variety and quality of the ideas produced by the WordTree Method?
- Question 5: What are some avenues for improvements to the WordTree Method?

NOISE FACTORS IN DESIGN METHOD EVALUATION

In the evaluation of design methods, numerous noise factors exists and can dominant the outcomes. Therefore it is important to identify and control, as much as possible, the noise factors. Table 20 lists the noise factors that are expected to be the most influential when evaluating design methods. For the evaluation of the WordTree Design-by-Analogy method, these factors were controlled as much as possible. One of the more importance factors is "how well a method is taught and then subsequently learned by the participants." If a method is not well taught or learned by the participants, the outcomes of the method are not likely to be positive, due to inadequate teaching rather than an ineffective method. For the experiments in the evaluation, the method was taught by the author. The enthusiasm of the person teaching the method along with the power of their illustrations impacts the participants' perception of the approach.

The design problem can cause significant amount of variability in the design outcomes. Many methods work better for certain types of design problems. For the controlled experimental evaluation of the WordTree method, the design problem was chosen such that the WordTree method was expected to be very effective for the problem. The robustness of the WordTree method was also evaluated with a variety of design problems from the Senior Design Methods Class. This also assists in highlighting the variety of problems the WordTree methods is effective for.

The participants in the experiment influence the outcomes for the design methods. Their individual cognitive abilities, problem domain experience, method experience, effort, personality and culture can all affect opinions of the method and the design outcomes. The receptiveness of the participants to design methods in general affects their evaluation of the method and their results. The entire evaluation of the WordTree Method was completed with designers who had been trained in design methodology. The participants in the evaluations are provided with extra credit in their design class for their participation and told the extra credit is based on their effort and their results. This approach helps to provide motivation and needed incentive to the participants.

Acknowledging the various noise factors provides opportunity to consider and to attempt to control for them. By also documenting the controls for the noise factors, it creates more repeatable results.

Table 19: List of some noise sources in design methods evaluation.

Noise Factors for Design Methods Evaluation
• How well the method is taught to the participants
• Presentation of the method, enthusiasm of the presenter and how well the presenter highlights the benefits of the new approach
• Characteristics of the design problem
• Receptiveness of individuals to design methods in general
• Individual differences (cognitive abilities, personality, cultural, previous experience, expertise)
• Individual's motivation for using the method
• Level of expertise for the problem domain
• Level of expertise for the design method being evaluated

EVALUATION OF THE WORDTREE METHOD

Prior research guided the creation of the WordTree method. Evaluation of the method is critical to improve and evolve the approach and to determine if potential impact and benefits exist. The WordTree method was evaluated in a three-pronged approach: using a case study, application with three teams working on industry sponsored senior design projects, and finally a controlled experimental evaluation.

Case Study: Laundry Folding Device

The WordTree Design-by-Analogy Method was applied to the design problem of "creating a laundry folding device for students with serve physical and mental disabilities." A local Austin school does their laundry at the school and wanted to involve their students in the process. The goal was to be able to fold wash cloths, hand towels and small bath towels. Folding an item requires fine motor skills that the students do not possess. The author was a member of the six-person design team that created a solution to this problem (Ajetunmobi, et al., 2006). This project was completed as part of a graduate product development class, and the final solution won a design competition award from RESNA (Rehabilitation Engineering & Assistive Technology Society of North America).

The initial team created an effective solution and spent considerable time on the project. This case study illustrates an innovative solution found using the WordTree Method that was not identified by the original team. The team, who found a solution to this problem initially, developed over 40 concepts for the function of folding and actively sought analogies. At the time when the first solution was being sought, it was known that the representation of the design problem influenced the analogies and solutions developed. One of the phrasing used by the team was a "device to prepare laundry for storage". The school ultimately needed to be able to store the laundry items. They had no preferences for how the items were folded as long as they were capable of being stored. This lead the design team to consider a number of different approaches to folding, see examples in Figure 71. The final solution used a quarter fold and is shown in Figure 72.

Figure 71: Different approaches to folding.

Application of the WordTree Method to this problem results in the WordTree shown in Figure 65 and a number of analogies and analogous domains not considered by the original design team. Unusual words or unusual senses of words shown WordNet are frequently very domain specific terms. Stickle is one example from the fold WordTree. A stickle is a device used to smooth the inner and outer surface of a bell when it is being built (Figure 73). An interesting analogous domain presented by the WordTree is the domain of sailing, with specific analogies of dousing a sail and reefing a sail. A quick search using Google image provides the two analogous solutions for dousing a sail shown in Figure 74.

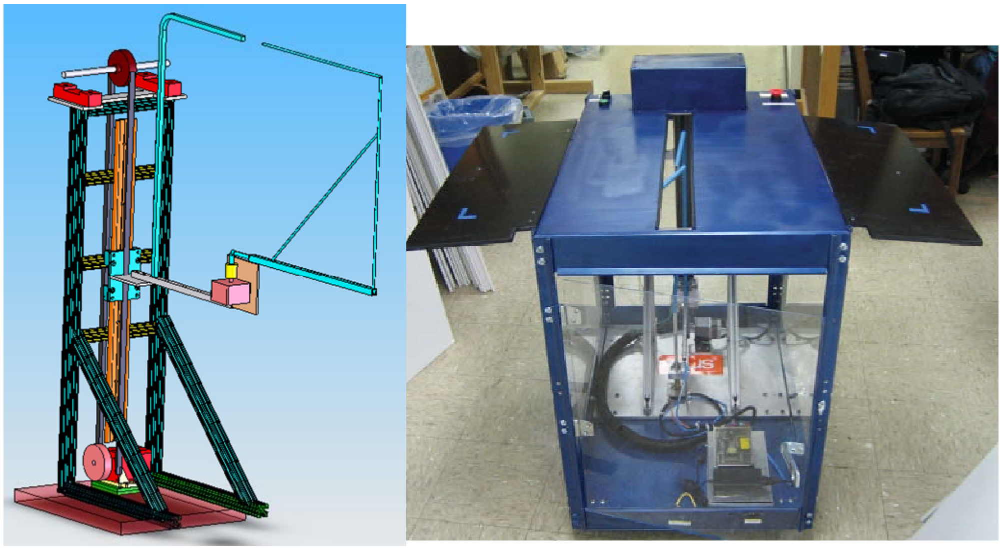


Figure 72: Original team's award winning solution to the laundry folding problem. The image on the right shows the final solution and the left image is the internal mechanism. The towel or wash cloth is spread out on the top surface of the device. A bar rises in the center causing the item to fold in half. Half of the bar rotates around causing another half fold in the towel.

The original design team did not focus on the fact that the laundry items needed to be prepared for storage but not necessarily folded. They did not evaluate various approaches to storage. Later, it was realized an effective solution for the problem of "storing laundry" was the shopping bag storage tube (Figure 75). Examples of storage devices for another design project had been collected and the shopping bag storage tube was a rather unique example that had been identified. The shopping bag storage tube is a very effective solution to the laundry storage problem. The need for an easy and effective method to store washcloths also plagues the author's home. The wash clothes generally exist in a random pile on a shelf. A solution was developed based on the analogy (Figure 75). The wash cloth storage tube shown in Figure 75 could be scaled up to hold larger items such as small bath towels.

Table 20: Analogies and analogous domains for the laundry folder.

Analogies & Analogous Domains Identified using the WordTree Method	Original Team's Analogies & Analogous Domains
cogging	sheet metal design (metal folding)
douse (douse a sail)	napkin folding
raking	origami
sandblasting	industrial laundry machines
stickle	

Figure 73: A stickle is used in the process of creating a bell. A stickle smoothes the inner and outer surface of a bell (Putman, 1970, http://www.cccbr.org.uk/prc/pubs/slides/16startingCore.jpg).

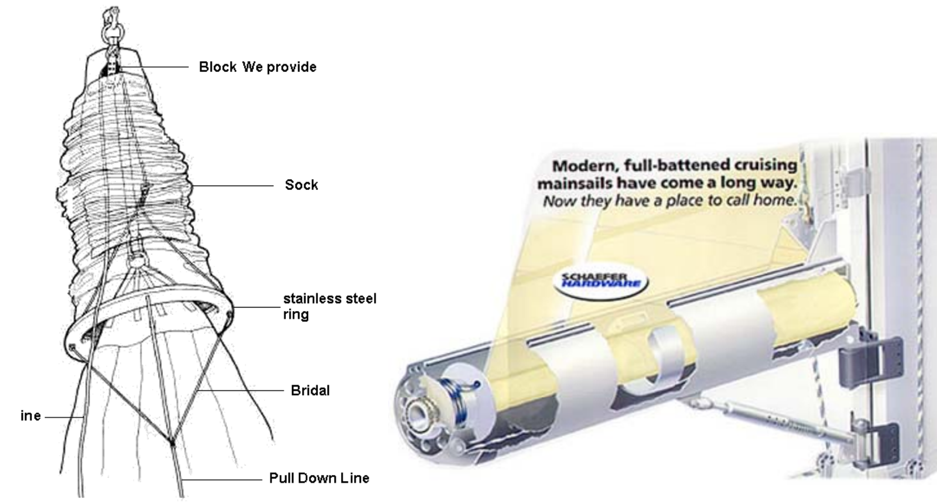


Figure 74: Two solutions for dousing a sail (“Hallett Canvas And Sails – Rigging”, 2007; “Fareastsails.com”, 2007).

Figure 75: A solution for the laundry storage problem.

APPLICATION OF THE METHOD WITH INDUSTRIAL SPONSORED SENIOR DESIGN PROJECTS

As an early evaluation and to provide guidance for improving the WordTree Design-by-Analogy Method, a version of the WordTree method (Figure 76) was implemented with three teams working on industrial-sponsored senior design projects. For the design projects, teams determine the methods their projects require. Prior to the study, teams were asked to complete their process through finishing their concept generation. The teams were given extra credit for their participations and were aware a new design method was being evaluated.

Procedure

Prior to showing each team the WordTree Method, the teams gave the experimenter a list of patents, analogies and solutions they have thought of. The teams also provided the experimenter with a list of six key problem descriptors, which were used to provide two WordNet WordTrees to each team. The teams were taught the WordTree method and stepped though the process finishing with the identification of analogies and analogous domains in approximately 1 hour. Teams were also provided with a Matlab Patent tool which allowed them to enter the search terms and then sorted the results by domain, the patent class (Murphy, 2008). Teams were left to research the analogies, write new problems statements, find patents in the analogous domains and generate more ideas on their own. Each team was taught the method separately using an unscripted slide presentation (see Appendix E).

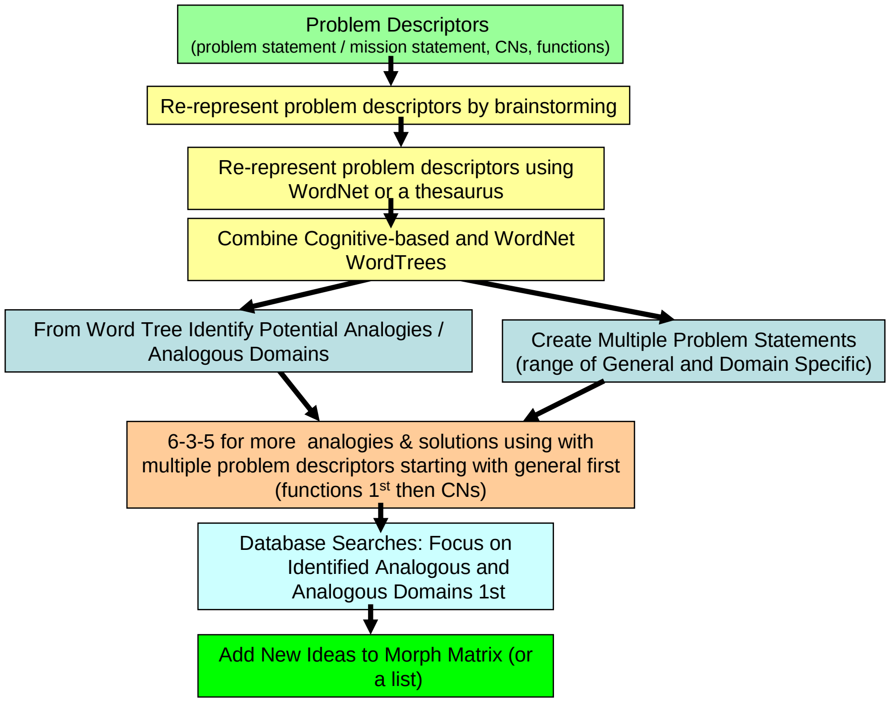


Figure 76: Preliminary version of the WordTree Method

After completing the method on their own, teams provided a final list of analogies, useful patents, ideas to the experimenters and filled out a survey. The survey (Appendix E) asked the participants to provide feedback on the WordTree method using Likert and open-ended question. The survey also required participants to rate how valuable each design method was and the likelihood they would use the method in the future. Demographic information including engineering work experience, overall GPA, GPA in major, grade in Design Methods Class, gender, expected grade in Senior Design Project Class, SAT verbal and math scores was also collected.

Industrial-Sponsored Team Project Results

Prior to completing the WordTree Design-by-Analogy Method, the design teams believed they were finished with concept generation and satisfactory results had been found. All of the teams were able to find additional analogies and solutions to their design problems using the WordTree Method (Table 21). Figure 77 shows the analogous solution in the domain of “Handling: hand and hoist-line implements, Patent Class 294” found by Team 1 using the WordTree Method. The team was designing a gripper system for a robot capable of holding cylinders. This solution was one of their final concepts (Halverson, Kottlowski and Smith, 2007). Another concept was chosen as a final concept because the team was unable to locate a standard off-the-shelf actuator for the concept. A custom sized actuator would have allowed this concept to be feasible.

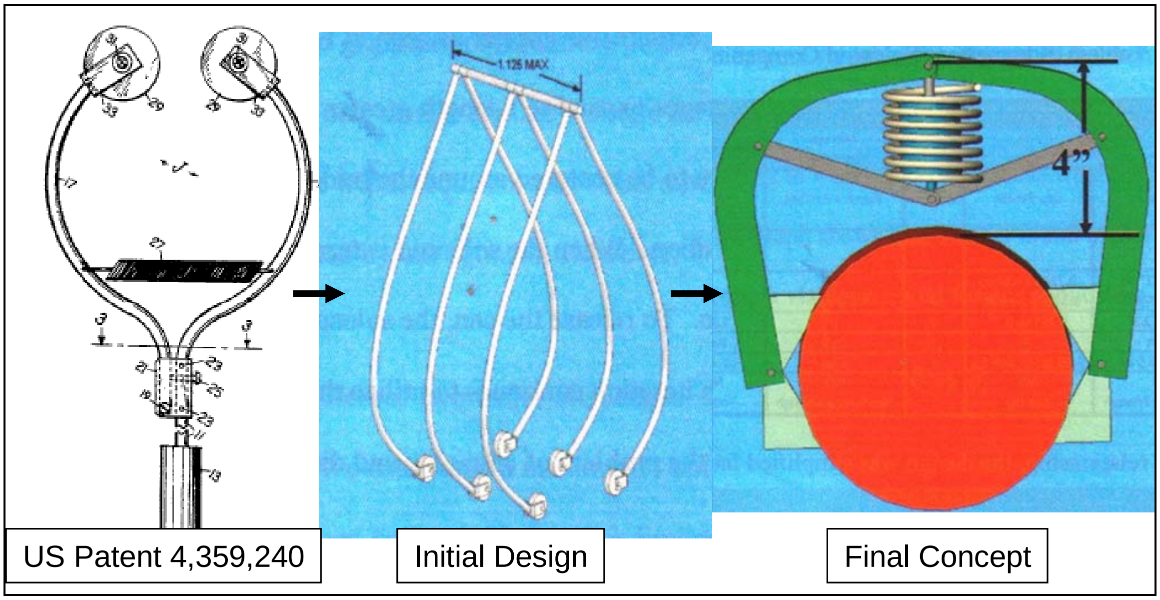


Figure 77: A solution based on results from the WordTree Design-by-Analogy Method. The concept shown above was one of the final solutions proposed by the team.

Table 21: Student design teams working on industrial sponsored projects were able to find additional analogies using the WordTree Method.

	Team 1	**Team 2**	**Team 3**
Number of New Analogies from WordTree Method	9	3	2

Figure 78 shows the survey responses for a series of questions (Table 21) designed to evaluate the WordTree Method and provide information for further improvement. The teams felt the WordTree Method helped them to generate more analogies, more ideas and higher quality ideas. The method was not a waste of time and they generally liked the method but also felt improvements could be made. The general assessment of the method was generally positive and provided useful results to the teams.

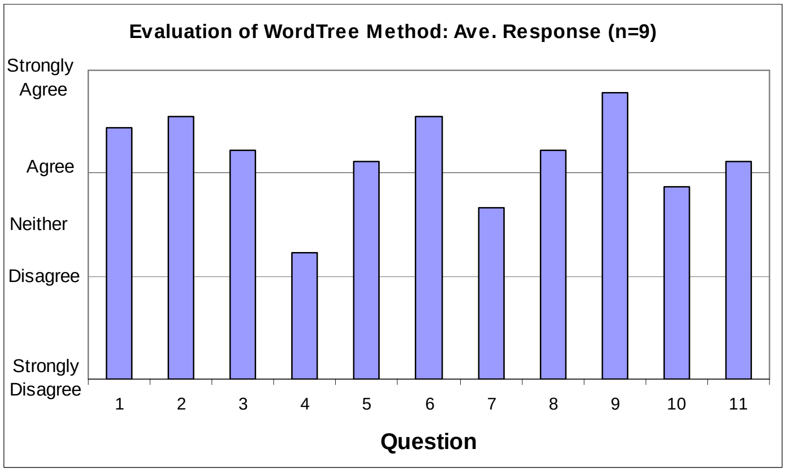


Figure 78: Survey response for WordTree Method (corresponding questions in Table 22).

The survey also asked the teams to rate the value of a set of design methods (Figure 79) for their design problem and also for a design problem that requires an innovative solution. The teams gave a higher than average value to the WordTree Method for both their design problems and also for design problems requiring innovative solutions. This set of teams evaluated many of the design methods, including QFD, TRIZ and Morph Matrix, as having very little value. The teams generally felt the methods are more valuable for innovative design problems than for their industry sponsored projects.

Table 22: Survey questions evaluating the WordTree Method.

1.	This method helped me to find analogies for my design problem.
2.	This method helped me to generate more ideas.
3.	This method helped me to generate higher quality ideas.
4.	This method was a waste of time.
5.	The presentation of this method was easy to understand.
6.	The method was easy to use.
7.	I expect to use this method in the future.
8.	This method needs improvements.
9.	This method was useful.
10.	I liked using the method.
11.	I expect to use this method in the future for design problems that require an innovative solution.

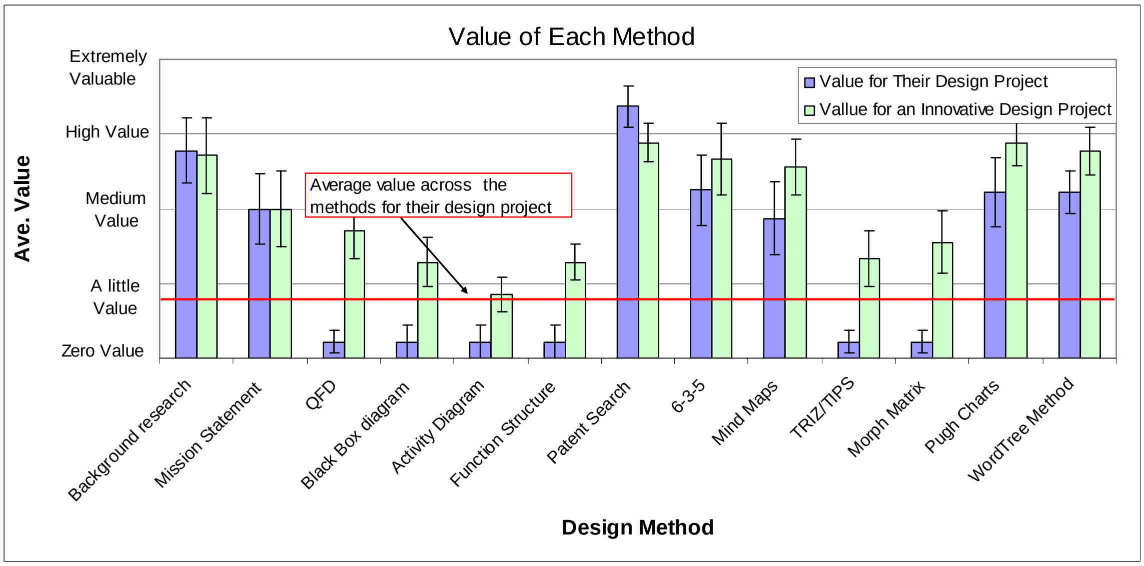


Figure 79: The teams found the WordTree Method to be valuable for their industrial sponsored project. Each error bar is +/- one standard error.

SENIOR DESIGN METHODS CLASS EVALUATION

To further evaluate the WordTree Design-by-Analogy Method it was also taught in the Senior Design Methods Course. The author of this dissertation taught the WordTree Method as part of a lecture series on idea generation which included brainstorming, 6-3-5, MindMapping and TIPS/TRIZ (Otto and Wood, 2001).

Procedure

As part of their Design Methods Class, 92 students used the WordTree Design Method. In the Senior Design Methods Class, students work in teams of four to six students redesigning a commercial product that they choose. The entire semester is spent learning various design approaches. 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 (Figure 80). The teams learned the method in one 50 minute lecture and then spent a second lecture period working with their teams to complete the method. During the second lecture period, the author reminded the teams of the steps in the process, answered any questions they had and helped guide them through the method. Many of the teams had their WordTrees finished at the end of the second lecture period.

For extra credit, teams were asked to individually fill out a survey which was very similar to the survey used for Industrial-Sponsored Team Projects (Appendix E). Students' personalities using the TIPI (Ten Item Personality Inventor) (Gosling, Rentfrow and Swann, 2003) were also measured.

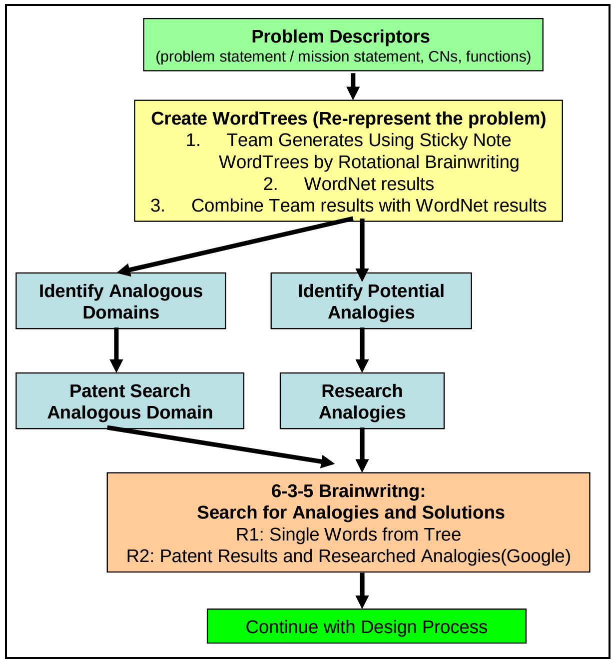


Figure 80: WordTree Method as presented to the Design Methods Class.

Results and Discussion

Figure 81 shows one team's resulting analogies and analogous domains for the redesign of an automatic cat litter box. The WordTrees for both the team-based and WordNet generation were generally carried out correctly and showed positive results, but there also was significant variation in the resulting analogies and solutions. Some teams, like the cat litter box team, found very novel analogies and unexpected analogous domains. Other teams had more disappointing results for a number of different reasons. Correctness of the method implementation varied. One team used their industrial design shift rather than the functional design shift. The industrial design shift focuses on changing the aesthesis, 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. Occasionally the wrong sense of the verb was selected. Some of the words used for the WordTree Method were constraints 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.

A few teams obtained poor sets of analogies 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 have a higher risk of not obtaining useful results. Distant domain analogies have more risk but also have much greater potential for innovative solutions. One solution to this issue is to alter the grading structure such that students believe the reward is worth the possible risk.

There was one generally consistent issue for almost all of the teams with the WordTree Method. 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.

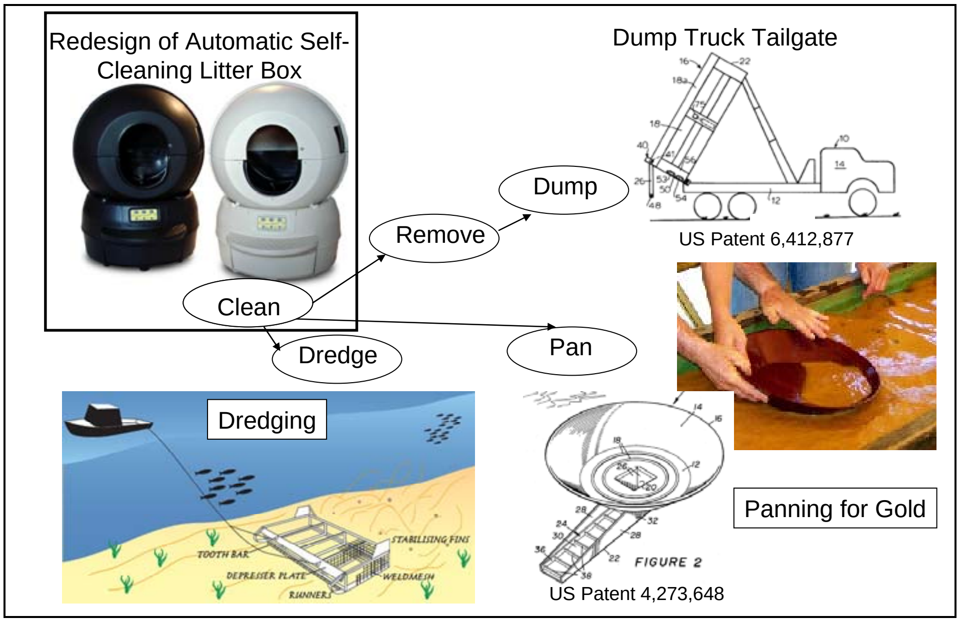


Figure 81: Analogies and analogous domains identified by a team who was redesigning a self-cleaning cat litter box.

A series of survey questions asked for the students' opinions of the WordTree Method (Figure 82). The students were generally neutral but their opinions ranged greatly. This group of students was generally more negative about the method than the students working on the Industry-Sponsored Design Projects. It is important to also note that the results obtained from the WordTree method and the quality of the process used to implement the method varied greatly. This likely influenced the survey results.

Students were also asked to evaluate the usefulness of each step in the WordTree Method (Figure 83), rate the value of various design methods (Figure 84) and state the likelihood they would use the method in the future (Figure 85). They generally felt the steps were somewhat useful and that the steps are more useful for a design problem requiring an innovative solution. The WordTree Method was given medium value. Virtually all of the methods were perceived to have greater value for design problems that require innovative solutions than for the design problems the students were working on in class. The differences are statistically significant using t-test comparison ($p<0.05$).

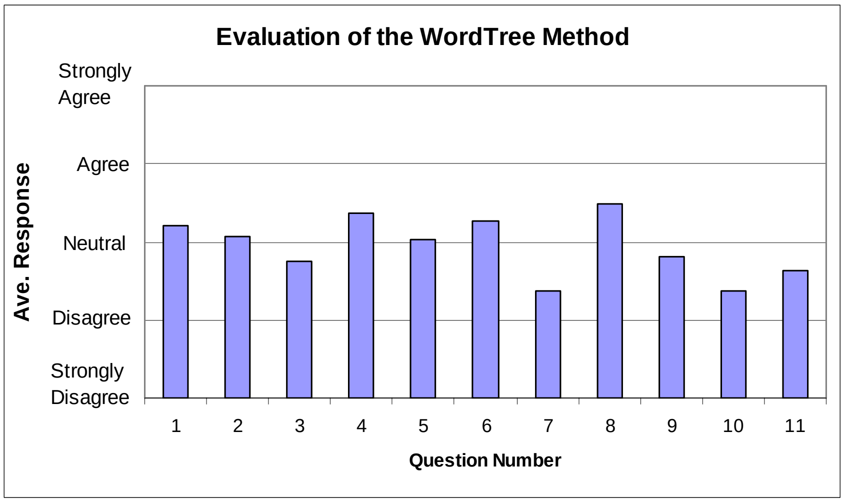


Figure 82: Student opinions regarding the WordTree Method. Questions listed in Table 22.

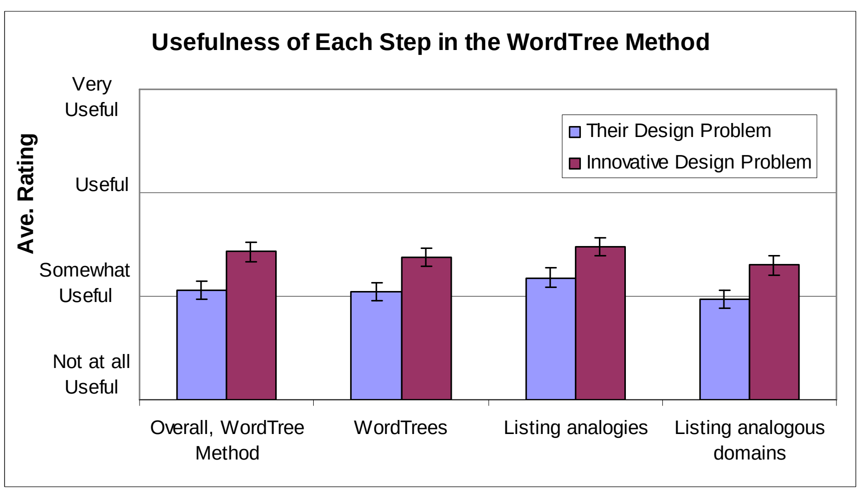


Figure 83: Most individuals felt the various steps in the method were somewhat useful. Each error bar is +/- one standard error (n=67).

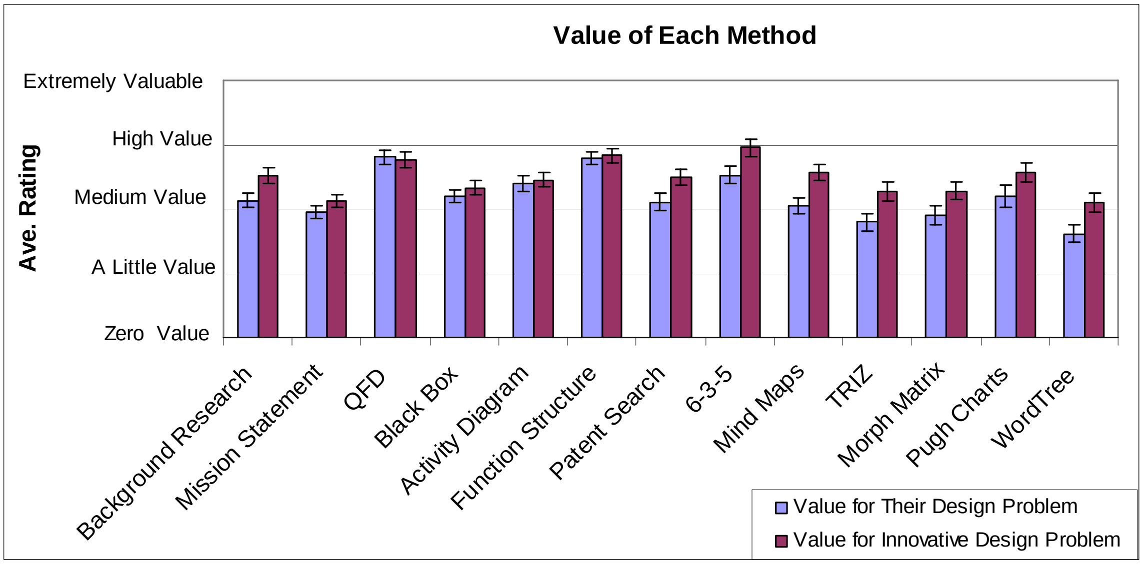


Figure 84: The WordTree Method was given a medium value rating. The methods were generally rated as having greater value for innovative design problems. Each error bar is +/- one standard error (n=67).

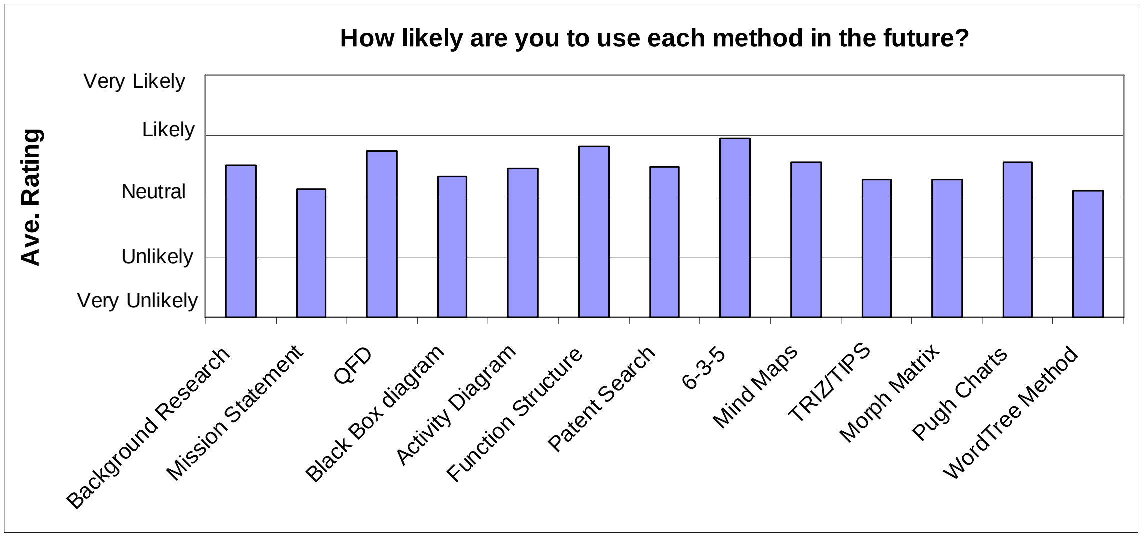


Figure 85: Participates were asked how likely they were to use each method in the future (n=67).

CONTROLLED EVALUATION

To further understanding the effects and benefits of the WordTree Design-by-Analogy Method, a controlled experimental study was undertaken. The prior evaluations provided confidence that the WordTree Method could produce useful analogies and enhance a designer's conceptual design ability. The controlled experiment compared the WordTree Method to having participates generate ideas without the method.

Procedure

The WordTree Method was taught to the Senior Design Projects Class during one 50 minute lecture. This version of the method did not include idea generation with a design team that had not seen the original design problem (this aspect of the method was not evaluated). Participants were recruited from the Senior Design Projects Class 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 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 email sessions that occurred as control groups prior to lecture and the other half received session times after the WordTree lecture. Participants who missed their first session time or signed up later were assigned to available time slots. Two participates were assigned to the WordTree group sessions but did not attend the WordTree lecture so they were run in the control condition but their data was not included in the results. Participants knew this was a new method being evaluated.

The design problem was to develop a device to shell peanut for use in third world countries, identical to the Group Idea Generation Experiment problem in Chapter 3. Participants in both conditions were guided by the experimenter using scripted instructions. They 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 minutes participates 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. At the end of the session, participants were asked to record their search strategy including what terms they searched for and which 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.

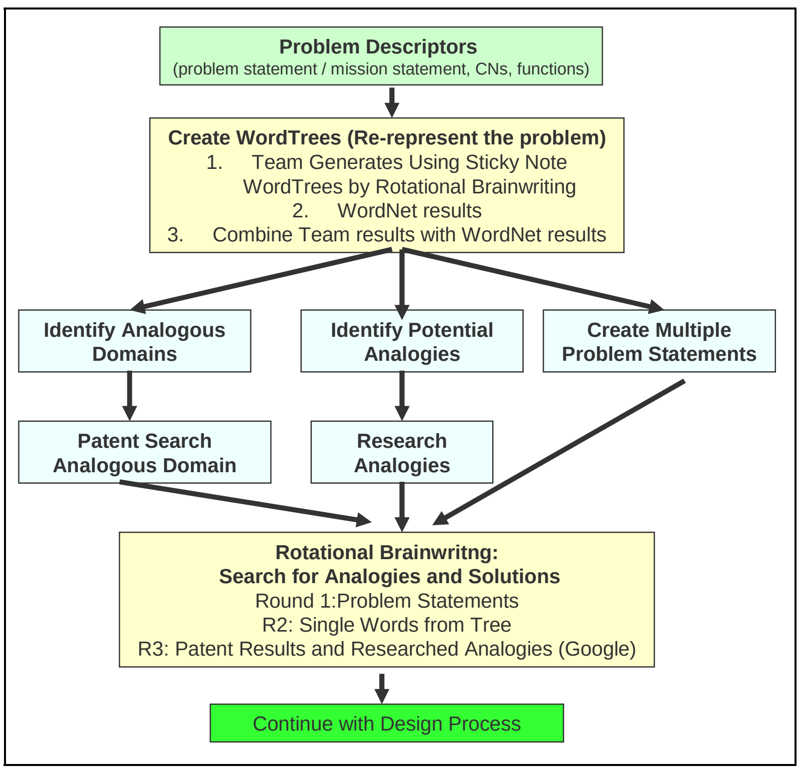


Figure 86: WordTree Method used for the controlled evaluation.

When participants decided to end idea generation, the time was recorded and they were given a sheet asking them why they decided to end 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. Participants were run in groups of one to five individuals and were given a five minute break after 60 minutes. This first session lasted about two hours.

Participants in the control group were told to generate ideas and analogies using any method they learned in the design methods class. The control group had a total of ninety minutes for idea generation. Throughout the entire session for both groups, the color of pens being used was switched every fifteen minutes so that the time an idea occurred could be documented.

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 WordTree for the following Key Problem Descriptors (20 minutes):
    - Shell
    - Remove
    - Separate
    - Import energy
- Combine sticky not WordTree with WordNet WordTree (5 minutes)
- Identify and list potential analogies and analogies domains (10 minutes)
- Write new problem statements (10 minutes)
- Generate ideas (45 minutes)
- Generate ideas using database support if desired (15 minutes)

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. Complete WordTrees are shown in Appendix E and part of the "shell" WordTree is in Figure 87. The WordTrees are filtered versions of the words provided by WordNet and were chosen as a combination of words possibly relevant and miscellaneous words.

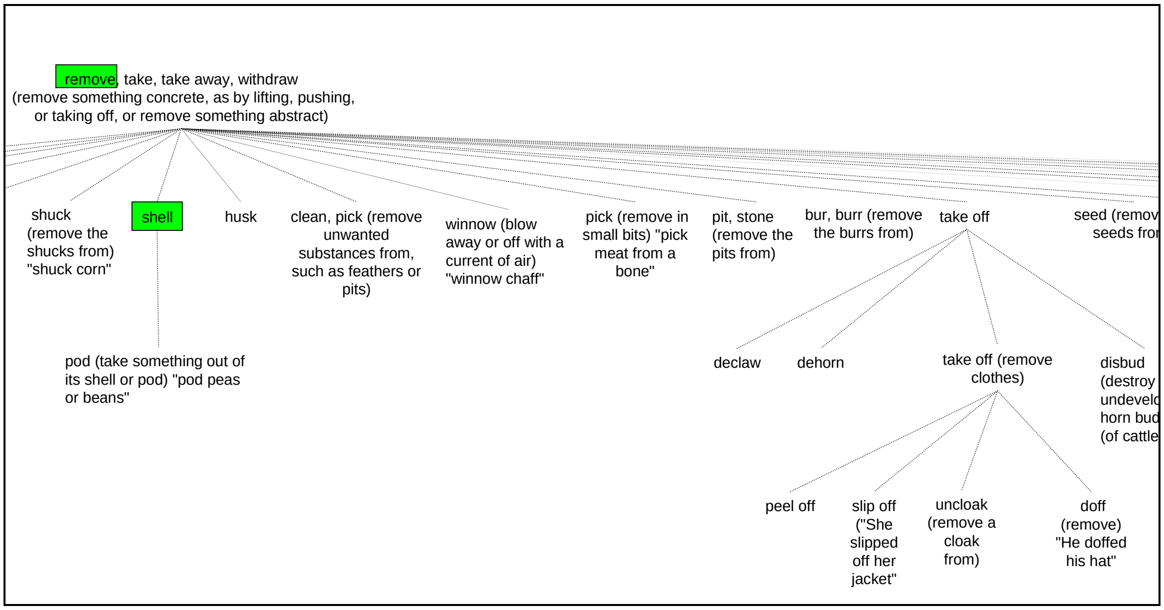


Figure 87: Part of the WordNet WordTree provided to the participants. See Appendix E for the complete WordTree.

During a second session hour-long session, participants documented the analogies they had generated, put all of their ideas into a morph matrix and filled out a post-session survey. The matrix contained some common pre-defined functions for the peanut shelling machine but participants were encouraged to add additional functions as needed. The survey was identical to the survey used in the Design Methods Class evaluation expect it only contain questions regarding the methods' use on a design problem requiring an innovative solution and asked if the students had seen the WordTree Method lecture. The participants' documentation facilitated measurement. When participants finished the list of analogies, morph matrix, and the survey, they were told to spend any remanding time generating ideas. This step prevented participants from rushing through these final steps.

Measures

The controlled experimental set-up allowed for quantitative and qualitative measures to be made. All metrics were scored by the author and the condition information was removed as much as possible during evaluation. 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 non-redundant analogies listed in either the first or second session.

The search strategy used by the participants was scored for containing words outside the domain of peanut shelling or not. Not all of the participants chose to use databases to assist them and a few of the participants' search strategies could not be determined. 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. The number of ideas generated was based on the number of boxes filled in for the morph matrix. The novelty, quality and variety of the resulting ideas were qualitatively evaluated.

Controlled Evaluation Results and Discussion

The number of analogies identified by the participants and the number of ideas is shown in Table 23 and Table 24. Participants in the WordTree condition found significantly more analogies than the control group. A t-test shows this difference to be statistically significant ($p<0.01$). Based on the participants' scores, the number of ideas did not vary between the two groups. All results shown are calculated for the first 60 minutes of idea generation. The control group had a total of 90 minutes for idea generation whereas the

WordTree group had only 60 minutes.

Table 25 shows the percentage of the analogies identified by the WordTree group that were implemented in solutions. Similar to the results from the design methods class, participants are not using the analogies to find solutions to the design problem.

Table 23: Number of analogies as scored by the participants and the evaluator.

	Evaluator Scores (S. E.)	**Raw Participant Scores (S.E.)**	**N**
Ave. Control	7.6 (4.8)	7.6 (4.8)	10
Ave. WordTree	25.0 (16.1)*	15.6 (13.2)	10

*statistically significant difference $p<0.01$

Table 24: Average number of ideas per person as indicated by the participants.

Condition	**Number of Ideas (s.e.)**
Ave. Control	16.2 (7.1)
Ave. WordTree	16.0 (8.6)

Table 25: The participants implemented only a small fraction of the analogies that they identified.

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

A coarse qualitative assessment indicated a difference in novelty, variety or quality was not likely between the two conditions. Therefore, a more robust quantitative assessment was not undertaken. In addition, the participants appear to not be using their listed analogies to support their concept generation which further supports the conclusion that the two conditions show similar levels of novelty, variety and quality.

Results from Database Searches

Table 26 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 Figures 89-92. The WordTree Method supports participates in finding novel cross-domain analogies and substantially modified their search strategy. Examples of terms within the domain of peanut shelling included shell, nut, peanut and crack. Terms that were considered outside the domain were peel, panning and winnowing. 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. They located the current solution for this problem which is Malian peanut shelling machine (Figure 91) and industrial large-scale solutions for peanut shelling.

All available data were included in this analysis for the entire time participants spent searching databases. This means that the WordTree group had a maximum of 15 minutes to find solutions whereas the control group had up to 45 minutes with most participants in the control group having at least 30 minutes. Not all participants chose to use the assistance of databases. Web history information was also used to evaluate the search strategy. Web histories were available for six of the participants.

Table 26: 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

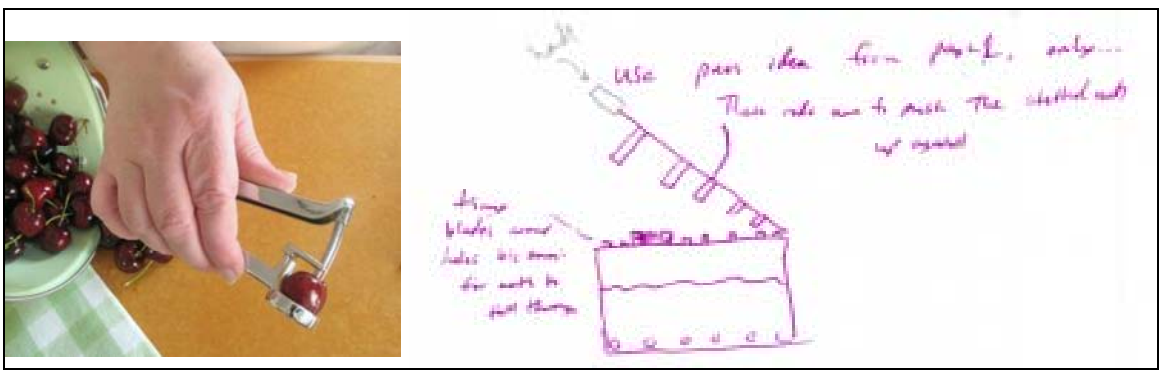


Figure 88: Another analogy identified and implemented by a participant in the WordTree group was a cherry pitting device (image source: “How to Pit Cherries”, 2007).

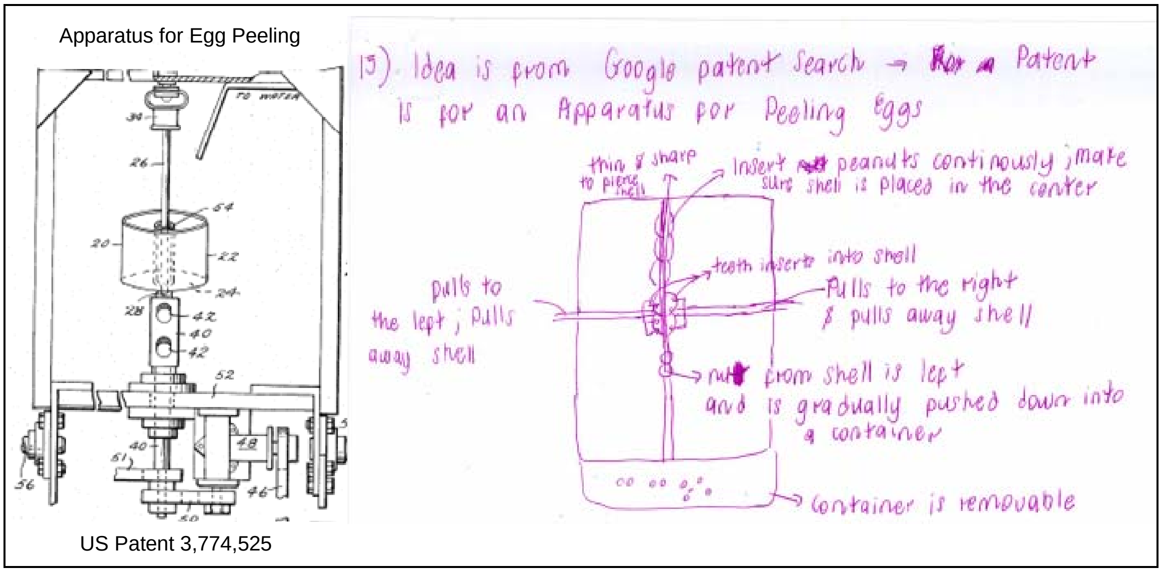


Figure 89: An analogous solution found by a participant in the WordTree group. The egg peeling device was used as an analogy to find a solution to the peanut shelling problem.

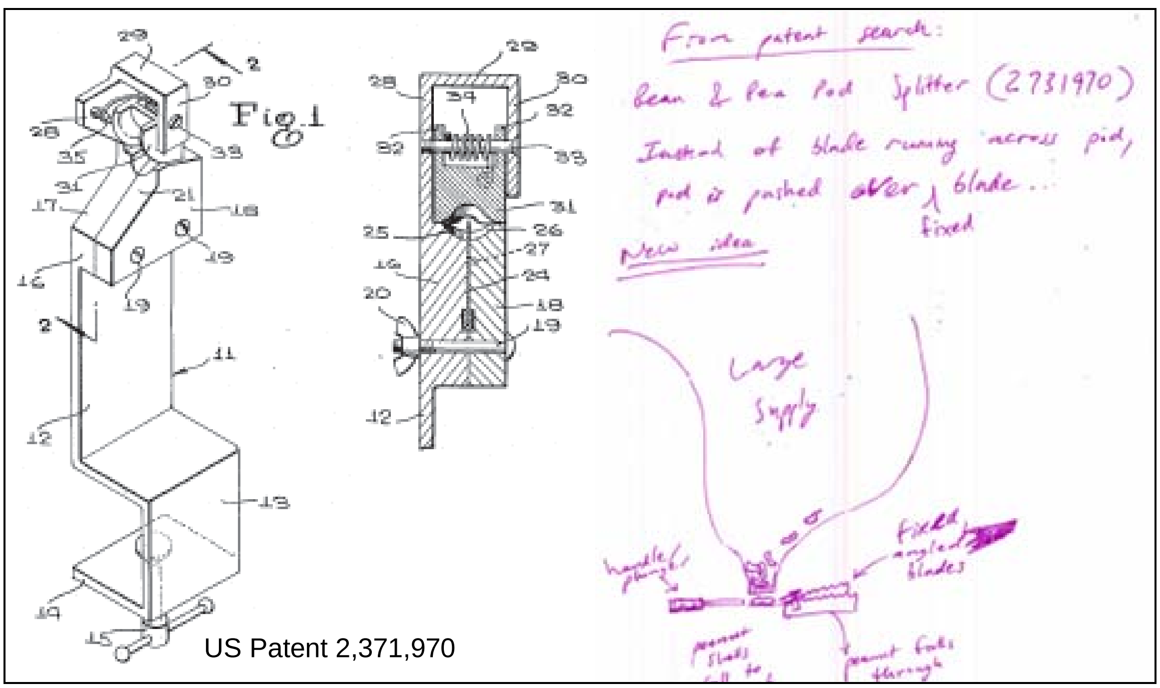


Figure 90: A device to split bean and pea pods, located by one of the WordTree condition participants, provides an analogous solution to the peanut shelling problem.

Figure 91: 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).

Figure 92: A search result from the control condition for an existing peanut shelling machine for developing countries (“The Appropriate Genius: Documentary,” 2007). This machine uses the same shell removing mechanism as the hand-powered device and also separates the shells and the nuts.

Survey

Figures 93-96 and Table 27 show the survey results for the WordTree Method. Some important results from Table 27 are the participants feel that the WordTree Method is more effective for finding analogies than the method they were taught in their Senior Design Methods class and the WordTree method is just as effective for producing high quality solutions. In their Senior Design Methods Class, they were introduced to the concept of analogy and given the current the state-of-art guidance in how to find analogies which is to seek analogies in nature and from similar products.

Table 27: Comparison of WordTree Method to method for design-by-analogy taught in the Senior Design Methods Class

	Most Effective Method (number of responses)		
	Method in Design Methods Class	**Both are Equal**	**WordTree Method**
Finding analogies	4	3	**12**
Generating ideas	**9**	**8**	2
Approach that felt most comfortable	**11**	6	2
Most willing to use in the future	**11**	5	3
Generating high quality ideas	5	**13**	1
Quickly generating ideas	5	**7**	**7**

No statistically significant differences for the survey results were obtained so all results are collapsed across the conditions. For example for the value of the WordTree

Method, the averages and standard errors were 1.9 (0.2) and 2.1(0.2) for the WordTree and Control conditions, respectively (Figure 95). Unexpectedly, greater experience with the method did not change the WordTree group's opinion of the method. Both groups had seen the same lecture presenting the method, but it is unexpected that greater experience with the method does not appear to influence the students' opinions. The participants' generally felt that the WordTree Method was valuable and helped them to generate more analogies (Figures 94 and 95).

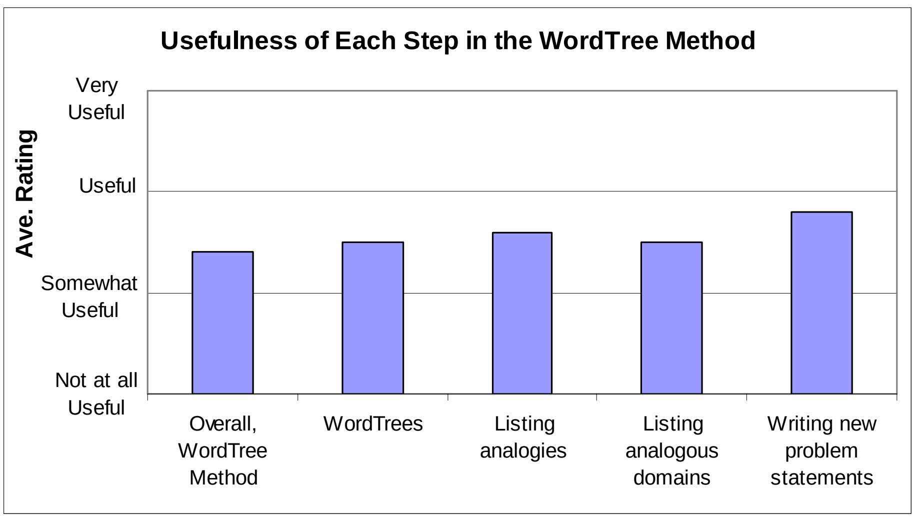


Figure 93: Usefulness of each step in the WordTree Method. This question was only given to the WordTree Condition.

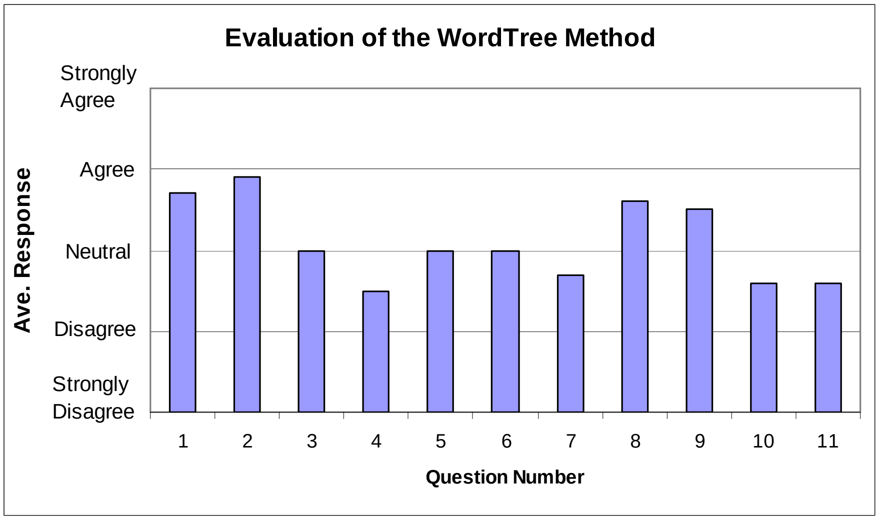


Figure 94: Participants evaluation of the WordTree Method. Questions are in Table 22.

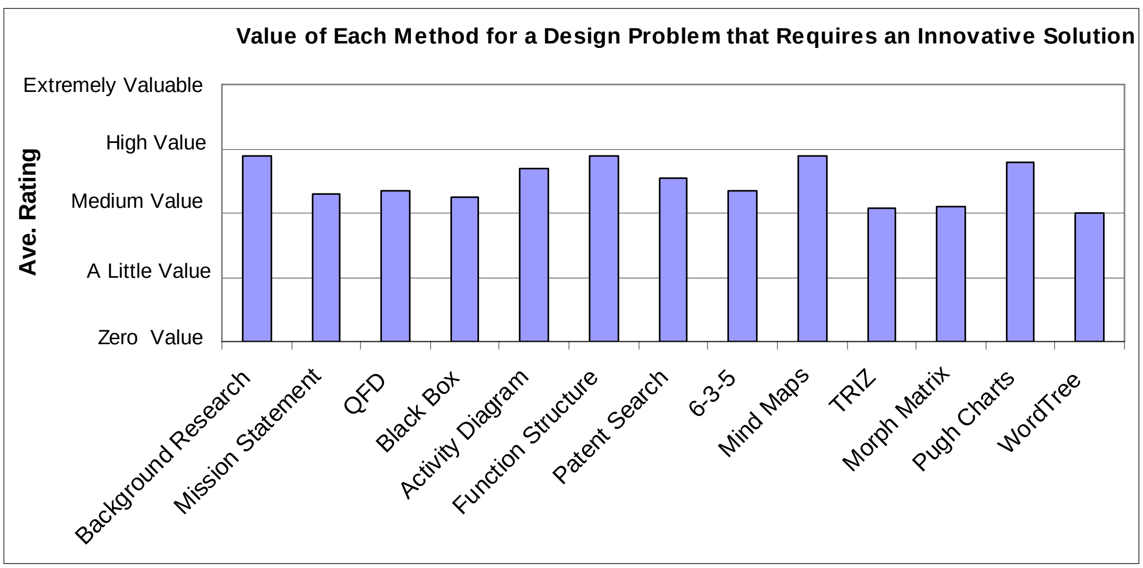


Figure 95: Participants were asked how valuable each method is.

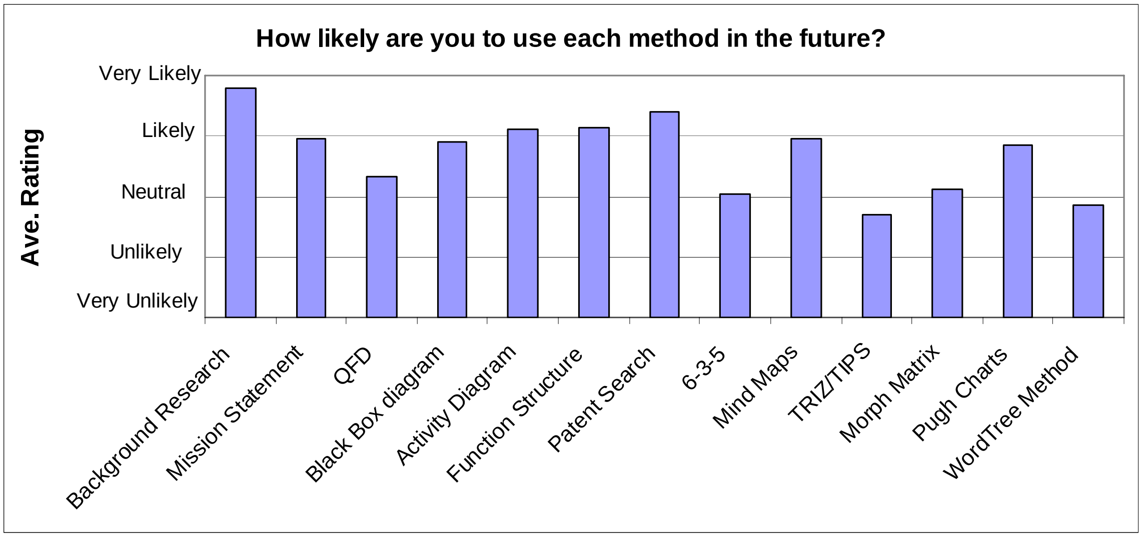


Figure 96: Participates were asked how likely they were to use each method in the future.

ADDRESSING THE RESEARCH QUESTIONS

Question 1: Does the WordTree Method increase the number of analogies identified? Does the WordTree Method produce unexpected, useful analogies and solutions? The WordTree Method increases the number of analogies identified by the designers. The controlled experiment showed a statistically significant increase in the number of analogies identified. The other evaluations and applications of the method illustrated a number of unusual and effective analogies found for the design problems.

Question 2: What are engineering designers' opinions of the method? The designers' who participated in the evaluation generally felt the method assisted them in finding analogies and was valuable. There was a variation in the opinions likely due in part to some of the designers' incorrect usage of the method which resulted in poor results.

Question 3: Does the WordTree Method change how designers search for solutions using databases? Designers who were using the WordTree Method used a distinctly different strategy for seeking analogous solutions. They expanded their searches to analogous domains which then provided novel analogies for them.

Question 4: Is there an increase in the novelty, variety and quality of the ideas produced by the WordTree Method. From the case study and the design methods class evaluation, it is clear the WordTree Method does lead to unexpected, novel, quality solutions. Qualitatively, the novelty, variety and quality of the ideas for the controlled experiment appear to be similar across the conditions. It is also noted that participates in the WordTree condition are using only a small fraction of the analogies they identify as a basis for ideas. This is a likely cause for the novelty, variety and quality to be similar across the conditions.

Question 5: What are some of the avenues for improvements to the WordTree Design-by-Analogy Method? As with any new method, there are avenues for improvement. A more streamlined and simplified version of the WordTree Method would be ideal. The presentation of the method needs to include more powerful examples and strongly highlight the high level purpose. For reasons that are not completely clear, the engineers are not effectively using the analogies they identify. The WordTree needs to support this process better.

CONCLUSIONS

The WordTree Design-by-Analogy Method provides a systematic approach for identifying analogies and analogous domains for a given design problem. Through re-

representation of the design problem, unexpected analogies and analogous domains can be explored. 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 and products being located. The case study demonstrates the potential of this method for a design problem that had previously been solved with other methods. Students in the Design Methods Class successful implemented the WordTree Method on their redesign projects and found unexpected analogies and analogous domains. The WordTree Method is a single powerful approach to the re-representation of the design problems and many other approaches are possible and will be future research.

Chapter 7: Conclusion and Future Work

Design-by-analogy is an important tool for innovation. Unfortunately, little guidance is available to systematically and predictably identify analogies and analogous domains for design problems. A new design-by-analogy method, the WordTree Design-by-Analogy Method, had been developed based on knowledge gained from a series of experiments and prior literature. The WordTree Method linguistically re-represents the design problem and leads the designer to unexpected, novel analogies and analogous domains. The following sections first detail the conclusions about the WordTree Method and then summarize the experiments used to derive the WordTree Method. Future work for the WordTree Method, additional idea generation techniques, analogy in design and methods is then discussed.

Conclusions: WordTree Method

The WordTree Design-by-Analogy Method guides engineers in seeking unexpected, innovative analogies to their design problems and supports analogous design. A controlled evaluation of the method highlighted the fact that the method assists designers in identifying more analogies and alters their database search patterns resulting in cross-domain solutions being found. Application of the method to a set of engineering projects resulted in unexpected, novel analogies and solutions. Participants found cross-domain analogies for their redesign projects and felt the method had value. Other participants working on industrial sponsored projects were able to find additional analogies and solutions after they believed they were finished with the concept generation process. An analogy uncovered was adapted into a team’s final design concept. While the method is beneficial in its current form, the evaluations illustrated areas where the method could be improved and designers need more support. These evaluations also exposed new research questions.

Conclusions: Design-by-Analogy Experiments

A key outcome from the design-by-analogy experiments is that the representation of the problem statement plays an important role in a designer's ability to recall and use analogous solutions. These results provide an avenue to enhance design-by-analogy thereby increasing innovation. The experiments' results also show learning analogies in more domain-general linguistic representations increases success when solving novel design problems. The representation of the design problem that increases success depends on how the analogy is stored in memory. Therefore, multiple representations of the design problem will maximize the chances of finding effective, innovative analogies.

Conclusions: Group Idea Generation Experiment

Engineering design occurs in a team setting due to the complexity of the problems and the speed at which products are delivered to market. Teams have a greater knowledge base than any of their individuals. Any created design method needs to be implemented in a team setting and ideally exploits this. It was therefore important in the development of a design-by-analogy method to have an effective approach for team idea creation. The choice of group idea generation method significantly impacts the total quantity of ideas and number of high quality ideas. Over a 40 minute session, 50% more ideas are generated using rotational viewing combined with ideas being described with words and sketches as compared to using only words displayed gallery style. This experimental condition corresponds to a hybrid 6-3-5/C-Sketch method. In contrast, more high quality ideas result when all concepts are displayed on the wall (gallery viewing) and represented using only sketches. These results suggest an improved process for concept generation consists of first using a gallery communication method to generate a large number of high quality concepts and then moving to a rotational viewing method using words and sketches to develop the details of the concepts and a large number of ideas.

The group idea generation study also shows that both individual and group interactions are important in the idea generation process. As group members add ideas, the overall concept becomes more complete and improves. Participants do not simply create their own concepts in isolation. An equal or greater number of new ideas are developed that build upon or are directly influenced by other group members. Visualizing others' ideas produces even more ideas is not just an anecdote. The data shows that group member's ideas "spark" other members to a greater level of productivity. The experiment also found a strong correlation between the number of concepts a team produced and the number of high quality concepts. This pattern may not hold for all idea generation methods but does support the principle of seeking a large quantity of ideas.

FUTURE WORK

The experiments answered a number of research questions while at the same time uncovering numerous directions for future research. While the WordTree Method enhances analogous design, areas for improvement were uncovered and additional evaluation is needed. The WordTree Method is an approach for re-representing design problems. A series of other options for re-representation exist. Analogy in design is a rich and high impact area that deserves serious further study. Ultimately, to be more effective in all of these areas, better methods and metrics for design research are required. The subsections detail the future research in these areas.

Future Work on the WordTree Method

The WordTree Method is effective for increasing the number of analogies identified but much work is still needed. The method needs to be streamlined and better support the mapping of identified analogies into solutions. The method needs to more clearly emphasize the purposes of the WordTrees, which is to provide other ways of conceptualizing the design problem to identify analogies and ultimately novel solutions. More research is needed to determine why the participants tended to identify a large number of analogies but then a high percentage did not inspire conceptual solutions. This could be caused by the designers' lack of experience with the method or a lack of skill in design-by-analogy. The designers could also be prematurely judging the analogies as impractical solutions and therefore focusing their efforts elsewhere.

Guidance needs to be provided for what to do when WordNet does not provide helpful results and how to take better advantage of the inherent structure in WordNet. Further evaluation of the method is required. Evaluation needs to be completed with experienced engineers to obtain their opinions and illicit the benefits for a more experienced group. Other available databases should be explored in identifying analogies, for example, the Analogical Thesaurus which is based on HowNet (Veale, 2006).

Idea Generation Methods Future Work

Idea generation methods require a significant amount of future work to understand the currently available approaches and to expand the repertoire of techniques. The WordTree Method is a single approach to linguistically re-represent the design problem. The experiments showed that functional models have great potential for supporting design-by-analogy. The series of experiments also gives insights for other potential enhancements to idea generation. The analogy experiments used a series of constraints in the design problems to reduce the design space, thereby increasing the probability a solution would be found. An insight from this experiment is to create a design method that systematically adds and removes constraints from a design problem so that various sections of the design space are explored.

Group Idea Generation Future Work

Additional work to more fully understand the various idea generation methods is required. Two factors are explored in the group idea generation study but many more are present in the methods, including periods of discussion for clarifying ideas. Further evaluation is needed to understand the influence of limiting communication to sketches and to more fully explain the pattern of results for the sketch-only conditions.

The form used to represent ideas may cause biases in the metrics and needs to be evaluated. An investigation is needed to evaluate if judges tend to measure concepts as higher in quantity based on the form of representation, the quality of the sketch or handwriting. A second bias could be due to student behavior. One reason that sketches combined with words may result in more ideas is students may tend to inherently include more support functions when sketching then when writing ideas in words. This may benefit the design process but could bias idea generation results. One possible test for this would be to ask students to make a sketch of an idea on one sheet of paper and then to write a verbal description of the same idea on a separate sheet of paper.

In the area of brainwriting techniques, there is much to explore and understand. Brainwriting techniques could potentially be effective approaches for group communication but work still needs to be done to validate this. The results from the brainwriting approaches explored in the study need to be compared with the non-redundant results from equal number of participants working individually (known as nominal groups). Data from the controlled WordTree experiment can be used as a preliminary evaluation since the same design problem was used in both experiments.

Physical Models

The use of physical materials, models and prototypes in the idea generation process is an intriguing area for future research. Engineers and other designers use a variety of physical objects during the development process. These range from simple physical representations that are quickly developed, much like a sketch, to full scale working prototypes. Little research exists on the benefits and limitations provided by physical models. Certain types of ergonomic and geometry configuration problems are obvious with physical models but many times difficult to spot with other representations. Open questions include: Do simple physical models behave in a manner similar to sketches which act as external memory storage? Do physical models also implicitly provide more accurate models of the physical phenomena being explored? Do they cause fixation on certain aspects of the design or is the apparent fixation related to the design process stage? Are the effects similar for a very rough model compared to a full-scale working prototype? Why are physical artifacts used and how do they support the design process in various design fields including engineering, industrial design and architecture?

Physical models are likely useful for correcting any incorrect mental models the engineer has and for off-loading the working memory, allowing more of the engineer's mental resources to be focused on generating and exploring ideas rather than mental simulation. This research will be explored through a combination of highly controlled studies and less controlled, longer term design team measurements. Controlled studies will be used to lead engineers through a set of prescribed idea generation approaches using sketches and physical models. The major goal and outcome of this thread of research would be sets of guidelines for when physical models should be built and what features and characteristics need to be represented accurately.

Analogy in Design Future Work

Much work is left unfinished in understanding and improving the use of analogy for innovative design. Individual skill in analogical reasoning varies greatly. Currently this is a large noise factor in the experiments. Cognitive measures are required to measure this skill. This will allow noise reductions in the experiments and also create a measure for determining how various methods increase an individual's skill in this area. Numerous other questions surround analogy usage.

Finding the Non-Standard Inferences, Multiple Inferences, Evaluating and Revising Analogy Inferences

A given analogy can produce multiple inferences. Occasionally, when the same analogy is given to a number of participants, a few designers will create very novel and unusual solutions. A few participants are able to find highly unique and unexpected solutions (Figure 97). In particular, how do we assist designers in training their thought processes to generate such solutions? What type of cognitive models can better represent this process to include the highly unexpected results?

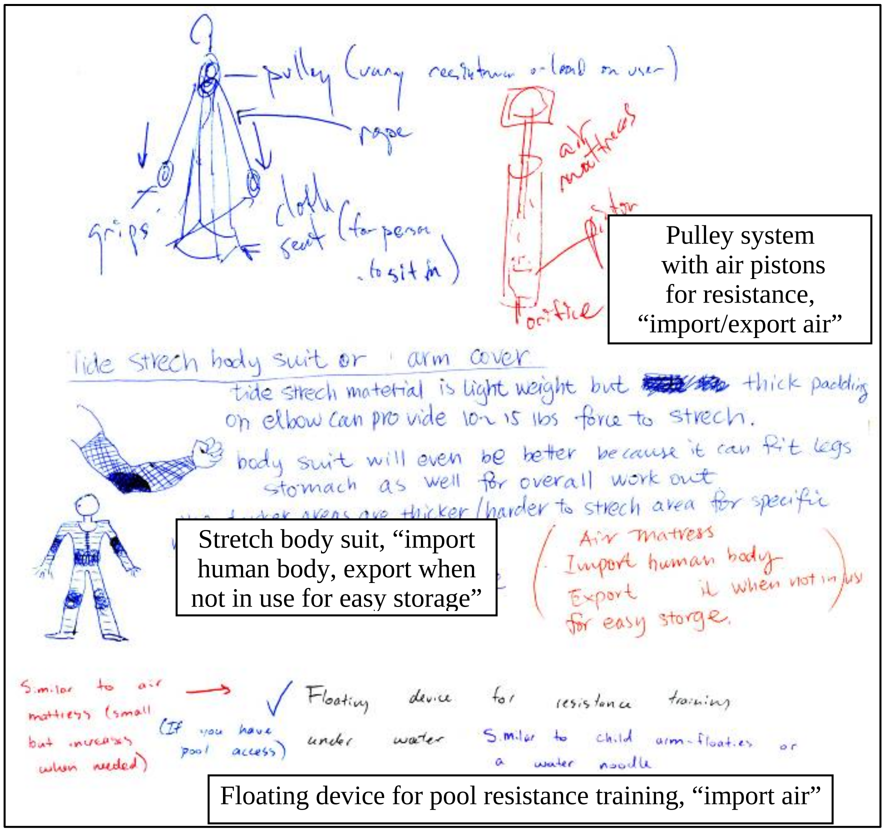


Figure 97: Unique solutions to the constrained problem of designing exercise equipment that can be carried in a suitcase.

Once an analogy is retrieved and an inference is made, how can designers create a multitude of inferences from the single analogy? Many times in the experiments, the designers were able to retrieve an appropriate analogy but were unable to make an effective inference. Other times they mapped inappropriate, too many or too few of the features from the analogy. How can designers be taught to re-evaluate their analogies to create better inferences and search in more promising areas of the design space?

Influences on the design by analogy process

Design-by-analogy is a complex process with numerous factors influencing the outcome. The analogy between the airplane and the kayak design illustrate the influence of domain knowledge and expertise in this process. This warrants further experimental exploration. A long-term goal should be to develop a cognitive model that accounts for all of these variables and parameters. Clearly, the information that is available to and stored in a designer's memory has a clear impact on the design by analogy process. Common solutions (Dugosh and Paulus, 2005; Perttula and Sipila, 2007) and category exemplars (Ward, 1998) also influence the idea generation process but cognitive models are not available to determine when these effects dominate. Individual ability plays a role. The analogy experiments indicate a few of the additional factors influencing design-by-analogy including the effects of and the interactions of visual information. A deeper understanding of the cognitive abstraction process would support further developments in design methodology. A design method is needed to highlight areas where domain knowledge is lacking and approaches for facilitating the recognition of the underlying principles would also enhance the design process.

Design Education

The series of studies in this thesis have many implications for design education and open new research questions. From the group idea generation experiment, the importance of sketching in engineering communication is highlighted. The results from both the group idea generation study and the analogy studies clearly demonstrate the general lack of skill in sketching that most undergraduates posses. Drawing communication needs to be taught as a part of engineering communication skills.

More research needs to be done to determine effective approaches for engineers as they learn about new products. The analogy studies showed that the way an engineer learns about a product determines how easily the analogous solution can be retrieved from memory and used to solve a novel design problem. Teaching methods need to be developed that provide engineers with systematic approaches to help highlight more domain general ways of thinking and learning about the products they encounter.

Methods and Metrics for Understanding and Evaluating Design

Methods and metrics for design research need continued improvement. Many metrics currently used are reliable but are relative to the data set being measured. The novelty and variety metrics used for the group idea generation experiments measure relative to the design space found by the participants. Novelty is a function of the frequency that an idea occurred. This relative metric is not effective for comparing the WordTree Method to a control condition since certain ideas would occur frequently in the WordTree group but not in the control condition. A novelty score could be calculated for the WordTree condition based on the frequency of the ideas occurring in the control condition. An absolute measure would be more effective but requires research.

External validity for a given metric to positive design outcomes are not well-established. Ideal metrics are highly repeatable and valid, and easily measured on an absolute scale not relative to the design problem, experiment or data set. Engineering provides an analogy for establishing how to approach understanding and correlating the behavior of a system in the real-world to that of a laboratory. Improvements to the safety and performance of cars and airplanes have been made through an understanding of parameters such as vehicle speed, wind conditions and road conditions that influence the system’s behavior prior to and during an accident. Laboratory experiments have been used to develop and establish important metrics and measures. Once the metrics are established, they will be correlated with real-world measurements including black box data recorders that invisibly measure critical data allowing detailed accident reconstruction. A long term goal in design research needs to be to define instruments that unobtrusively provide critical information about the design process. These scales need incremental development starting with repeatable metrics that are relative to a particular data set, moving ultimately to absolute metrics that are easily measurable.

APPENDICES

Appendix A: Group Idea Generation Experiment Materials

Note: Pages from the experiment materials were cropped to reduce required space.

PARTICIPANT INSTRUCTION SHEETS

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

What you need to do:

Round 1:

- Use sketches and words to describe at least two ideas.
- Put one idea on each page.
- Hand in your sketches as you finish them.
- You will have 10 minutes for this round 1.

Rounds 2,3,4,5:

For these round you can do one of three things:

1. Add your ideas either as sketches or words to one of the posted drawings. Request a drawing by writing down its number on the small sheets of white paper.

2. Make a separate drawing that is related to the ideas that are already posted. In the corner write down the number of the ideas or ideas it is related to.

3. Start a completely new sheet with a new ideas.

At the end of each round you will hand in the idea you are working on and switch to a new idea.

Experiment 5

EXPERIMENTER SCRIPT- GALLERY VIEW, SKETCHES ONLY

Participant Instructions-Experiment 3

Explain What the Session is about

- This session is being used to test idea generation methods and to find the best method.
- If you are uncomfortable with any part of this experiment you are not required to participate
- A new method will be described to you and then you will be given a design problem to solve using the prescribed method.
- This is a real problem that does not have a good solution available. Your ideas may be given to design teams trying to solve this problem.

Rules/Goals

- **Briefly I will go over a few basic rules and goals for this session.**
- The goal is to generate as many solutions as possible with as high of quality as possible and with as great of variety as possible.
- Wilde, technically infeasible and far out ideas are also encouraged. This helps to generate unique feasible solutions.
- You are not allowed to criticize other people's ideas and you are not allowed to write negative comments.
- Do not laugh at anyone ideas or drawings
- No talking during the session expect when I ask if you have any questions.
- You are encouraged to build people from other people's ideas and to add variations or improvements to those ideas.

Any questions?

Describe the method

- During this session I will be able to identify your ideas but your teammates will not be able to.
- In the first round you will be given 10 minutes to draw **sketches only** to describe at least two ideas to solve the design problem.
- All of the solutions will be displayed on the wall. Please sure to draw large enough so everyone can see your ideas.
- You will then continue to generate more ideas by building off other people's ideas or generating new ideas.
- After the initial round you can do one of three things:
    - 1. Add your ideas as sketches to one of the posted drawings. Request a drawing by writing down its number on the small sheets of white paper.
    - 2. Make a separate drawing that is related to the ideas that are already posted. In the corner write down the number of the ideas or ideas it is related to.
    - 3. Start a completely new sheet with a new ideas.

Use of Colors (show examples as the options are described)

- You're using markers because they help increase the size of your words and sketches making it easier for everyone to see your pictures when they are posted.
- The colored markers can be used any way you would like.
- You can only use your set of markers.
- Some ways that color can be use are shown on this piece of paper.
- Color can be used to shown different parts of a design.
- It can also be used to shown variations on an idea. In this drawing the handle shape had been changed and the square holes have been changed to round holes.
- Color can also be used to help explain an ideas such as coloring water blue.

Any questions?

Describe the problem

- This is a real problem that does not have a good solution.

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

Round 1

- You will be given 10 minutes to **sketch** two ideas to solve the design problem.
- Put one idea on each page.
- Your ideas will be posted on the wall so be sure to write big enough so other people can see them
- You can give me your sketches as you finish them. I will 30 seconds before the end of the round so you can finish your idea.

What I need to be doing:

- *Collecting the drawings*
- *Numbering the drawings as they are collected*

- *calling time,*

*****Collect Black Pens at the end of this round.*

Round 2 and beyond (*These are reviewed right after the first round)*

- You will have 7.5 minutes to work and then you will be asked to hand in the idea you are working on and switch to a new idea
- For this round you can do one of three things:
  - 1. Add your ideas as sketches to one of the posted drawings. Request a drawing by writing down its number on the small sheets of white paper.
  - 2. Make a separate drawing that is related to the ideas that are already posted. In the corner write down the number of the ideas or ideas it is related to.
  - 3. Start a completely new sheet with a new ideas.

- *I need to record the order that the ideas are posted (number them as them come in) 11, 12, 13, 14, 15, 16*
- *I need to record the time they are posted*
- *Write down who I give the various sheets to*
- *Return the sheets to the same spot on the wall*
- *Number new sheets*
- *I am letting them request the drawing they were just working on*

Questionnaire

- Some questions are the same and some are similar but not exactly the same.
- I have a copy of your Myers-Briggs results if you do not remember which personality type you are.

End of Session

- Please do not discuss the idea generation problem with anyone else until May 7^{th} because if you discuss this with them it will invalidate the experimental results.
- All of the methods I am testing fall into the category of Brainwriting techniques.
- These type of techniques may be very useful when one or two group members tend to dominate a group or you have a group member or two that tends to be shy.
- This is not a hypothesis of the experiment. I am testing these type of techniques because they have been shown to generate more ideas than brainstorming with group sizes greater than four people.
- Any thing you would like to ask about?

Items to set-up ahead of time

1. 5+ sheets of paper marked with the starting point for each of the five seats
2. Sheets of paper to request ideas.
3. Markers

4. Have pins ready/ cut tape
5. Number sheet ready to go

Pre-Session Checklist

- ☐ 5 Marker Sets
- ☐ Extra Markers
- ☐ 5 Sets of Paper and Extra Paper
- ☐ Pins/Masking tape
- ☐ Stop watch
- ☐ Post-Session Surveys
- ☐ Digital Camera
- ☐ Number and Time sheet
- ☐ MBTI sheets
- ☐ Honor Code
- ☐ Slips of Paper
- ☐ What to do with the colors sheet
- ☐ Stapler

Post-Session Checklist

- ☐ Post-Session Surveys
- ☐ Take Picture of the wall

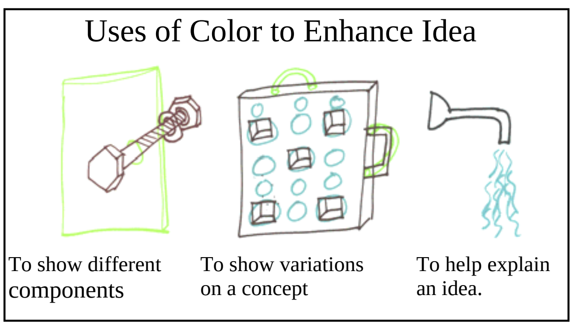


Figure 98: Participants were given examples of how to use the assortment of colored markers.

Sketched Examples of Known Solutions to Peanut Shelling Problem

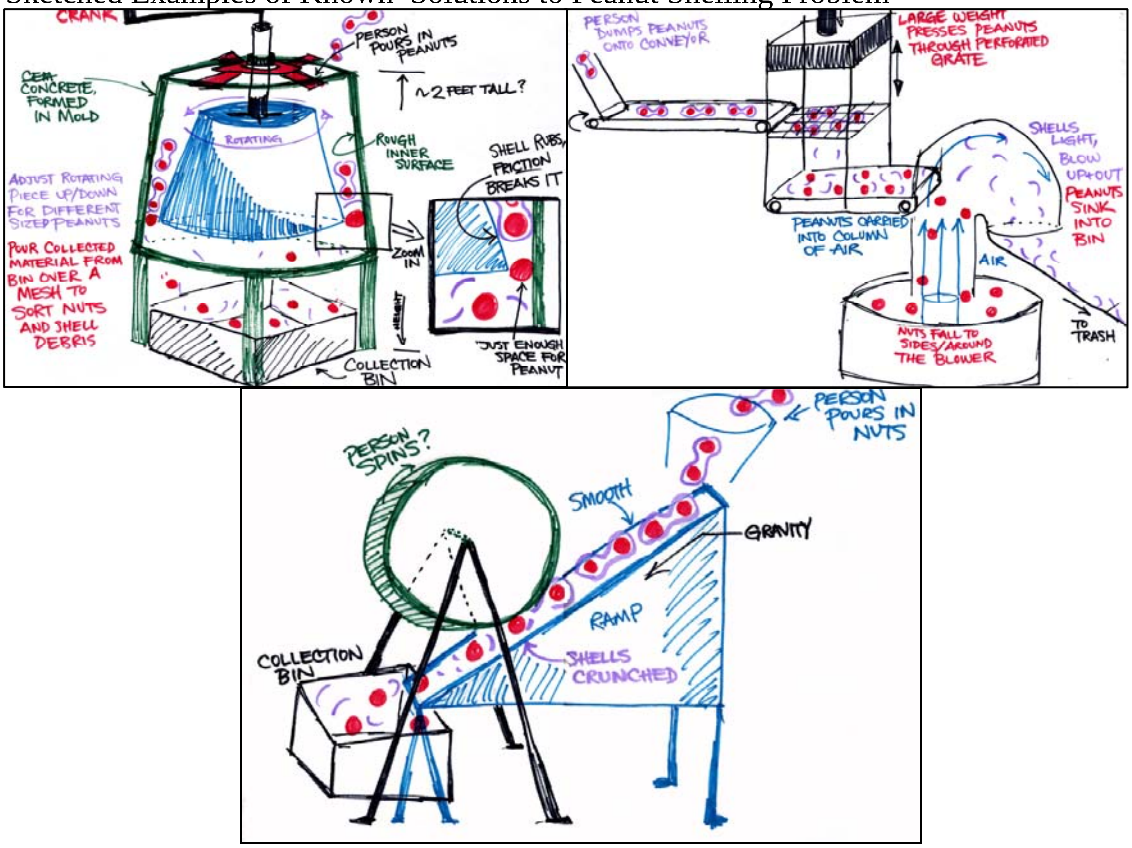


Figure 99: Three example solutions found on the web for the peanut shelling problem (“Full Belly Project”, 2006; American Peanut Council,” 2006; DelHagen, Hussam, Mohdramli &Yi, 2003).

SURVEY FORMS

SURVEY FOR CONDITIONS WITH SKETCHING

Put an X in the box that most represents your feelings on the given topic. Your responses to this survey will have no bearing on the extra credit you are given for this session.

What you thought of this idea generation session

Fun						Boring
Not Interesting Problem						Interesting Problem
Easy						Difficult
I had enough time						I did not have enough time

About your teammate's ideas

I can identify my teammate's ideas						I cannot identify my teammate's ideas
I cannot identify my teammate's ideas by their writing						I can identify my teammate's ideas by their writing

How did you perform during this session

Worked hard						Did the minimum
Felt Motivated						Not at all motivated

Circle your answer.

1. Did you feel any apprehension about generating your ideas?

A lot of Apprehension		Neutral/ undecided		No Apprehension
1	2	3	4	5

2. How at ease were you during the idea generation session?

Definitely not at ease		Neutral/ undecided		Very at ease
1	2	3	4	5

3. Did you hear about this design problem before the experiment? Please answer honestly. This will have no effect on the credit you are given for participation.

Yes No If Yes, did you try to generate ideas before the session began? Yes No

4. Did you use any technique you learned previously (such as analogies or search by physical principle) to help you generate ideas?

Yes No If yes, what technique? ________________________

5. Rate the following techniques on a scale from 1 to 9, you can use 2.5, 4.0, 3.75 etc.

1 is a technique you like the most.
5 is a technique you neither like nor dislike
9 is a technique you dislike the most:

__ Method used in this session
__ 6-3-5/C-Sketch
__ Brain Mapping
__ Analogies
__ TIPS
__ Brainstorming
__ Morph Matrix
__ External Search/Benchmarking
__ Other (please fill in) ______________

6. Male/ Female

7. Myers-Briggs Personality: Introvert/Extrovert, Sensor/Intuitor, Thinker/Feeler, Perceiver/Judger, Don't Remember, Prefer Not to Answer

Mark the answer that best represents how you feel about each of the statements below. Your responses to this survey will have no bearing on the extra credit you are given for this session.

		Strongly Disagree	Disagree	Neutral	Agree	Strongly Agree
1	During the session I tried to identify my teammates' ideas.					
2	I can identify my teammates' ideas by their handwriting.					
3	Completing this idea generation session was boring.					
4	I enjoy generating ideas.					
5	During this idea generation session, my ideas were ignored by my teammates.					
6	Helping to solve this design problem was not important to me.					
7	My teammates can identify my ideas by my handwriting.					
8	I helped contribute to the solution of this problem.					
9	My team tends to ignore the ideas of certain group members.					
10	I was concerned about what the other group members would think of my ideas.					

11	I generated as many ideas as I could in the given amount of time.					
12	I felt that my ideas were ignored less by my team than in the past.					
13	I can identify my teammate's ideas.					
14	I was not concerned about what the facilitator would think of my ideas.					
15	I liked using the multiple colors.					
16	I could have worked harder during this session.					
17	I cannot identify my teammates' ideas.					
18	My teammates cannot identify my ideas.					
19	The extra colors did not enhance the idea generation process.					
20	Using the method in this session my team ignored ideas of certain members more than in the past.					

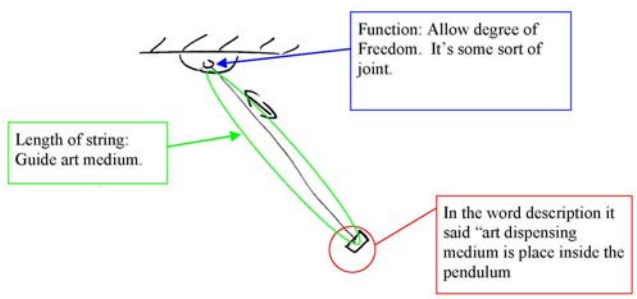
Please make any comments you would like to about the idea generation session. Use the back of the paper if necessary.

DATA EVALUATION GUIDELINES

Counting Rules for Quantity of Ideas Contained in a Sketch

1.	Each idea must meet one of the functions in the functional basis
2.	An idea can meet either a primary or secondary function
3.	Each idea or component counts as only one idea even if it solves more than one function
4.	New combinations of previous concepts do not count as ideas
5.	Categories only count as ideas when no subordinates are given. For examples saying use a "gear" and then listing "spur gear, and worm gear" counts as 2 ideas not 3. If instead only "gear" was listed then this would count as 1 ideas.
6.	A component being used in multiple places counts as one idea

- **If ideas or components are mentioned in the problem statement then they do not count (none were listed for the CGI data).**
- Identifiable components / ideas
  - Count identifiable components as an idea when it meets a function
  - Count components/ideas even if they are not needed or cause the system not to function.
  - **Components usually occur when lines cross or when one line ends at a continuous line.**



  - **Be sure the break-down of an idea is shown and not just implied. The break down of idea or component must be explicitly described verbally or drawn. Each piece of a sketch or description must have an identifiable function.**

- Function sharing

- Count each idea only once even when it meets more than one function. **A component that serves more than one function counts as only one idea**.

- Categories
  - If only the category is given, count it as one idea. **(For example electric machines or gears are categories)**
  - If a category and items in the category are given count only the items as ideas. **(For example if use a gear is given and use a spur gear or a helical gear is also given, this counts as only 2 ideas not 3)**
  - Mark the categories

- Primary and secondary functions
  - Count all ideas that meet either a primary function or a secondary support function. *The functional basis we are using is only for the primary functions of a product and does not include the secondary and support functions.*

- Ideas that do not specifically address the described problem
  - Count them if they are related to the situation such as:
    - Environmental concerns relate to the situation
    - Reduction in waste products resulting from solutions to the problem
    - Another method to address the situation.

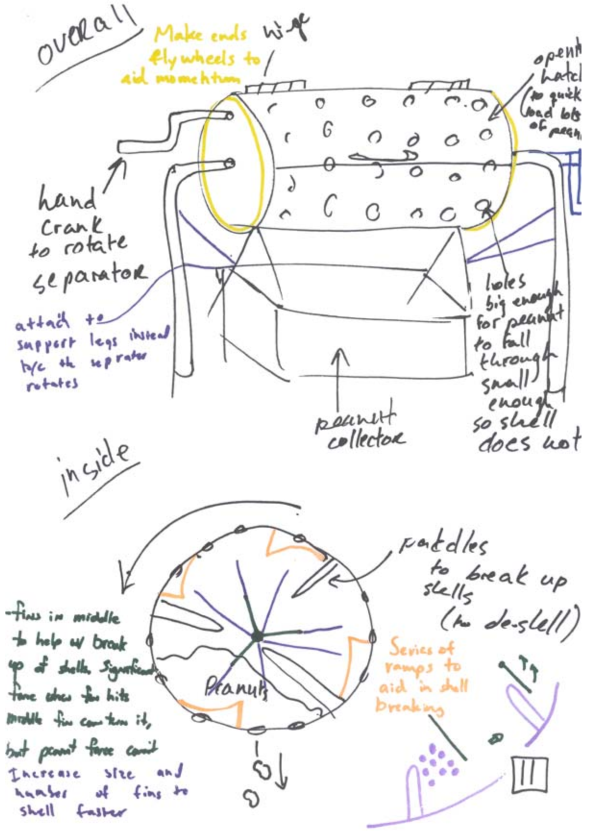
- Combinations of previous ideas
  - **When the only change between ideas is a new combination of previous ideas mark it as "New combination only".** Count new combinations as a separate measure. **one sheet to the next

- When the same idea/component is used in more than one place:
  - Count it only as one idea

- **For ideas that reframe the problem such as producing a slightly different product or ways to reduce waste product, count these in a separate category call *"Problem Reframing."* These will usually be ideas that do not specifically address the describe problem**
  - **These will usually not meet a function.**
  - **They must add something to the system.**
  - **Count them if they are related to the situation such as**
    - **Environmental concerns relate to the situation**
    - **Reduction in waste products resulting from solutions to the problem**
    - **Produce a slightly different product.**

- **For the data where there are words only, if a new color is used and there is not identifiable idea, add one to the new color category.**

EXAMPLE RESULTS WITH ASSOCIATED METRICS



List of Ideas within the Concept
• ramps
• handle
• door
• fixed fins
• rotating fins
• rotating drum
• container
• filter holes
• support legs
• container hangers
• flywheel
• hinge
• pivot
• hand crank
Metrics for this Concept (Rater 1, Rater 2)
• Quality= 2, 2
• Novelty= 0.992, 0.952

Figure 100: Example of one sketched concept and the list of ideas contained within the concept.

Appendix B: Analogy Experiment 1 Materials

Note: Pages from the experiment materials were cropped to reduce required space.

PILOT PARTICIPANT INSTRUCTION SHEET: DOMAIN

Task 1 part A: Study the devices

Participant #: ☐

In this experiment you will complete the following three tasks and a 5-minute survey:
Task 1: Learn about and study a set of products. You will then be asked to recall the verbal descriptions.
Task 2: Evaluate a series of conceptual designs.
Task 3: Develop concepts for a few products.

Multiple colors of writing implements are being used to keep track of when items are written. If you have any questions at any time during this experiment, please ask.

Task 1: Read the descriptions for how the following five devices work. These devices may be familiar to you, but you may not have thought about the details of how they work. After studying how the devices work, you will be asked to **recall the verbal description of each device**. You may read and study each device for as long as you would like. Please let the experimenter know when you are finished studying all the devices.

Kitchen flipper

This spatula meshes with the hand and slides between the pancake and the pan. It also supports the pancake and allows the pancake to be flipped.

Air Mattress

The air bed is inflated with air in the home where it will be slept on. The air required to cause the air bed to inflate is available in the home. The primary purpose of the air bed is to provide a comfortable bed for the person. The air bed accomplishes this by using the air to inflate and deflate the air bed. This allows the device to be easily put into a closet.

Deflated and rolled-up air mattress

Deflated air mattress laying flat

Inflated air mattress

Air mattress being stored in a closet

Football

A person throws the American football. As it flies through the air it spirals. This spiraling reduces air friction allowing the ball to travel more.

Travel Cart

The travel cart carries a large suitcase easily. The bottom and the wheels fold-up causing the travel device to have a smaller volume. The handle telescopes to fit in an overhead storage bin.

Whisk

The whisk scoops up and adheres to the batter.

The whisk adheres to the batter while it is translated to the waffle iron.

The whisk is rotated and the clumps within the batter are strained as the batter drips from the whisk.

The batter is covering the waffle iron surface.

Task 1 part B: Recall How the Device Works

From memory, reproduce the descriptions of the devices that you just read.

Kitchen flipper

Air Mattress

Football

Travel Cart

6

Whisk

Task 1 part C: Solutions

Compare your descriptions to the ones shown on the following pages. What is different and what is similar? Look at the sentences you wrote. Give yourself one point for each of your sentences that are generally correct. Write the number of generally correct sentences on the following solution pages.

Number of Correct Sentences for this device: ________

Kitchen flipper

This spatula meshes with the hand and slides between the pancake and the pan. It also supports the pancake and allows the pancake to be flipped.

Number of Correct Sentences for this device: ________

Air Mattress

The air bed is inflated with air in the home where it will be slept on. The air required to cause the air bed to inflate is available in the home. The primary purpose of the air bed is to provide a comfortable bed for the person. The air bed accomplishes this by using the air to inflate and deflate the air bed. This allows the device to be easily put into a closet.

Number of Correct Sentences for this device: ________

Football

A person throws the American football. As it flies through the air it spirals. This spiraling reduces air friction allowing the ball to travel more.

Number of Correct Sentences for this device: ________

Travel Cart

The travel cart carries a large suitcase easily. The bottom and the wheels fold-up causing the travel device to have a smaller volume. The handle telescopes to fit in an overhead storage bin.

10

Number of Correct Sentences for this device: ________

Whisk

The whisk scoops up and adheres to the batter.

The whisk adheres to the batter while it is translated to the waffle iron.

The whisk is rotated and the clumps within the batter are strained as the batter drips from the whisk.

The batter is covering the waffle iron surface.

Group the concepts into a set of 5 piles based on how similar the solutions in terms of them solving the design problem in a similar manner. Put the most similar solutions into the same pile.

The design problem was to develop a conceptual solution for a device to quickly shell peanuts in a third-world country.

Once you have a set of piles, rate how similar the piles are to each other on a scale of 1-little similarity to 7-very similar.

Piles 1 & 2	
Piles 1 & 3	
Piles 1 & 4	
Piles 1 & 5	
Piles 2 & 3	
Piles 2 & 4	
Piles 2 & 5	
Piles 3 & 4	
Piles 3 & 5	
Piles 4 & 5	

Task 3: Design Problem 1

Design Problem 1

Design a piece of exercise equipment that can be carried in a suitcase. Sketch and/or use words to describe your ideas. Spend about 10-15 minutes generating ideas. Please let the experimenter know when you are finished.

Design Problem 1- Additional Constraints

- Design a piece of exercise equipment that can be carried in a suitcase.
- This device must provide at least 15 lbs of resistance but add less than 4 lbs to the suitcase.
- It must take up very little space when it is packed in a suite case.
- Maximum volume is 120 in^3 (~750 cm^3) or about half the size of a briefcase.
- It must be capable of being used for exercises normally done with hand weights (see example exercises below).
- It can not use an elastomer (for example, rubber) for resistance.

You need to find only one solutions that meets this constraint. If any of the solutions you generated previously meet this constraint, put a check mark next to the solution and move on to the next design problem.

Design Problem 2

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

Design Problem 2- Additional Constraints

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

You need to find only one solution that meets this constraint. If any of the solutions you generated previously meet this constraint, put a check mark next to the solution and move on to the next design problem.

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

Design Problem 3- Additional Constraints

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

You need to find only one solution that meets this constraint. If any of the solutions you generated previously meet this constraint, put a check mark next to the solution and move on to the next design problem.

If you used any analogies to generate some of your solutions write a description of the analogy next to your design. For example a pair of scissors could be used as an analogy for designing a finger nail clipper. If you had used this analogy, you would write "scissors" next to your solution.

In addition, if you did not use analogies to solve each of the constrained design problems try and see if you can find at least one analogy for each problem.

Some of the products shown in the first task (studying the products) of this experiment can be used as analogies to develop solutions to the constrained design problems. See if you can find a solution based on the products shown in the first task. Also write down which product is analogous. If you already found a solution using products from the first session just place a check next to the solutions and be sure to list which product was used for the analogy.

Shown below is a list of the design problems and the product from the first task that can be used to find a solution to the constrained design problem. If you found a solution to the design problem using the product listed below place a check next to your solution. If you did not, see if you can use the analogies given below to find a solution.

Design Problem 1- Analogy is the Air Mattress

Design Problem 2- Analogy is the Football

Design Problem 3- Analogy is the Whisk

Post-Session Questions

1. How many years have you lived in an English-speaking country? _________ years

2. How many languages are can you either speak and/or read fluently? __________

3. How many years ago did you first learn English? _________ years

4. How much engineering work experience (experience not part of a class) do you have?
   Full-time (40 + hrs/week) engineering work (internships or full-time work)
   _________months __________years
   Part-time (less than 40 hrs/week) engineering work
   Part time experience 1_________hrs/week
   _________months __________years

   Part time experience 2_________hrs/week
   _________months __________years

   Part time experience 3_________hrs/week
   _________months __________years

   Part time experience 4_________hrs/week
   _________months __________years

5. How experienced are you with functional modeling? How many functional models have you done?
   - ☐ 0 functional models: No experience or no idea what a functional model is.
   - ☐ 1-3 functional models: A little experience
   - ☐ 4-6 functional models: Some experience
   - ☐ 7+ functional models: A lot of experience

6. Have you seen or heard of any of the following products before this experiment?


AquaBells® Travel Weights ☐ Yes ☐ No

Gyro Towable Tube ☐ Yes ☐ No


Precision Mini-Sifter ☐ Yes ☐ No

Please state any additional comments you have about the experiment. Use the back of the paper if needed.

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PILOT PARTICIPANT INSTRUCTION SHEET: GENERAL

Task 1 part A: Study the devices

Participant #: ☐

In this experiment you will complete the following three tasks and a 5-minute survey:
Task 1: Learn about and study a set of products. You will then be asked to recall the verbal descriptions.
Task 2: Evaluate a series of conceptual designs.
Task 3: Develop concepts for a few products.

Multiple colors of writing implements are being used to keep track of when items are written. If you have any questions at any time during this experiment, please ask.

Task 1: Read the descriptions for how the following five devices work. These devices may be familiar to you, but you may not have thought about the details of how they work. You will also be asked to draw a simple function structure for each device. After studying how the devices work and drawing function structures you will be asked to **recall the verbal description of each device.** You may read, draw function structures and study each device for as long as you would like. Please let the experimenter know when you are finished studying all the devices and drawing the function structures.

<u>Device to separate and move object</u>

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

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

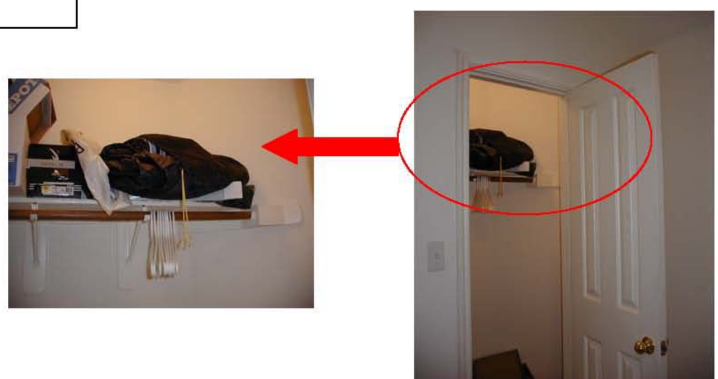
<u>Device to import and export a substance</u>

The device is filled with a substance at the location where it will be used. The substance required to cause the device to function is available at the location. The primary purpose of the device is to distribute the force of the person during the task. The device accomplishes this by importing, storing and exporting the substance. This allows the device to be easily stored.

Device after exporting the substance and being compacted

Device after exporting the substance laid flat

Device after importing the substance



Device being stored

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

<u>Moving Device</u>

Another object gives energy to this device. As it moves through a substance it turns about. This motion changes the forces allowing the device to move more.

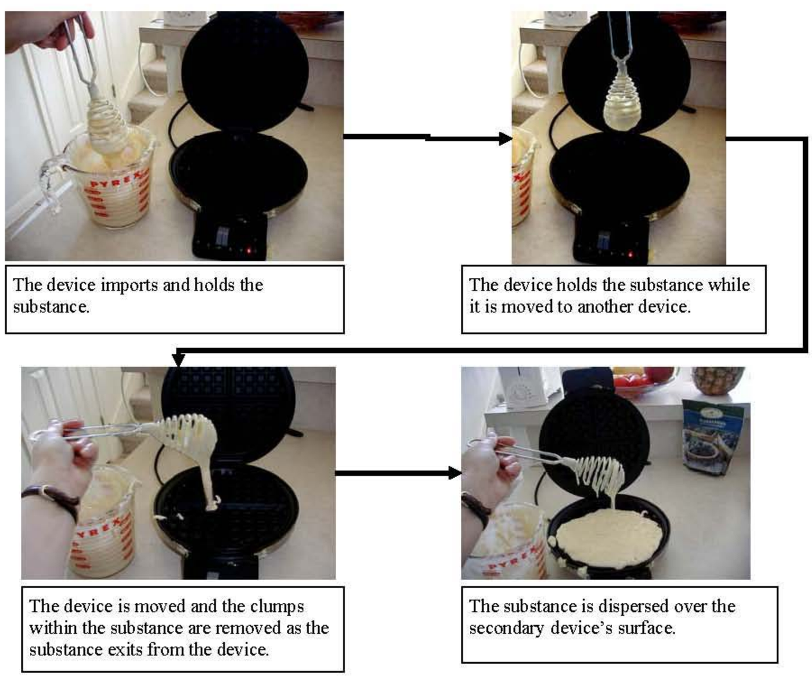
Draw a function structure for this device. Remember each box in the function structure has a function (a verb) in it. Be sure to use the functions (the verbs) given in the device description.

Load positioning device

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

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

Device to import and hold substances



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

Task 1 part B: Recall How the Device Works

From memory, reproduce the descriptions of the devices that you just read.

Device to separate and move object

Device to import and export a substance

Moving device

Load positioning device

Device to import and hold substances

Task 1 part C: Solutions

Compare your descriptions and function structures to the ones shown on the following pages. What is different and what is similar? Look at the sentences you wrote. Give yourself one point for each of your sentences that are generally correct. Give yourself one point for each of the functions in your function structure that is generally correct. Write the number of generally correct sentences and functions on the following solution pages.

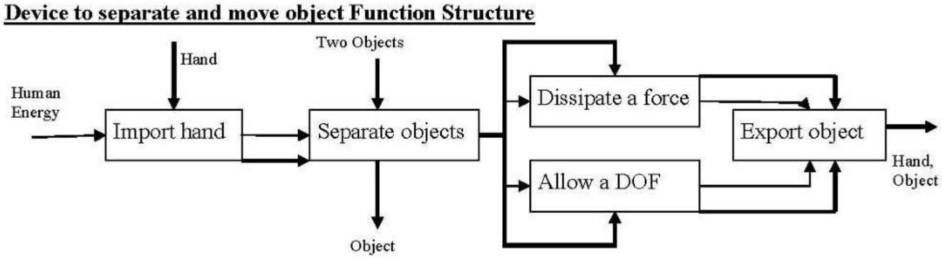
Number of Correct Sentences for this device: ________

Number of Correct Functions for this device: ________

Device to separate and move object

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

Device to separate and move object Function Structure



Number of Correct Sentences for this device: ________

Number of Correct Functions for this device: ________

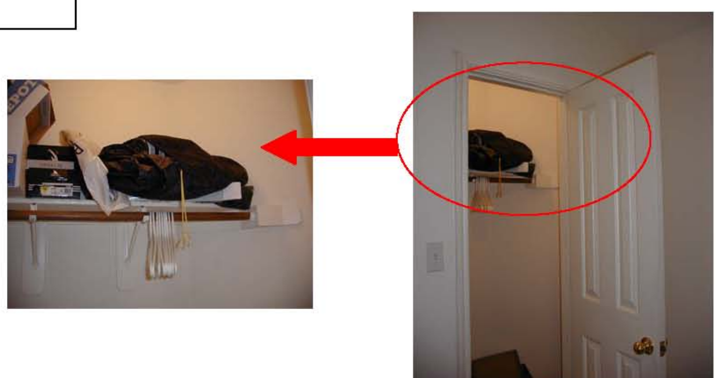
<u>Device to import and export a substance</u>

The device is filled with a substance at the location where it will be used. The substance required to cause the device to function is available at the location. The primary purpose of the device is to distribute the force of the person during the task. The device accomplishes this by importing, storing and exporting the substance. This allows the device to be easily stored.

Device after exporting the substance and being compacted

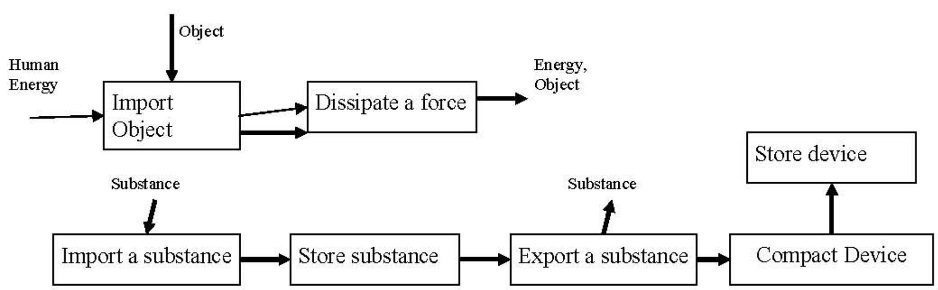
Device after exporting the substance laid flat

Device after importing the substance



Device being stored

<u>Device to import and export a substance Function Structure</u>



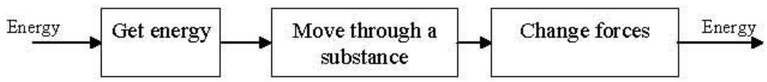
Number of Correct Sentences for this device: ________

Number of Correct Functions for this device: ________

<u>Moving Device</u>

Another object gives energy to this device. As it moves through a substance it turns about. This motion changes the forces allowing the device to move more.

<u>Moving Device Function Structure</u>



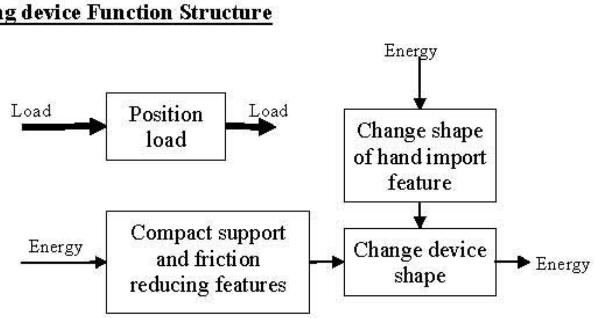
Number of Correct Sentences for this device: ________

Number of Correct Functions for this device: ________

<u>Load positioning device</u>

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

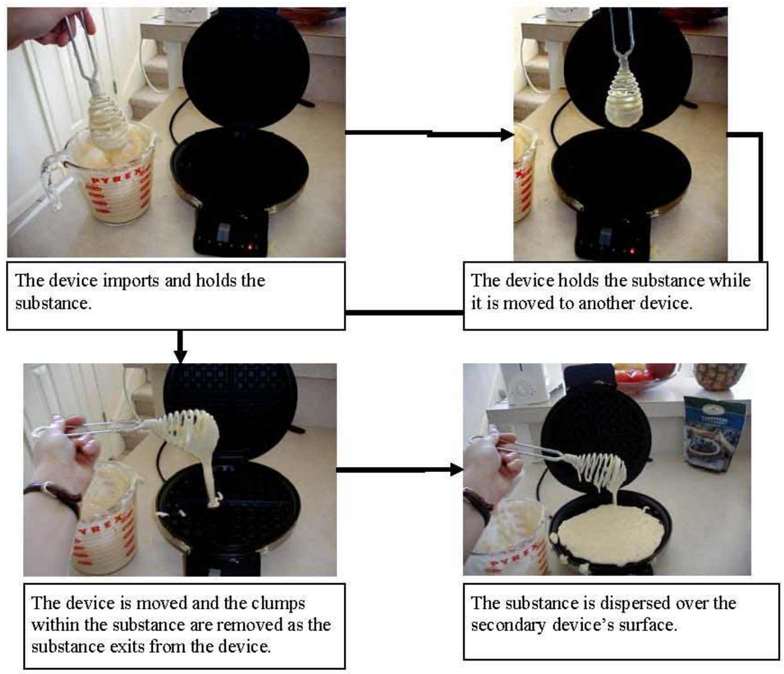
<u>Load positioning device Function Structure</u>



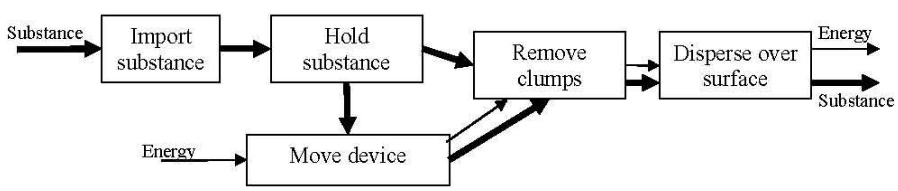
Number of Correct Sentences for this device: ________

Number of Correct Functions for this device: ________

<u>Device to import and hold substances</u>



<u>Device to import and hold substances</u>



Group the concepts into a set of 5 piles based on how similar the solutions in terms of them solving the design problem in a similar manner. Put the most similar solutions into the same pile.

The design problem was to develop a conceptual solution for a device to quickly shell peanuts in a third-world country.

Once you have a set of piles, rate how similar the piles are to each other on a scale of 1-little similarity to 7-very similar.

Piles 1 & 2	
Piles 1 & 3	
Piles 1 & 4	
Piles 1 & 5	
Piles 2 & 3	
Piles 2 & 4	
Piles 2 & 5	
Piles 3 & 4	
Piles 3 & 5	
Piles 4 & 5	

Task 3: Design Problem 1

Design Problem 1

Design a piece of exercise equipment that can be carried in a suitcase. Sketch and/or use words to describe your ideas. Spend about 10-15 minutes generating ideas. Please let the experimenter know when you are finished.

Design Problem 1- Additional Constraints

- Design a piece of exercise equipment that can be carried in a suitcase.
- This device must provide at least 15 lbs of resistance but add less than 4 lbs to the suitcase.
- I must take up very little space when it is packed in a suite case.
- Maximum volume is 120 in^3 (~750 cm^3) or about half the size of a briefcase.
- It must be capable of being used for exercises normally done with hand weights (see example exercises below).
- It can not use an elastomer (for example, rubber) for resistance.

You need to find only one solutions that meets this constraint. If any of the solutions you generated previously meet this constraint, put a check mark next to the solution and move on to the next design problem.

Design Problem 2

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

Design Problem 2- Additional Constraints

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

You need to find only one solution that meets this constraint. If any of the solutions you generated previously meet this constraint, put a check mark next to the solution and move on to the next design problem.

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

Design Problem 2- Additional Constraints

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

You need to find only one solution that meets this constraint. If any of the solutions you generated previously meet this constraint, put a check mark next to the solution and move on to the next design problem.

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

Design Problem 3- Additional Constraints

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

You need to find only one solution that meets this constraint. If any of the solutions you generated previously meet this constraint, put a check mark next to the solution and move on to the next design problem.

If you used any analogies to generate some of your solutions write a description of the analogy next to your design. For example a pair of scissors could be used as an analogy for designing a finger nail clipper. If you had used this analogy, you would write "scissors" next to your solution.

In addition, if you did not use analogies to solve each of the constrained design problems try and see if you can find at least one analogy for each problem.

Some of the products shown in the first task (studying the products) of this experiment can be used as analogies to develop solutions to the constrained design problems. See if you can find a solution based on the products shown in the first task. Also write down which product is analogous. If you already found a solution using products from the first session just place a check next to the solutions and be sure to list which product was used for the analogy.

Shown below is a list of the design problems and the product from the first task that can be used to find a solution to the constrained design problem. If you found a solution to the design problem using the product listed below place a check next to your solution. If you did not, see if you can use the analogies given below to find a solution.

Design Problem 1- Analogy is the Air Mattress (Device to import and export a substance)

Design Problem 2- Analogy is the Football (Moving Device)

Design Problem 3- Analogy is the Whisk (Device to import and hold substances)

Post-Session Questions

1. How many years have you lived in an English-speaking country? _________ years

2. How many languages are can you either speak and/or read fluently? __________

3. How many years ago did you first learn English? _________ years

4. How much engineering work experience (experience not part of a class) do you have?
   Full-time (40 + hrs/week) engineering work (internships or full-time work)
   _________months __________years
   Part-time (less than 40 hrs/week) engineering work
   Part time experience 1_________hrs/week
   _________months __________years

   Part time experience 2_________hrs/week
   _________months __________years

   Part time experience 3_________hrs/week
   _________months __________years

   Part time experience 4_________hrs/week
   _________months __________years

5. How experienced are you with functional modeling? How many functional models have you done?
   - ☐ 0 functional models: No experience or no idea what a functional model is.
   - ☐ 1-3 functional models: A little experience
   - ☐ 4-6 functional models: Some experience
   - ☐ 7+ functional models: A lot of experience

6. Have you seen or heard of any of the following products before this experiment?


AquaBells® Travel Weights ☐ Yes ☐ No


Gyro Towable Tube ☐ Yes ☐ No


Precision Mini-Sifter ☐ Yes ☐ No

Please state any additional comments you have about the experiment. Use the back of the paper if needed.

PARTICIPANT INSTRUCTION SHEET: DAY 1, DOMAIN

Month and day of your birthday ☐☐ ☐☐

You will learn about a set of products. You will then be asked to **recall the verbal descriptions.**

Please do not discuss this experiment with your classmates until after Saturday, Nov. 19th.

Multiple colors of pens are being used to keep track of when items are written. If you have any questions at any time during this experiment, please ask.

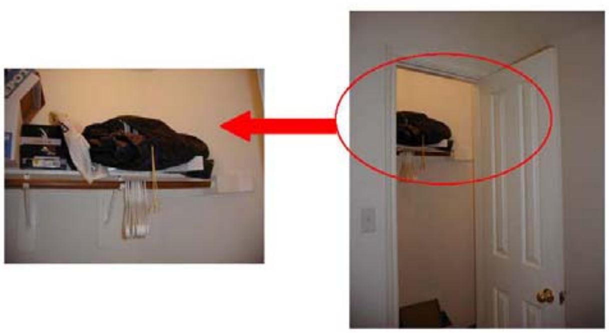
Task 1: Read the descriptions for how the following five devices work. These devices may be familiar to you, but you may not have thought about the details of how they work. After studying how the devices work you will be asked to **recall the verbal description of each device.** You will have **30 minutes** to complete this task.

Kitchen flipper

This spatula meshes with the hand and slides between the pancake and the pan. It also supports the pancake and allows the pancake to be flipped.

Air Mattress

The air bed is inflated with air in the home where it will be slept on. The air required to cause the air bed to inflate is available in the home. The primary purpose of the air bed is to provide a comfortable bed for the person. The air bed accomplishes this by using the air to inflate and deflate the air bed. This allows the device to be easily put into a closet.

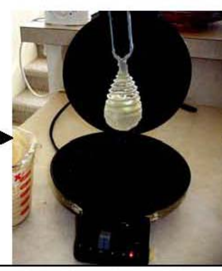


Football
A person throws the American football. As it flies through the air it spirals. This spiraling reduces air friction allowing the ball to travel more.

Travel Cart
The travel cart carries a large suitcase easily. The bottom and the wheels fold-up causing the travel device to have a smaller volume. The handle telescopes to fit in an overhead storage bin.

Whisk

The whisk scoops up and adheres to the batter.



The whisk adheres to the batter while it is translated to the waffle iron.

The whisk is rotated and the clumps within the batter are strained as the batter drips from the whisk.

The batter is covering the waffle iron surface.

Recall How the Device Works

From memory, **reproduce the verbal descriptions** of the devices that you just read.

Kitchen Flipper

Air Mattress

Football

Travel Cart

Whisk

Solutions

Compare your descriptions to the ones shown on the following pages. What is different and what is similar? Look at the sentences you wrote. Give yourself one point for each of your sentences that are generally correct. Write the number of generally correct sentences on the following solution pages.

Number of Correct Sentences for this device: ________

Kitchen flipper

This spatula meshes with the hand and slides between the pancake and the pan. It also supports the pancake and allows the pancake to be flipped.

Number of Correct Sentences for this device: ________

Air Mattress

The air bed is inflated with air in the home where it will be slept on. The air required to cause the air bed to inflate is available in the home. The primary purpose of the air bed is to provide a comfortable bed for the person. The air bed accomplishes this by using the air to inflate and deflate the air bed. This allows the device to be easily put into a closet.

Number of Correct Sentences for this device: ________

Football

A person throws the American football. As it flies through the air it spirals. This spiraling reduces air friction allowing the ball to travel more.

Number of Correct Sentences for this device: ________

Load positioning device

The travel cart carries a large suitcase easily. The bottom and the wheels fold-up causing the travel device to have a smaller volume. The handle telescopes to fit in an overhead storage bin.

PARTICIPANT INSTRUCTION SHEET: DAY 1, GENERAL

Month and day of your birthday ☐☐ ☐☐

You will learn about a set of products. You will then be asked to **recall the verbal descriptions.**

Please do not discuss this experiment with your classmates until after Saturday, Nov. 19th.

Multiple colors of pens are being used to keep track of when items are written. If you have any questions at any time during this experiment, please ask.

Task 1: Read the descriptions for how the following five devices work. These devices may be familiar to you, but you may not have thought about the details of how they work. After studying how the devices work you will be asked to **recall the verbal description of each device.** You will have **30 minutes** to complete this task.

Device to separate and move object

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

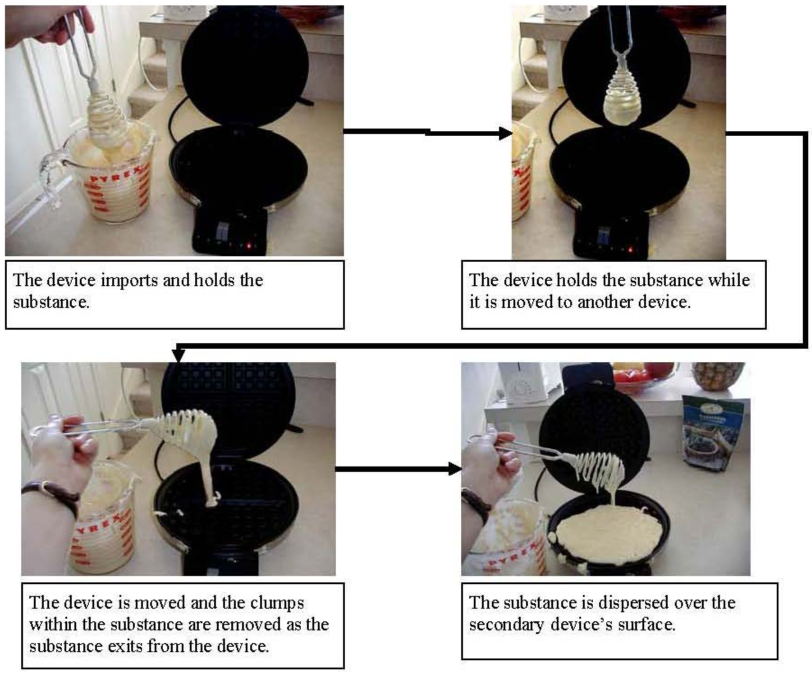
Device to import and export a substance
The device is filled with a substance at the location where it will be used. The substance required to cause the device to function is available at the location. The primary purpose of the device is to distribute the force of the person during the task. The device accomplishes this by importing, storing and exporting the substance. This allows the device to be easily stored.

Moving Device
Another object gives energy to this device. As it moves through a substance it turns about. This motion changes the forces allowing the device to move more.

Load positioning device

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

<u>Device to import and hold substances</u>



Recall How the Device Works

From memory, **reproduce the verbal descriptions** of the devices that you just read.

Device to separate and move object

Device to import and export a substance

Moving device

Load positioning device

Device to import and hold substances

Solutions

Compare your descriptions to the ones shown on the following pages. What is different and what is similar? Look at the sentences you wrote. Give yourself one point for each of your sentences that are generally correct. Write the number of generally correct sentences on the following solution pages.

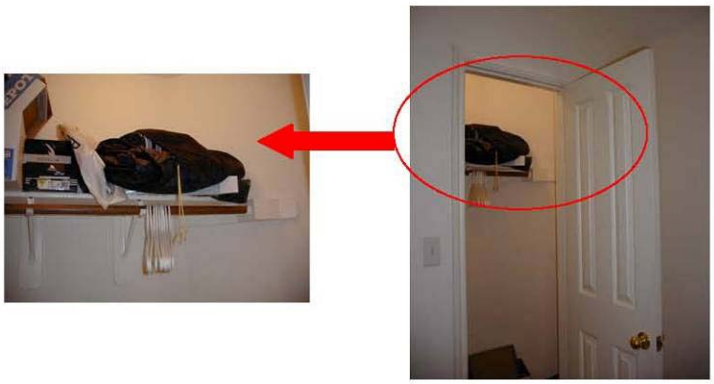
Number of Correct Sentences for this device: ________

Device to separate and move object

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

Number of Correct Sentences for this device: ________

Device to import and export a substance
The device is filled with a substance at the location where it will be used. The substance required to cause the device to function is available at the location. The primary purpose of the device is to distribute the force of the person during the task. The device accomplishes this by importing, storing and exporting the substance. This allows the device to be easily stored.



Number of Correct Sentences for this device: ________

Moving Device
Another object gives energy to this device. As it moves through a substance it turns about. This motion changes the forces allowing the device to move more.

Number of Correct Sentences for this device: ________

Load positioning device

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

Number of Correct Sentences for this device: ________

Device to import and hold substances

The device imports and holds the substance.

The device holds the substance while it is moved to another device.

The device is moved and the clumps within the substance are removed as the substance exits from the device.

The substance is dispersed over the secondary device's surface.

EXPERIMENTER SCRIPT: DAY 1, DOMAIN & GENERAL

Experimenter script: **(1&2) Abstract Source & Domain Specific Source**
Items required for the experiment

- ☐ Participant Instruction Packets
- ☐ Consent forms
- ☐ Stop watch
- ☐ Multiple colored writing utensils (black, red)
- ☐ Extra paper
- ☐ Stapler

a) Give participants the consent form
b) Black pens

1) **"This study is evaluating various skills used in the design process. Your task today is to understand how a machine works. Next week you will generate ideas for some design problems. The total time required for this study is 3 hours, 1 hour today and two hours next week. If you agree to participate please sign the consent form. Any questions?"**

a) Collect signed form
b) Give participant a copy of the consent form

2) <u>Encode the sources phase</u>
"Write the Month and Day of your birthday in the upper right-hand corner. This will be used to match your results from this experiment to the results from the second experiment."

"You will have 30 minutes to study the following 5 products. At the end of the 30 you will be given a quiz requiring you to write down the product descriptions word for word. Multiple colors of pens are being used to keep track of when items are written. If you have any questions at any time during this experiment, please ask."

"Read the descriptions for how the following five devices work. These devices may be familiar to you, but you may not have thought about the details of how they work. After studying how the devices work you will be asked to recall the verbal description of each device. You can use any memory tricks you know to help you remember the devices. Any questions?"

At 15 minutes: **"You have only 15 minutes left to finish memorizing the verbal descriptions"**
a) Give participants Task 1a: Study the devices
(1) make sure all participants are using black pen or pencil

3) <u>Recall how the devices work</u>

i) Take the Encode the source sheets
ii) give them the quiz "Recall the how the devices work"

"Please stop what you are doing. Turn over the sheets and place them off to the side. Be sure you can not read the information through the backside of the paper."

"For each of the five following products, as best as you can, please write down a word for word description of the device. You will have up to 15 minutes to do this. Please raise your hand when you are finished."

4) <u>Evaluate your results:</u>

"You are now being asked to evaluate your results. Give your self one point for each sentence that says pretty much the same thing as the solution sentence. Be sure to write the number of generally correct sentences on the following solution pages. You will have up to 10 minutes to do this. Bring me all of your sheets when you are finished."

a) Give back Study the devices.
b) Take away Black and give them **red.** Participants write down their scores

5) <u>End of the experiment</u>: **"Thank you for your participation. Please do not discuss this experiment with your classmates until after Saturday, Nov. 19th since discussing the experiment could bias the data. See you next week at this location at the same time to do some idea generation."**

EXPERIMENTER SCRIPT: DAY 2

Experimenter script: **(1) Domain Specific Problem Description**

Items required for the experiment

- ☐ Participant Instruction Packets
- ☐ Stop watch
- ☐ Multiple colored writing utensils (black, blue, purple, green, red)
- ☐ Extra paper
- ☐ Stapler

a) Give participants the first design problem
b) Black pens

1) **Black-** Design Problem 1-
"This study is evaluating various skills used in the design process. Your task today is to generate ideas for a series of design problems. The time required for this study today is two hours. Please turn over the sheet. "

- **Generate as many solutions as possible in the allotted time to the following design problems.**
- **Write down everything you can think of even if it does not meet the constraints of the problem.**
- **The goal is to generate as many solutions with as high of quality and with as great of variety as possible.**
- **Wilde, technically infeasible and far out ideas are also encouraged. This helps to generate unique feasible solutions.**

Sketch and/or use words to describe your ideas

You will have 11 minutes to generate solutions to the design problem.

Multiple colors of pens are being used to keep track of when items are written. If you have any questions at any time during this experiment, please ask.

Design Problem 1: Design a piece of exercise equipment that can be carried in a suitcase. You will have 11 minutes."

a) make sure all participants are using black pen or pencil

2) Design Problem 1- Constrained
   a) Give them the next sheet.

"Please stop. Switch to the Blue pen and flip over the next sheet. Constrained design problem 1: Design a piece of exercise equipment that can be carried in a suitcase. The additional constraints are:

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

You have 11 minutes to generate additional solutions that meet these constraints.

Put a check mark next to all of your solutions that meet these constraints including the ones you generated previously."

b) **Blue pen .**

3) Design Problem 2
   a) Take away **Blue** and give them **Black.**
   b) Give them the next sheet.

"Please stop. Switch to the Black pen and flip over the next sheet. Design Problem 2: Design a device to be pulled behind a boat for a person to ride on. You will have 11 minutes. Go ahead and start. "

4) Design Problem 2- Constrained
   a) Give them the next sheet.

"Please stop. Switch to the Blue pen and flip over the next sheet. Design Problem 2: Design a device to be pulled behind a boat for a person to ride on. The additional constraints are:

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

You have 11 minutes to generate additional solutions that meet these constraints.

Put a check mark next to all of your solutions that meet these constraints including the ones you generated previously. Go ahead and start. "

b) check **Blue.**

5) Design Problem 3
   a) Give them the next sheet.

"Please stop. Switch to the Black pen and flip over the next sheet. Design Problem 3: Design a device to sprinkle flour over a surface. You will have 11 minutes. Go ahead and start. "

   b) Check **Black.**

6) Design Problem 3- Constrained
   a) Take away **Black** and give them **Blue.**
   b) Give them the next sheet.

   "Please stop. Switch to the Blue pen and flip over the next sheet. Design Problem 3: Design a device to sprinkle flour over a surface. The additional constraints are:

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

   You have 11 minutes to generate additional solutions that meet these constraints.

   Put a check mark next to all of your solutions that meet these constraints including the ones you generated previously. Go ahead and start. "

7) Break **"Please turn all of your sheets over and take a five minute break. Please do not discuss the experiment or your solutions during the break."**

8) Analogies
   a)
   b) Give them the next sheet.

"Step 1: write down a description of any analogies you remember using to help you generate ideas next to the solution you generated. For example a pair of scissors could be used as an analogy for designing a finger nail clipper. If you had used this analogy, you would write "scissors" next to your solution.

If you did not use any analogies then do not write anything down.

Step 2: try using analogies to help find solutions to the <u>constrained design problems</u>. Try to find at least one analogy for each constrained design problem. You will have 15 minutes. Go ahead and start. "

Give a **Purple** pen. List any analogies you used. Use analogies.

9) **Analogies** part 2
   a) Give them the next sheet.

"Some of the products you saw in the experiment last week can be used as analogies to develop solutions to the constrained design problems. Find solutions based on the products from the experiment last week.

Also write down which product is analogous. You may have already used some of the products for analogies. Please write these down also.

You will have 10 minutes to do this. Go ahead and start. "
   b) Give **Green** pen.

10) Tell them which devices are analogous
   a) Give **Red** pen.
   b) Give them the next sheet.

"Shown below is a list of the design problems and the product from the experiment last week that can be used to find a solution to the constrained design problem. **If you found a solution to the constrained design problem using the product listed below place a check next to your solution.**

If you did not use the analogy listed, see if you can use the analogies given below to find a solution.

You will have up to 10 minutes to do this. Please raise your hand when you are finished. I will not tell you what the devices were last week. You will have to rely on your memory. Go ahead and start. "

11) End of the experiment:
Survey: **"This experiment is testing the effects on design by analogy of giving engineers either a very abstract description of a product or a very domain specific description. Due to the fact all descriptions are in English, how long you have spoken English may affect the results so the survey asks a few questions regarding your language skills."**

"Thank you for your participation. Please do not discuss this experiment with your classmates until after Saturday, Nov. 19th since discussing the experiment could bias the data."

Criteria 1st design problems >=6 concept
Constrained >=4
New analogies >=5

PARTICIPANT INSTRUCTION SHEET: DAY 2

Four Digit Code (Month and day of your birthday) ☐☐ ☐☐

Design Problems

- Generate as many solutions as possible in the allotted time to the following design problems.
- Write down everything you can think of even if it does not meet the constraints of the problem.
- The goal is to generate as many solutions with as high of quality and with as great of variety as possible.
- Wilde, technically infeasible and far out ideas are also encouraged. This helps to generate unique feasible solutions.

Sketch and/or use words to describe your ideas.

Please do not discuss this experiment with your classmates until after Saturday, Nov. 19th.

Design Problem 1

Design a piece of exercise equipment that can be carried in a suitcase. You will have 11 minutes.

Design Problem 1- Additional Constraints

Design a piece of exercise equipment that can be carried in a suitcase. Here are the additional requirements:

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

You have 11 minutes to **generate additional solutions** that meet these constraints.

Put a check mark next to all of your solutions that meet these constraints including the ones you generated previously.

Design Problem 2
Design a device to be pulled behind a boat for a person to ride on. You will have 11 minutes.

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

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

You have 11 minutes to **generate additional solutions** that meet these constraints.

Put a check mark next to all of your solutions that meet these constraints including the ones you generated previously.

Design Problem 3
Design a device to sprinkle flour over a surface. You will have 11 minutes.

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

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

You have 11 minutes to **generate additional solutions** that meet these constraints.

Put a check mark next to all of your solutions that meet these constraints including the ones you generated previously.

Analogies

Write down a description of any analogies you used to help you generate ideas. For example, a pair of scissors could be used as an analogy for designing a finger nail clipper. If you had used this analogy, you would write "scissors" next to your solution.

Try using analogies to help find solutions to the constrained design problems. Try to find at least one analogy for each constrained design problem. You will have 15 minutes.

Analogies part 2

Some of the products you saw in the experiment last week can be used as analogies to develop solutions to the **constrained design problems**. **Find solutions based on the products from the experiment last week**.

Also write down which product is analogous.

You will have 10 minutes to do this.

Analogous Products from Last Week

Shown below is a list of the design problems and the product from the experiment last week that can be used to find a solution to the constrained design problem. **If you found a solution to the constrained design problem using the product listed below place a check next to your solution.**

If you did not use the analogy listed, see if you can use the analogies given below to find a solution. You will have 10 minutes to do this. Please raise your hand when you are finished.

Design Problem 1- Analogy is the Air Mattress (Device to import and export a substance)

Design Problem 2- Analogy is the Football (Moving device)

Design Problem 3- Analogy is the Whisk (Device to import and hold substances)

Post-Session Questions

1. How many years have you lived in an English-speaking country? _________ years

2. How many languages are can you either speak and/or read fluently? __________

3. How much engineering work experience (experience not part of a class) do you have?
   Full-time (35 + hrs/week) engineering work (internships or full-time work)
   _________months __________years

   Part-time (less than 35 hrs/week) engineering work _________hrs/week
   _________months __________years

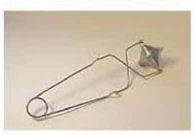
4. Did you hear about any of the design problems prior to participating in the experiment? Please be honest, your reply will have no effect on the credit you are given.
   ☐ Yes ☐ No

5. How many functional models have you done?
   - ☐ 0 functional models: No experience or no idea what a functional model is.
   - ☐ 1-3 functional models: A little experience
   - ☐ 4-6 functional models: Some experience
   - ☐ 7+ functional models: A lot of experience

6. Have you seen or heard of any of the following products before this experiment?

AquaBells® Travel Weights ☐ Yes ☐ No

Gyro Towable Tube ☐ Yes ☐ No



Precision Mini-Sifter ☐ Yes ☐ No

Please state any additional comments you have about the experiment. Use the back of the paper if needed.

EXAMPLE RESULTS

Participant 13: Pages were cropped to reduce required space.

13 **Month and day of your birthday** 10 10

You will learn about a set of products. You will then be asked to **recall the verbal descriptions.**

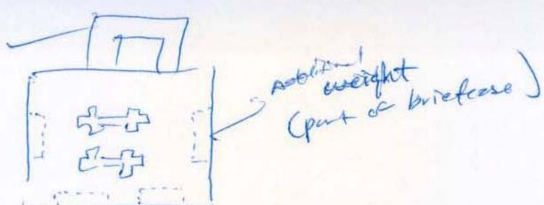
Please do not discuss this experiment with your classmates until after Saturday, Nov. 19th.

Multiple colors of pens are being used to keep track of when items are written. If you have any questions at any time during this experiment, please ask.

Task 1: Read the descriptions for how the following five devices work. These devices may be familiar to you, but you may not have thought about the details of how they work. After studying how the devices work you will be asked to **recall the verbal description of each device.** You will have **30 minutes** to complete this task.

<u>Device to separate and move object</u>

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



Four Digit Code (Month and day of your birthday) 1 0 1 0

Design Problems

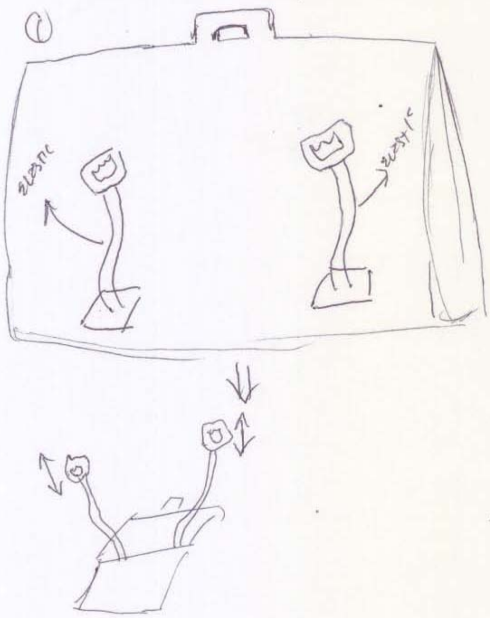
- Generate as many solutions as possible in the allotted time to the following design problems.
- Write down everything you can think of even if it does not meet the constraints of the problem.
- The goal is to generate as many solutions with as high of quality and with as great of variety as possible.
- Wilde, technically infeasible and far out ideas are also encouraged. This helps to generate unique feasible solutions.

Sketch and/or use words to describe your ideas.

Please do not discuss this experiment with your classmates until after Saturday, Nov. 19th.

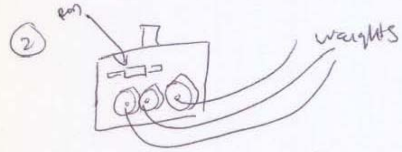
<u>Design Problem 1</u>

Design a piece of exercise equipment that can be carried in a suitcase. You will have 11 minutes.



depend what exercise you want

A jump rope is exercise equipment.



probably best if light

Design Problem 1- Additional Constraints

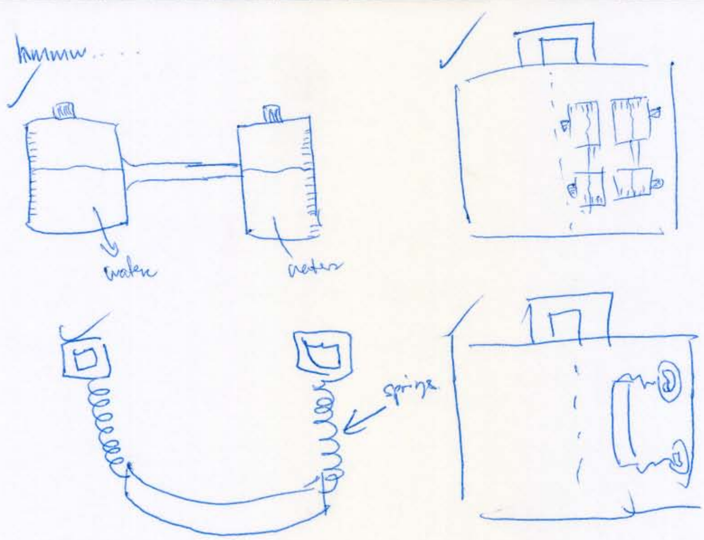
Design a piece of exercise equipment that can be carried in a suitcase. Here are the additional requirements:

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

You have 11 minutes to **generate additional solutions** that meet these constraints.

Put a check mark next to all of your solutions that meet these constraints including the ones you generated previously.

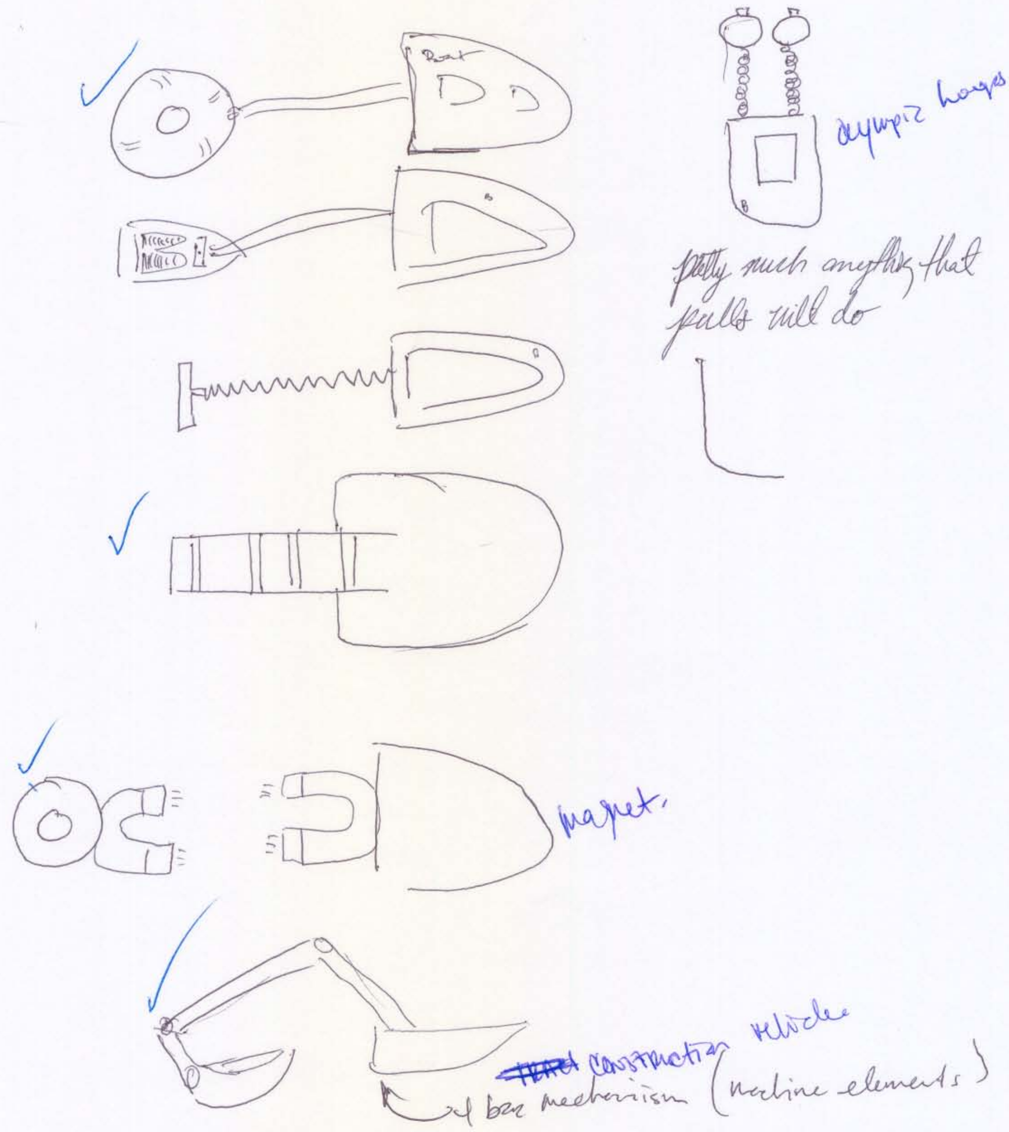
hmmm....



getting pretty creative.

Design Problem 2

Design a device to be pulled behind a boat for a person to ride on. You will have 11 minutes.



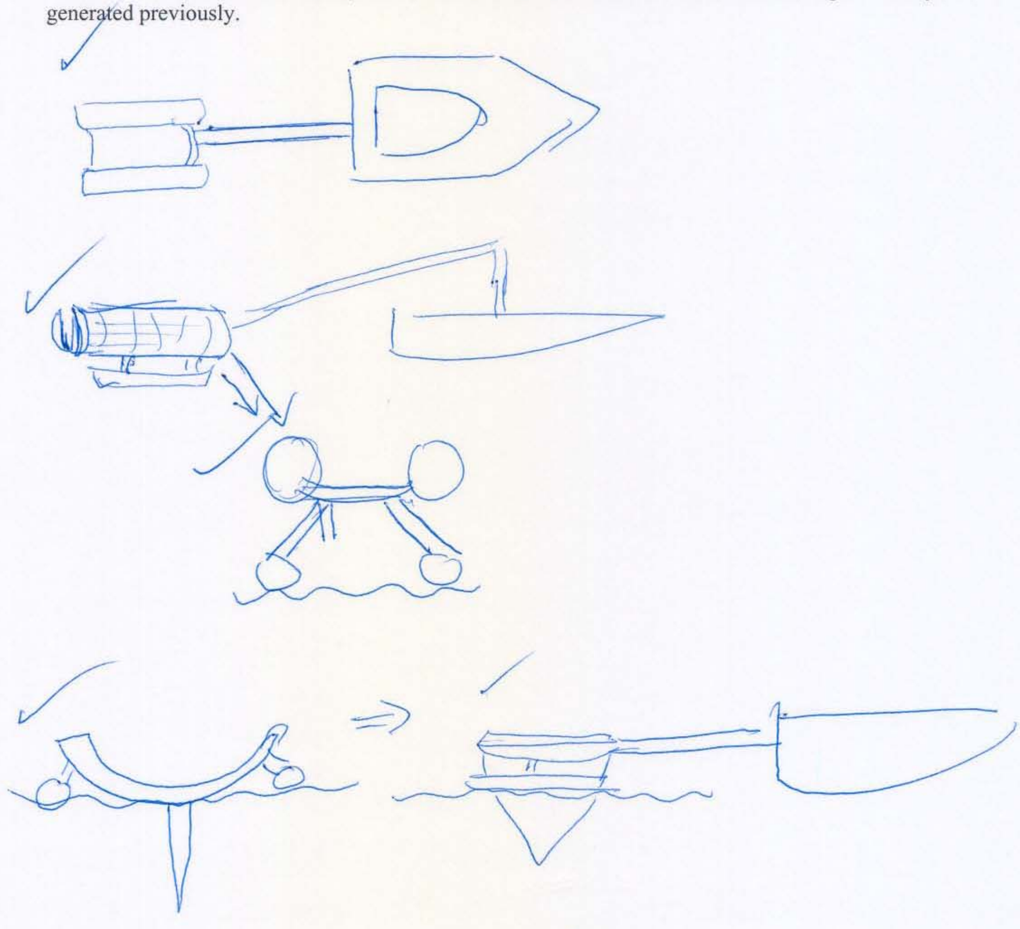
Design Problem 2- Additional Constraints

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

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

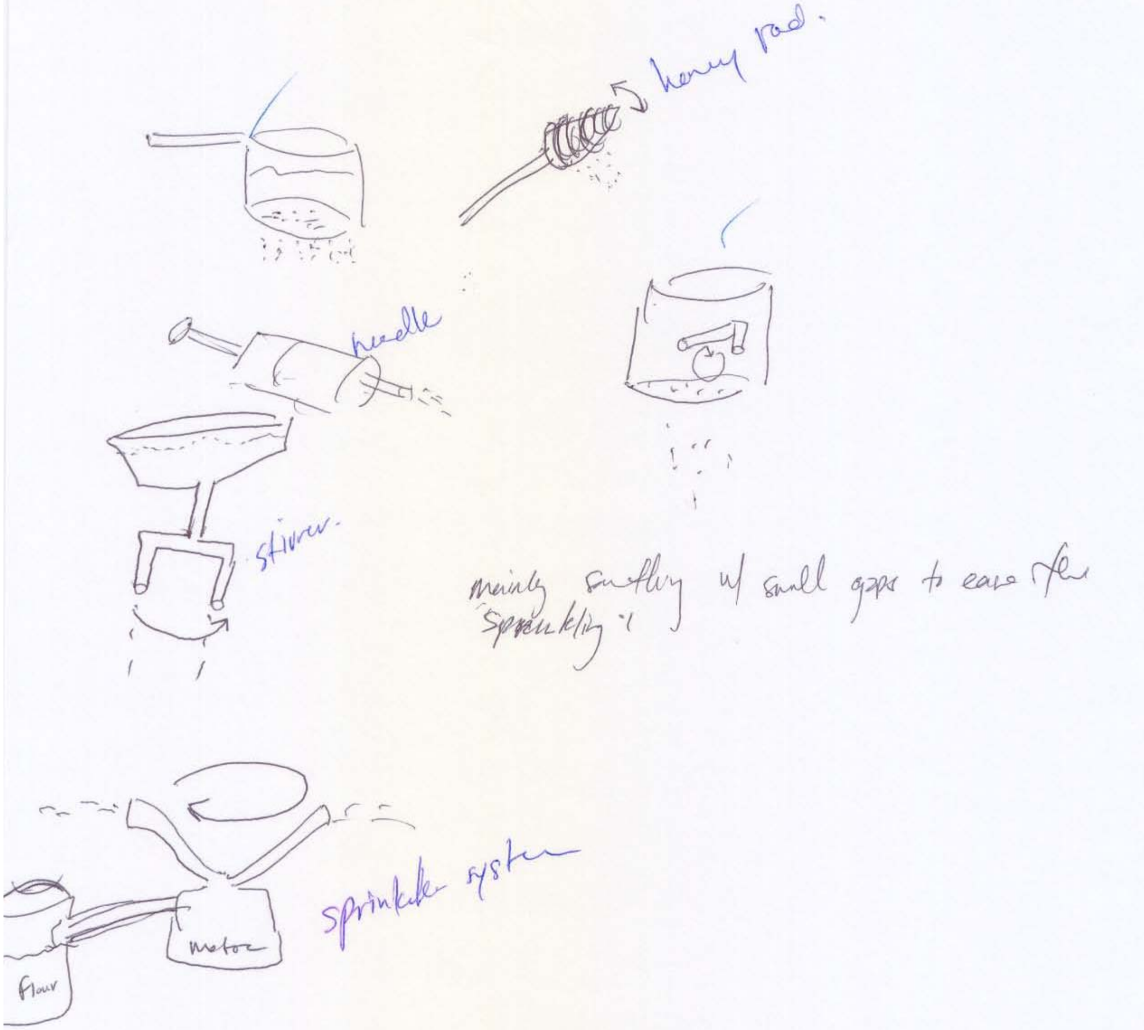
You have 11 minutes to **generate additional solutions** that meet these constraints.

Put a check mark next to all of your solutions that meet these constraints including the ones you generated previously.



Design Problem 3

Design a device to sprinkle flour over a surface. You will have 11 minutes.



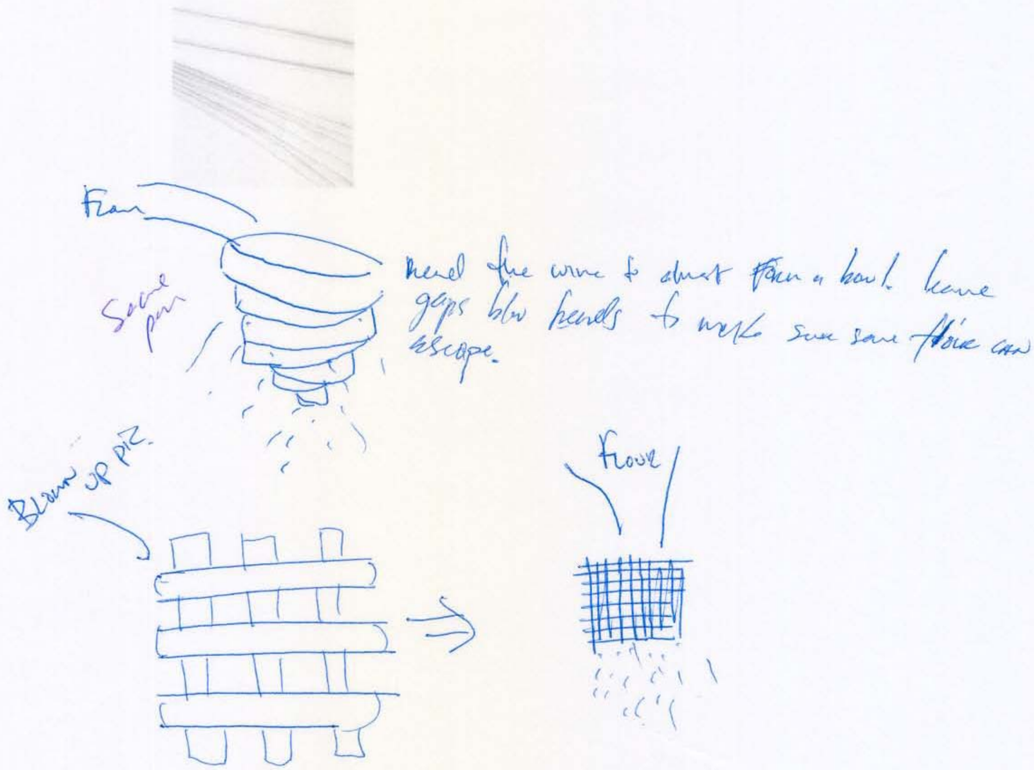
Design Problem 3- Additional Constraints

Design a device to sprinkle flour over a surface.

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

You have 11 minutes to **generate additional solutions** that meet these constraints.

Put a check mark next to all of your solutions that meet these constraints including the ones you generated previously.

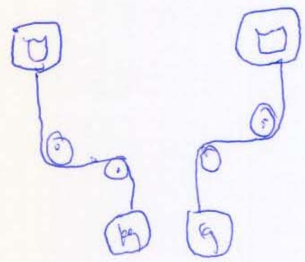


Analogies

Write down a description of any analogies you used to help you generate ideas. For example, a pair of scissors could be used as an analogy for designing a finger nail clipper. If you had used this analogy, you would write "scissors" next to your solution.

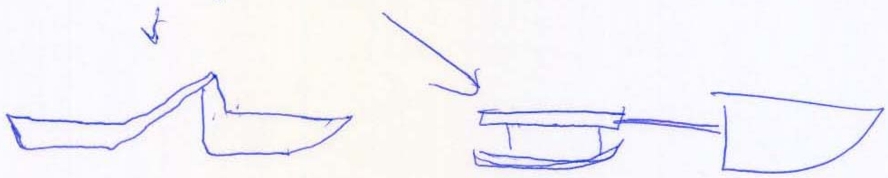
Try using analogies to help find solutions to the **<u>constrained design problems</u>**. Try to find at least one analogy for each constrained design problem. You will have 15 minutes.

1) pulley system

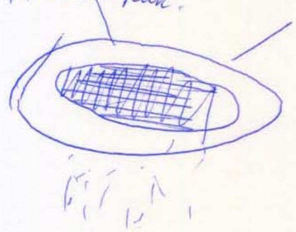


* pulleys can be fastened & loosened & increase or decrease resistance *

2) car tow, sled,



3) filter. fan.

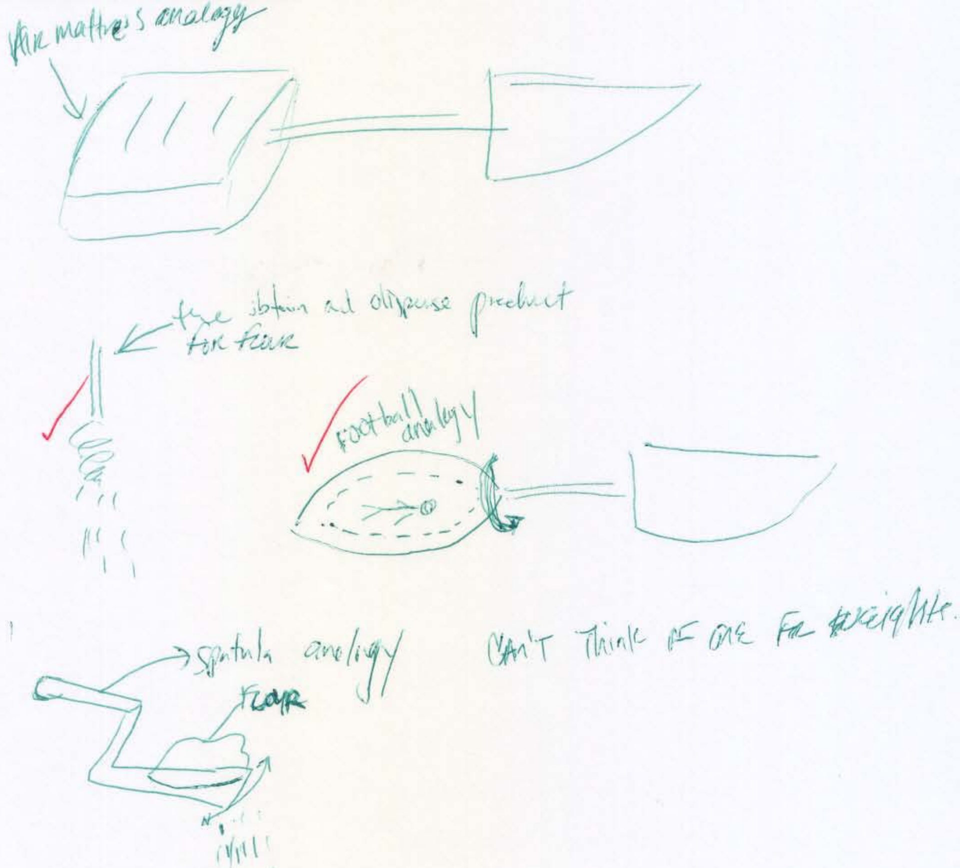


Analogies part 2

Some of the products you saw in the experiment last week can be used as analogies to develop solutions to the **constrained design problems**. **Find solutions based on the products from the experiment last week**.

Also write down which product is analogous.

You will have 10 minutes to do this.



Analogous Products from Last Week

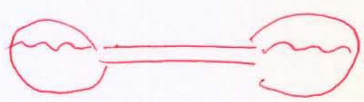
Shown below is a list of the design problems and the product from the experiment last week that can be used to find a solution to the constrained design problem. **If you found a solution to the <u>constrained design problem</u> using the product listed below place a check next to your solution.**

If you did not use the analogy listed, see if you can use the analogies given below to find a solution. You will have 10 minutes to do this. Please raise your hand when you are finished.

Design Problem 1- Analogy is the Air Mattress (Device to import and export a substance)

✓ Design Problem 2- Analogy is the Football (Moving device)

✓ Design Problem 3- Analogy is the Whisk (Device to import and hold substances)



water is imported and exported to create resistance

Post-Session Questions

1. How many years have you lived in an English-speaking country? __18__ years
2. How many languages are can you either speak and/or read fluently? __2__
3. How much engineering work experience (experience not part of a class) do you have?
   Full-time (35 + hrs/week) engineering work (internships or full-time work)
   __7__ months __0__ years

   Part-time (less than 35 hrs/week) engineering work __—__ hrs/week
   __—__ months __—__ years

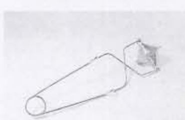
4. Did you hear about any of the design problems prior to participating in the experiment? Please be honest, your reply will have no effect on the credit you are given.
   ☐ Yes ☑ No

5. How many functional models have you done?
   - ☐ 0 functional models: No experience or no idea what a functional model is.
   - ☑ 1-3 functional models: A little experience
   - [illegible]
   - ☐ 7+ functional models: A lot of experience

6. Have you seen or heard of any of the following products before this experiment?

AquaBells® Travel Weights ☐ Yes ☑ No

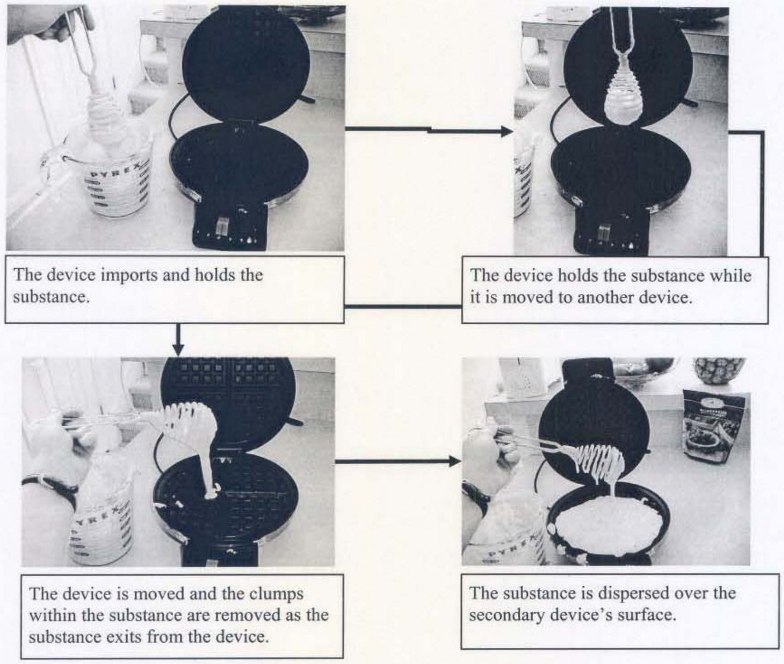
Gyro Towable Tube ☐ Yes ☑ No



Precision Mini-Sifter ☐ Yes ☑ No

Number of Correct Sentences for this device: 4

Device to import and hold substances



Recall How the Device Works

From memory, **reproduce the verbal descriptions** of the devices that you just read.

Device to separate and move object

The device imports a hand and seprates two objects. It also dissipates the force of an object + allows the object to be moved.

Device to import and export a substance

the device is filled w/ the substanc a the location where it will be used. the substance required for the device to function is available at the location. the primary function of the device is to distribute the force of a person during the task. The device accomplishes this by importing, storing, and exporting the substance. This allows the device to be easily stored.

Moving device

Another object gives energy to this device. As it moves through a substance it turns about. this motion changes the force allowing the device to move more.

Load positioning device

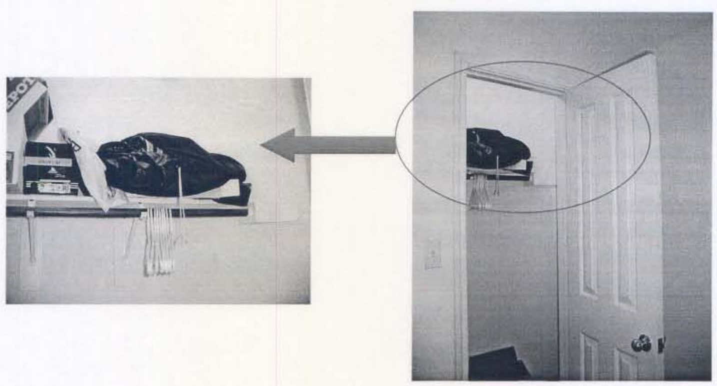
This device positions great loads easily. The lower support and friction reducing features impact allowing the device to chang ~~chang~~ shape. The import hand feature changes shape allowing the performance of a new function.

Device to import and hold substances

The device imports and holds ~~the~~ substance.
The device holds the substance while it is moved to another device.
The device is moved allowing clumps in the substance to be removed as it exits the device. The substance is dispersed in the second device's surface area.

Device to import and export a substance

The device is filled with a substance at the location where it will be used. The substance required to cause the device to function is available at the location. The primary purpose of the device is to distribute the force of the person during the task. The device accomplishes this by importing, storing and exporting the substance. This allows the device to be easily stored.



1) DEVICE FILLED w/ SUB @ LOCATION
2) SUB. available @ LOC.

Moving Device

Another object gives energy to this device. As it moves through a substance it turns about. This motion changes the forces allowing the device to move more.

Load positioning device

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

Device to import and hold substances

The device imports and holds the substance.

The device holds the substance while it is moved to another device.

The device is moved and the clumps within the substance are removed as the substance exits from the device.

The substance is dispersed over the secondary device's surface.

DEVICE TO IMPORT & HOLD SUBSTANCES

① ②

③ ④

Solutions

Compare your descriptions to the ones shown on the following pages. What is different and what is similar? Look at the sentences you wrote. Give yourself one point for each of your sentences that are generally correct. Write the number of generally correct sentences on the following solution pages.

Number of Correct Sentences for this device: 2

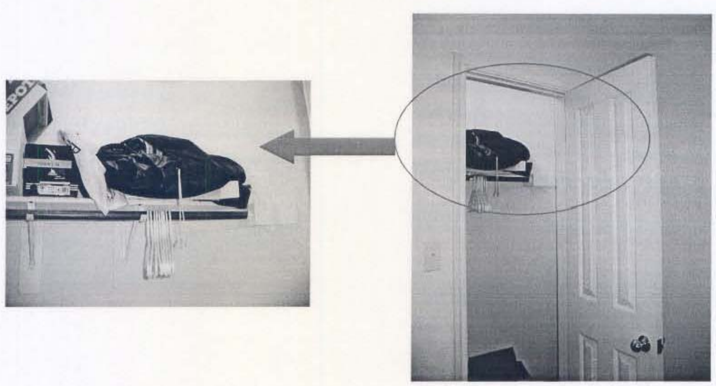
Device to separate and move object

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

Number of Correct Sentences for this device: 5

Device to import and export a substance

The device is filled with a substance at the location where it will be used. The substance required to cause the device to function is available at the location. The primary purpose of the device is to distribute the force of the person during the task. The device accomplishes this by importing, storing and exporting the substance. This allows the device to be easily stored.



Number of Correct Sentences for this device: 3

Moving Device

Another object gives energy to this device. As it moves through a substance it turns about. This motion changes the forces allowing the device to move more.

Number of Correct Sentences for this device: 3

Load positioning device

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

RAW DATA

Final Data

IA= Identified Analogy, FS= Found Solution		Factor 1 (1= domain, 2= abstract, 3= function)	List Analogies (Purple)	Use analogies (Purple)		mean # solved	Unconstrained (Black)		mean # solved
#	Design Problem		IA	FS	IA & FS	FS&IA	FS	FS&IA	FS&IA
1	1		0	0	0	1	0	0	0
	2	domain	0	0	0		0	0	
	3		1	1	1		0	0	
2	1		0	1	0	0	0	0	0
	2	domain	0	1	0		0	0	
	3		0	1	0		0	0	
3	1		0	1	0	0	0	0	0
	2	domain	0	1	0		0	0	
	3		0	1	0		0	0	

4	1		0	1	0	0	0	0	0
	2	domain	0	1	0		0	0	
	3		0	1	0		0	0	
5	1		0	0	0	0	0	0	0
	2	domain	0	1	0		0	0	
	3		0	1	0		0	0	
6	1		0	0	0	0	0	0	0
	2	domain	0	0	0		0	0	
	3		0	0	0		0	0	
7	1		0	1	0	0	0	0	0
	2	domain	0	1	0		0	0	
	3		0	0	0		0	0	
8	1		0	1	0	1	1	0	0
	2	domain	0	1	0		0	0	
	3		1	1	1		0	0	
9	1		0	1	0	0	0	0	0
	2	domain	0	0	0		0	0	
	3		0	0	0		0	0	
10	1		0	1	0	1	1	0	0
	2	abstract	0	1	0		1	0	
	3		1	1	1		0	0	
11	1		0	1	0	1	1	0	0
	2	abstract	0	1	0		1	0	
	3		1	1	1		0	0	
12	1		0	0	0	0	0	0	0
	2	abstract	0	0	0		0	0	
	3		0	0	0		0	0	
13	1		0	1	0	0	0	0	0
	2	abstract	0	0	0		0	0	
	3		0	0	0		0	0	
14	1		0	1	0	0	0	0	0
	2	abstract	0	1	0		0	0	
	3		0	1	0		0	0	
15	1		0	1	0	1	1	0	0
	2	abstract	0	1	0		0	0	
	3		1	1	1		0	0	
16	1		0	1	0	1	1	0	0
	2	domain	1	1	1		0	0	
	3		0	0	0		0	0	
17	1		0	1	0	1	1	0	0
	2	abstract	0	0	0		0	0	
	3		1	1	1		0	0	
18	1		0	0	0	0	0	0	0
	2	abstract	0	1	0		0	0	

	3		0	1	0		0	0	
19	1		0	1	0	0	1	0	0
	2	domain	0	1	0		0	0	
	3		0	0	0		0	0	
20	1		0	0	0	0	0	0	0
	2	domain	0	1	0		0	0	
	3		0	1	0		1	0	
21	1		0	1	0	0	1	0	0
	2	abstract	0	0	0		0	0	
	3		0	1	0		0	0	
22	1		0	1	0	0	0	0	0
	2	domain	0	0	0		0	0	
	3		0	1	0		0	0	
24	1		0	0	0	0	0	0	0
	2	domain	0	0	0		0	0	
	3		0	0	0		0	0	
25	1		0	0	0	1	0	0	0
	2	domain	1	1	1		0	0	
	3		0	1	0		0	0	
26	1		0	0	0	0	0	0	0
	2	domain	0	1	0		1	0	
	3		0	1	0		0	0	
27	1		0	0	0	1	0	0	0
	2	domain	0	1	0		0	0	
	3		1	1	1		0	0	
28	1		0	0	0	1	0	0	0
	2	abstract	0	1	0		0	0	
	3		1	1	1		0	0	
29	1		0	1	0	0	0	0	0
	2	abstract	0	1	0		0	0	
	3		0	1	0		0	0	
30	1		0	1	0	0	0	0	0
	2	abstract	0	1	0		0	0	
	3		0	0	0		0	0	
31	1		0	0	0	1	0	0	0
	2	domain	0	1	0		0	0	
	3		1	1	1		0	0	
32	1		0	1	0	0	0	0	0
	2	abstract	0	0	0		0	0	
	3		0	0	0		0	0	
33	1		0	1	0	0	0	0	0
	2	abstract	0	1	0		0	0	
	3		0	1	0		0	0	
34	1		0	0	0	0	0	0	0

	2	abstract	0	0	0		0	0	
	3		0	0	0		0	0	
34 b	1		0	1	0	0	1	0	0
	2	abstract	0	1	0		0	0	
	3		0	0	0		0	0	
35	1		0	0	0	0	0	0	0
	2	abstract	0	1	0		1	0	
	3		0	0	0		0	0	
36	1		0	1	0	1	0	0	0
	2	abstract	1	1	1		0	0	
	3		0	1	0		0	0	
37	1		0	1	0	1	0	0	0
	2	abstract	0	1	0		0	0	
	3		1	1	1		0	0	
38	1		0	1	0	2	0	0	0
	2	abstract	1	1	1		0	0	
	3		1	1	1		0	0	
39	1		0	1	0	0	1	0	0
	2	abstract	0	1	0		1	0	
	3		0	1	0		0	0	
40	1				0	0		0	0
	2	Bad data			0			0	
	3	Only did Phase 1			0			0	
41	1		0	1	0	1	0	0	0
	2	Function & Abstract	1	1	1		0	0	
	3		0	1	0		0	0	
42	1		0	0	0	0	0	0	0
	2	Function & Abstract	0	0	0		0	0	
	3		0	0	0		0	0	
43	1		0	1	0	0	1	0	0
	2	Function & Abstract	0	1	0		0	0	
	3		0	0	0		0	0	

Table Continued

#	Design Problem	Constrained (Blue)		mean # solved	1st Experiment has analogies (green)			mean # solved	given correct analogy (red)	mean # solved	Survey: Seen Solution Before
1	1	FS	FS&IA	FS&IA	IA	FS	IA&FS	FS&IA	FS	FS&IA	

	2	0	0	1	0	0	0	1	0	1	0
	3	0	0		0	0	0		0		0
2	1	1	1		1	1	1		1		0
	2	1	0	0	0	1	0	1	1	3	0
	3	1	0		0	1	0		1		0
3	1	1	0		1	1	1		1		0
	2	1	0	0	1	1	1	3	1	3	0
	3	1	0		1	1	1		1		0
4	1	1	0		1	1	1		1		0
	2	1	0	0	0	1	0	2	1	3	0
	3	1	0		1	1	1		1		0
5	1	1	0		1	1	1		1		0
	2	0	0	0	0	0	0	2	1	3	0
	3	1	0		1	1	1		1		0
6	1	1	0		1	1	1		1		1
	2	0	0	0	0	0	0	2	0	2	0
	3	0	0		1	1	1		1		0
7	1	0	0		1	1	1		1		0
	2	1	0	0	0	1	0	1	1	3	1
	3	1	0		0	1	0		1		0
8	1	0	0		1	1	1		1		0
	2	1	0	1	0	1	0	2	0	2	0
	3	1	0		1	1	1		1		0
9	1	1	1		1	1	1		1		0
	2	1	0	0	0	1	0	2	1	3	0
	3	0	0		1	1	1		1		0
10	1	0	0		1	1	1		1		0
	2	1	0	0	1	1	1	3	1	3	1
	3	1	0		1	1	1		1		0
11	1	1	0		1	1	1		1		0
	2	1	0	1	0	1	0	2	1	3	1
	3	1	0		1	1	1		1		0
12	1	1	1		1	1	1		1		0
	2	0	0	0	0	0	0	2	0	2	0
	3	0	0		1	1	1		1		0
13	1	0	0		1	1	1		1		0
	2	1	0	0	0	1	0	2	1	3	0
	3	0	0		1	1	1		1		0
14	1	0	0		1	1	1		1		0
	2	1	0	0	1	1	1	3	1	3	0
	3	1	0		1	1	1		1		0
15	1	1	0		1	1	1		1		0

	2	1	0	1	0	1	0	2	1	3	0
	3	1	0		1	1	1		1		0
16	1	1	1		1	1	1		1		0
	2	1	0	1	0	1	0	2	1	3	0
	3	1	1		1	1	1		1		0
17	1	0	0		1	1	1		1		1
	2	1	0	1	1	1	1	3	1	3	1
	3	0	0		1	1	1		1		0
18	1	1	1		1	1	1		1		0
	2	0	0	0	0	0	0	2	0	2	0
	3	1	0		1	1	1		1		0
19	1	1	0		1	1	1		1		0
	2	1	0	0	0	1	0	0	1	3	0
	3	1	0		0	1	0		1		0
20	1	0	0		0	0	0		1		0
	2	0	0	0	0	0	0	2	0	2	0
	3	1	0		1	1	1		1		0
21	1	1	0		1	1	1		1		0
	2	1	0	0	1	1	1	3	1	3	1
	3	0	0		1	1	1		1		0
22	1	1	0		1	1	1		1		0
	2	1	0	0	0	1	0	1	1	3	1
	3	0	0		0	0	0		1		0
24	1	1	0		1	1	1		1		0
	2	0	0	0	0	0	0	2	0	2	0
	3	0	0		1	1	1		1		0
25	1	0	0		1	1	1		1		0
	2	0	0	1	0	0	0	2	1	3	1
	3	1	1		1	1	1		1		1
26	1	1	0		1	1	1		1		0
	2	0	0	0	0	0	0	2	1	3	0
	3	1	0		1	1	1		1		1
27	1	1	0		1	1	1		1		0
	2	0	0	1	0	0	0	1	0	2	0
	3	1	0		0	1	0		1		0
28	1	1	1		1	1	1		1		0
	2	0	0	1	1	0	0	1	0	1	0
	3	1	0		1	1	0		0		0
29	1	1	1		1	1	1		1		0
	2	1	0	0	1	1	1	3	1	3	0
	3	1	0		1	1	1		1		0
30	1	1	0		1	1	1		1		0

	2	1	0	0	1	1	1	2	1	3	0
	3	1	0		1	1	1		1		0
31	1	0	0		0	0	0		1		0
	2	0	0	1	0	0	0	2	0	2	0
	3	1	0		1	1	1		1		0
32	1	1	1		1	1	1		1		0
	2	1	0	0	1	1	1	3	1	3	0
	3	0	0		1	1	1		1		0
33	1	0	0		1	1	1		1		0
	2	1	0	0	0	1	0	2	1	3	1
	3	1	0		1	1	1		1		1
34	1	1	0		1	1	1		1		0
	2	0	0	0	0	0	0	0	1	1	0
	3	0	0		1	0	0		0		0
34 b	1	0	0		1	0	0		0		0
	2	1	0	0	1	1	1	3	1	3	0
	3	1	0		1	1	1		1		0
35	1	0	0		1	1	1		1		0
	2	0	0	0	0	0	0	0	0	2	0
	3	1	0		0	1	0		1		0
36	1	0	0		0	0	0		1		0
	2	1	0	1	0	1	0	2	1	3	0
	3	1	1		1	1	1		1		0
37	1	1	0		1	1	1		1		0
	2	1	0	0	0	1	0	2	1	3	0
	3	1	0		1	1	1		1		0
38	1	0	0		1	1	1		1		0
	2	1	0	2	1	1	1	3	1	3	0
	3	1	1		1	1	1		1		0
39	1	1	1		1	1	1		1		0
	2	1	0	0	0	1	0	1	0	2	0
	3	1	0		1	1	1		1		0
40	1	1	0		0	1	0		1		0
	2		0	0			0	0		0	
	3		0				0				
41	1		0				0				
	2	1	0	1	1	1	1	3	1	3	0
	3	1	1		1	1	1		1		0
42	1	1	0		1	1	1		1		0
	2	0	0	0	1	1	1	3	1	3	0
	3	0	0		1	1	1		1		0
43	1	0	0		1	1	1		1		0

	2	1	0	0	1	0	0	1	0	2	0
	3	1	0		0	1	0		1		0
		0	0		1	1	1		1		0

RAW SURVEY DATA SUMMARY

	Years	Language	Work	Q4	Q5	
#	1 (years)	>1	3 (years)	(1=yes/no)	(0, 1-3, 4-6,7+)	comments
1	23	1	0.5	0	1	
2	*Did not fill out survey					
3	21	1	0.5	0	1	
4	2	4	3	3	4	
5	22	1	0.5	0	0	
6	21	1	?	0	4	
7	24	1	0	0	1	
8	20	3	0.166667	0	1	
9	16	1	0.583333	0	1	
10	21	1	0.75	0	1	It seemed like each section was a little longer than necessary. I used many of the old analogies without ever realizing.
11	23	1	2.3	0	0	
12	12	2	0.5	0	4	I want my 10 pt xtra credit on the last memo in the write up section (non-english) if possible thanks.
13	18	2	0.583333	0	1	
14	21	1	0.33	0	7	
15	31	1	1.67	0	1	
16	22	1	0.25	0	1	
17	22	2	1.004167	0	1	
18	23	1	0.25	0	4	
19	21	1	0	0	1	
20	23	1	1.4	0	1	
21	22	2	1.25	0	4	
22	22	1	0.333333	0	1	
24	23	2	0.75	0	1	Fun to think about about ideas
25	22	2	3.25	0	4	
26	22	1	0.25	0		
27	22	2	0.5	0	1	
28	15	3	0.375	0	1	
29	22	2	0.25	0	1	

30	3	2	0	0	1	
31	23	1	1	0	1	
32	21	1	1.5	0	0	
33	17	2	1	0	4	
34	23	1	0	0	1	
34b	21	1	0.5	0	1	
35	22	1	0.75	0	1	
36	21	1	0.75	0	1	
37	22	1	0	0	1	
38	6	2	0.83	0	4	
39						
40						
41	21	1	0	0	4	
42	22	1	1.5	0	1	
43	21	2	0.5	0	4	

Appendix C: Analogy Experiment 1 Materials

Note: Pages from the experiment materials were cropped to reduce required space.

PARTICIPANT INSTRUCTION SHEET: DAY 1, DOMAIN

Month and day of your birthday ☐☐ ☐☐
(or another 4-digit code you can remember)

You will learn about a set of products. You will then be asked to **recall the verbal descriptions.**

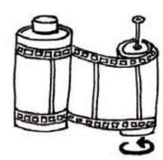
Please do not discuss this experiment with your classmates until after Saturday, April 29th.

Multiple colors of pens are being used to keep track of when items are written. If you have any questions at any time during this experiment, please raise your hand.

Task 1: Read the descriptions for how the following five devices work. These devices may be familiar to you, but you may not have thought about the details of how they work. After studying how the devices work you will be asked to **recall the verbal description of each device.** You will have **30 minutes** to complete this task.

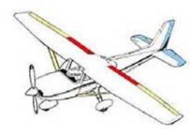
Pepper Mill
A small motor inside the pepper mill spins and grinds the peppercorns into ground pepper. A person presses a button to actuate a small dc motor.

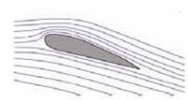
Film in a camera
Two reels feed the film in front of the stream of light. The film captures the image and then a new unexposed section of film is moved into place.



Football
A person throws the American football. As it flies through the air it spirals. This spiraling reduces air friction allowing the ball to travel farther.

Airplane
An airplane flies through the air allowing rapid flights. The airfoil shape of the airplane's wings causes a lift force as the plane flies through the air. As the plane increase altitude there is less drag due to the air being less dense.





Section view of a Wing

Shape-o-toy
This toy serves a number of purposes. The two halves contain the blocks allowing them to be carried. A child pulls the two halves apart and the blocks fall out.

Recall How the Device Works

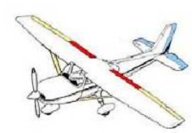
From memory, **reproduce the verbal descriptions** of the devices that you just read.

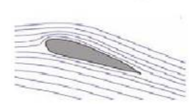
Pepper Mill

Film in a camera

Football

Airplane





Shape-o-toy

Solutions

Compare your descriptions to the ones shown on the following pages. What is different and what is similar? Look at the sentences you wrote. Give yourself one point for each of your sentences that are generally correct. Write the number of generally correct sentences on the following solution pages.

Number of Correct Sentences for this device: ________

Pepper Mill

A small motor inside the pepper mill spins and grinds the peppercorns into ground pepper. A person presses a button to actuate a small dc motor.

Number of Correct Sentences for this device: ________

Film in a camera

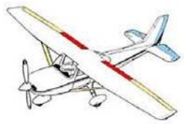
Two reels feed the film in front of the stream of light. The film captures the image and then a new unexposed section of film is moved into place.

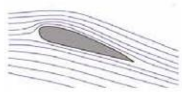
Number of Correct Sentences for this device: ________

Football
A person throws the American football. As it flies through the air it spirals. This spiraling reduces air friction allowing the ball to travel farther.

Number of Correct Sentences for this device: ________

Airplane
An airplane flies through the air allowing rapid flights. The airfoil shape of the airplane's wings causes a lift force as the plane flies through the air. As the plane increase altitude there is less drag due to the air being less dense.





Section view of a Wing

Number of Correct Sentences for this device: ________

Shape-o-toy
This toy serves a number of purposes. The two halves contain the blocks allowing them to be carried. A child pulls the two halves apart and the blocks fall out.

PARTICIPANT INSTRUCTION SHEET: DAY 1, GENERAL

Month and day of your birthday ☐☐ ☐☐

(or another 4-digit code you can remember)

You will learn about a set of products. You will then be asked to **recall the verbal descriptions.**

Please do not discuss this experiment with your classmates until after Saturday, April 22nd.

Multiple colors of pens are being used to keep track of when items are written. If you have any questions at any time during this experiment, please raise your hand.

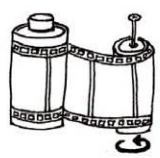
Task 1: Read the descriptions for how the following five devices work. These devices may be familiar to you, but you may not have thought about the details of how they work. After studying how the devices work you will be asked to **recall the verbal description of each device.** You will have **30 minutes** to complete this task.

Device to create a fine powder

A small motor inside the device turns and breaks down the substance into a fine powder. A force presses a switch to turn on a small actuator.

Film in a camera

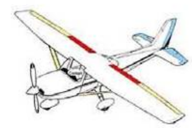
Two reels move a surface in the path of the incoming substance. The surface collects the substance and then a new unchanged surface is moved into place.

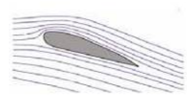


Moving Device

Another object gives energy to this device. As it moves through a substance it turns about. This motion changes the forces allowing the device to move more.

Device for Rapid Travel
This device moves through a fluid allowing rapid travel. The shape of the device's extensions causes a net force as the device moves through the fluid. As the device changes position there is less resistance due to the fluid being less dense.





Section view of an extension

Device to hold and release substances
This device serves a number of functions. The two sections hold the substances allowing them to be moved. A force separates the sections and the substance is released.

Recall How the Device Works

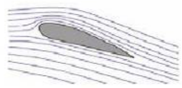
From memory, **reproduce the verbal descriptions** of the devices that you just read.

Device to create a fine powder

Film in a camera

Moving device

Device for Rapid Travel



Device to hold and release substances

Solutions

Compare your descriptions to the ones shown on the following pages. What is different and what is similar? Look at the sentences you wrote. Give yourself one point for each of your sentences that are generally correct. Write the number of generally correct sentences on the following solution pages.

Number of Correct Sentences for this device: ________

Device to create a fine powder

A small motor inside the device turns and breaks down the substance into a fine powder. A force presses a switch to turn on a small actuator.

Number of Correct Sentences for this device: ________

Film in a camera

Two reels move a surface in the path of the incoming substance. The surface collects the substance and then a new unchanged surface is moved into place.

Number of Correct Sentences for this device: ________

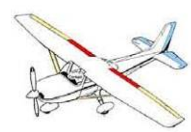
Moving Device

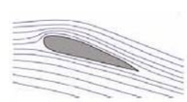
Another object gives energy to this device. As it moves through a substance it turns about. This motion changes the forces allowing the device to move more.

Number of Correct Sentences for this device: ________

Device for Rapid Travel

This device moves through a fluid allowing rapid travel. The shape of the device's extensions causes a net force as the device moves through the fluid. As the device changes position there is less resistance due to the fluid being less dense.





Section view of an extension

Number of Correct Sentences for this device: ________

Device to hold and release substances

This device serves a number of functions. The two sections hold the substances allowing them to be moved. A force separates the sections and the substance is released.

PARTICIPANT INSTRUCTION SHEET: DAY 2

Four Digit Code (Month and day of your birthday) ☐☐ ☐☐

Design Problems

- Generate as many solutions as possible in the allotted time to the following design problems.
- Write down everything you can think of even if it does not meet the constraints of the problem.
- The goal is to generate as many solutions with as high of quality and with as great of variety as possible.
- Wild, technically infeasible and far out ideas are also encouraged. This helps to generate unique feasible solutions.

Sketch and/or use words to describe your ideas.

Please do not discuss this experiment with your classmates until after Saturday, April 29th.

Design Problem 1
Design an fast kayak.

Design Problem 1- Additional Constraints
Design a fast kayak.

- A person is the only available power source.
- It must have a top speed of greater than 14 mph. Currently, typical human-powered boats have a top speed of less than 6 mph even for top athletes.
- The top speed is limited by drag, the faster a boat goes the greater the drag.
- Your design must reduce the drag.

You have 11 minutes to **generate additional solutions** that meet these constraints.

Put a check mark next to all of your solutions that meet these constraints including the ones you generated previously.

Design Problem 2
Design a set of goggles that removes dirt and mud from a dirt bike racer's goggles.

Design Problem 2- Additional Constraints

Design a set of goggles that removes dirt and mud from a dirt bike racer's goggles.

- Forcing the dirt and mud across the goggle's surface creates scratches. The goggle system must not scratch the surface of the goggles.
- The dirt and mud can not be forced across the surface of the goggles.
- The dirt bike racer's hands cannot leave the handle bars of the bike.
- A section of the goggles at least 1" by 2" must be completely clean.

You have 11 minutes to **generate additional solutions** that meet these constraints.

Put a check mark next to all of your solutions that meet these constraints including the ones you generated previously.

Design Problem 3

Design a kitchen utensil to sprinkle flour over a counter.
You will have 11 minutes.

Design Problem 3- Additional Constraints

Design a kitchen utensil to sprinkle flour over a counter.

- The only material that is available to build the kitchen utensil from is various thicknesses of stainless steel wire.
- The entire kitchen utensil must be made from only **one** thickness of wire.
- The kitchen utensil must be **manufactured by bending** and cutting the wire only.
- The kitchen utensil must be capable of containing the flour and carrying the flour 1 meter without losing the flour.

You have 11 minutes to **generate additional solutions** that meet these constraints.

Put a **check mark next to all of your solutions that meet these constraints** including the ones you generated previously.

Analogies

1. On previous sheets write down a description of any analogies you used to help you generate ideas next to your solution. For example, a pair of scissors could be used as an analogy for designing a set of finger nail clippers. If you had used this analogy, you would write "scissors" **next to your solution.**

2. Try using analogies to help find solutions to the **constrained design problems**. Try to find at least one analogy and solution for each constrained design problem. You will have 15 minutes.

3. Be sure to use sketches and/or words to describe your solution.

Analogies part 2

1. Some of the products you saw in the experiment last week can be used as analogies to develop solutions to the **constrained design problems**. **Find solutions based on the products from the experiment last week.**

2. On previous sheets be sure to write down which product is analogous next to your solution and describe the solution.

You will have 10 minutes to do this.

Analogous Products from Last Week

Shown below is a list of the design problems and the product from the experiment last week or analogous products that can be used to find a solution to the constrained design problem. **If you found a solution to the constrained design problem using the product listed below place a check next to your solution on previous sheets.**

If you did not use the analogy listed, see if you can use the analogies given below to find a solution. You will have 10 minutes to do this. Please raise your hand when you are finished.

	Found a solution to the **constrained problem** based on the listed analogy?	
Design Problem 1- Analogy is an airplane	☐ Yes	☐ No
Design Problem 2- Analogy is film in a camera	☐ Yes	☐ No
Design Problem 3- Analogy is the toy	☐ Yes	☐ No

Post-Session Questions

For the analogies on the previous pager, describe the features from the analogous product that you used in your solution.

Design Problem 1: airplane or airfoil
Features used in your solution from the airplane:

Design Problem 2: film in a camera
Features used in your solution from the film in a camera:

Design Problem 3: the toy
Features used in your solution from the toy:

Post-Session Questions

1. How many years have you lived in an English-speaking country? _________ years

2. List all languages you read and/or speak fluently:

   ____
   ____
   ____
   ____
   ____

3. How much engineering work experience (experience not part of a class) do you have?
   Full-time (35 + hrs/week) engineering work (internships or full-time work)
   _________months _________years

   Part-time (less than 35 hrs/week) engineering work _________hrs/week
   _________months _________years

4. Did you hear about any of the design problems prior to participating in the experiment? Please be honest, your reply will have no effect on the credit you are given.
   ☐ Yes ☐ No

5. How many functional models have you done?
   - ☐ 0 functional models: No experience or no idea what a functional model is.
   - ☐ 1-3 functional models: A little experience
   - ☐ 4-6 functional models: Some experience
   - ☐ 7+ functional models: A lot of experience

6. Have you seen or heard of any of the following products before this experiment?

Kayak with a hydrofoil ☐ Yes ☐ No

Dirt bike racing goggles
or similar approach used for NASCAR cameras ☐ Yes ☐ No

Precision Mini-Sifter ☐ Yes ☐ No

Please state any additional comments you have about the experiment. Use the back of the paper if needed.

EXPERIMENTER SCRIPT: DAY 1, DOMAIN

Experimenter script: **(1&2) General Source & Domain Specific Source**
Items required for the experiment

- ☐ Participant Instruction Packets
- ☐ Consent forms
- ☐ Stop watch
- ☐ Multiple colored writing utensils (black, red)
- ☐ Extra paper
- ☐ Stapler

a) Give participants the consent form
b) Black pens

1) **"This study is evaluating various skills used in the design process. Your task today is to understand how a machine works. Next week you will generate ideas for some design problems. The total time required for this study is 3 hours, 1 hour today and two hours next week. If you agree to participate please sign the consent form. Any questions?"**

a) Collect signed form
b) Give participant a copy of the consent form

2) <u>Encode the sources phase</u>
"Write the Month and Day of your birthday or another four digit code you will remember next week in the upper right-hand corner. This will be used to match your results from this experiment to the results from the second experiment."

"You will have 30 minutes to study the following 5 products. At the end of the 30 you will be given a quiz requiring you to write down the product descriptions word for word. Multiple colors of pens are being used to keep track of when items are written. If you have any questions at any time during this experiment, please raise your hand."

"Read the descriptions for how the following five devices work. These devices may be familiar to you, but you may not have thought about the details of how they work. After studying how the devices work you will be asked to recall the verbal description of each device. You can use any memory tricks you know to help you remember the devices. Go ahead and start. If you have any questions please raise your hand."

At 15 minutes: **"You have only 15 minutes left to finish memorizing the verbal descriptions"**
a) Give participants Task 1a: Study the devices
(1) make sure all participants are using black pen or pencil

3) Recall how the devices work

i) Take the Encode the source sheets

ii) give them the quiz "Recall the how the devices work"

"Please stop what you are doing. Turn over the sheets and place them off to the side. Be sure you can not read the information through the backside of the paper."

"For each of the five following products, as best as you can, please write down a word for word description of the device. You will have up to 15 minutes to do this. Please raise your hand when you are finished."

4) Evaluate your results:

"You are now being asked to evaluate your results. Give your self one point for each sentence that says pretty much the same thing as the solution sentence. Be sure to write the number of generally correct sentences on the following solution pages. You will have up to 10 minutes to do this. Bring me all of your sheets when you are finished."

a) Give back Study the devices.

b) Take away Black and give them **red.** Participants write down their scores

5) End of the experiment: **"Thank you for your participation. Please do not discuss this experiment with your classmates until after Saturday, April 29th since discussing the experiment could bias the data. See you next week at this location at the same time to do some idea generation."**

EXPERIMENTER SCRIPT: DAY 2

Experimenter script: **(1) Domain Specific Problem Description**

Items required for the experiment

- ☐ Participant Instruction Packets
- ☐ Stop watch
- ☐ Multiple colored writing utensils (black, blue, purple, green, red)
- ☐ Extra paper
- ☐ Stapler

a) Give participants the first design problem
b) Black pens

1) **Black-** Design Problem 1-
"This study is evaluating various skills used in the design process. Your task today is to generate ideas for a series of design problems. The time required for this study today is two hours. Please turn over the sheet. "

- **Generate as many solutions as possible in the allotted time to the following design problems.**
- **Write down everything you can think of even if it does not meet the constraints of the problem.**
- **The goal is to generate as many solutions with as high of quality and with as great of variety as possible.**
- **Wild, technically infeasible and far out ideas are also encouraged. This helps to generate unique feasible solutions.**

Sketch and/or use words to describe your ideas

You will have 11 minutes to generate solutions to the design problem.

Multiple colors of pens are being used to keep track of when items are written. If you have any questions at any time during this experiment, please raise your hand.

Design Problem 1: Design an innovative kayak. You will have 11 minutes."

a) make sure all participants are using black pen or pencil

2) Design Problem 1- Constrained
a) Give them the next sheet.

"Please stop. Switch to the Blue pen and flip over the next sheet. Constrained design problem 1: Design a fast kayak.

- **A person is the only available power source.**

- **It must have a top speed of greater than 14 mph. Currently, typical human-powered boats have a top speed of less than 6 mph even for top athletes.**
- **The top speed is limited by drag, the faster a boat goes the greater the drag.**
- **Your design must reduce the drag.**

You have 11 minutes to generate additional solutions that meet these constraints.

Put a check mark next to all of your solutions that meet these constraints including the ones you generated previously."

b) **Blue pen .**

3) Design Problem 2
   a) Take away **Blue** and give them **Black.**
   b) Give them the next sheet.

"Please stop. Switch to the Black pen and flip over the next sheet. Design Problem Design a set of goggles that removes dirt and mud from a dirt bike racer's goggles. You will have 11 minutes. Go ahead and start. "

4) Design Problem 2- Constrained
   a) Give them the next sheet.

"Please stop. Switch to the Blue pen and flip over the next sheet. Design Problem 2: Design a set of goggles that removes dirt and mud from a dirt bike racer's goggles.

- **Forcing the dirt and mud across the goggle's surface creates scratches. The goggle system must not scratch the surface of the goggles.**
- **The dirt and mud can not be forced across the surface of the goggles.**
- **The dirt bike racer's hands cannot leave the handle bars of the bike.**
- **A section of the goggles at least 1" by 2" must be completely clean.**

You have 11 minutes to generate additional solutions that meet these constraints.

Put a check mark next to all of your solutions that meet these constraints including the ones you generated previously. Go ahead and start. "

   b) check **Blue.**

5) Design Problem 3
   a) Give them the next sheet.

"Please stop. Switch to the Black pen and flip over the next sheet. Design Problem 3: Design a kitchen utensil to sprinkle flour over a counter.
You will have 11 minutes. Go ahead and start. "

b) Check **Black.**

6) Design Problem 3- Constrained
   a) Take away **Black** and give them **Blue.**
   b) Give them the next sheet.

"Please stop. Switch to the Blue pen and flip over the next sheet. Design Problem 3: Design a kitchen utensil to sprinkle flour over a counter.

- **The only material that is available to build the kitchen utensil from is various thicknesses of stainless steel wire.**
- **The entire kitchen utensil must be made from only one thickness of wire.**
- **The kitchen utensil must be manufactured by bending and cutting the wire only.**
- **The kitchen utensil must be capable of containing the flour and carrying the flour 1 meter without losing the flour.**

You have 11 minutes to generate additional solutions that meet these constraints.

Put a check mark next to all of your solutions that meet these constraints including the ones you generated previously. Go ahead and start. "

7) Break **"Please turn all of your sheets over and take a five minute break. Please do not discuss the experiment or your solutions during the break."**

8) Analogies
   a)
   b) Give them the next sheet.

"Step 1: On your previous sheets write down a description of any analogies you remember using to help you generate ideas next to the solution you generated. For example a pair of scissors could be used as an analogy for designing a finger nail clipper. If you had used this analogy, you would write "scissors" next to your solution.

If you did not use any analogies then do not write anything down.

Step 2: try using analogies to help find solutions to the <u>constrained design problems</u>. Try to find at least one analogy for each constrained design problem. Be sure to 1.

describe your solution and 2. write down the analogous device next to the solution. You will have 15 minutes. Go ahead and start. "

Give a **Purple** pen. List any analogies you used. Use analogies.

9) **Analogies** part 2
   a) Give them the next sheet.

"Some of the products you saw in the experiment last week can be used as analogies to develop solutions the <u>constrained design problems</u>. Find solutions based on the products from the experiment last week.

I will not tell you what the devices were last week. You will have to rely on your memory.

Be sure to write down which product is analogous. You may have already used some of the products for analogies. Please write these down also on your previous sheets.

Be sure to do two things: 1. describe the solution and 2. write down the analogous product.

You will have 10 minutes to do this. Go ahead and start. "
   b) Give **Green** pen.

10) Tell them which devices are analogous
   a) Give **Red** pen.
   b) Give them the next sheet.

"Shown below is a list of the design problems and the product from the experiment last week or analogous products that can be used to find a solution to the constrained design problem. If you found a solution to the <u>constrained design problem</u> using the product listed below place a check next to your solution on your previous sheets.

If you did not use the analogy listed, see if you can use the analogies given below to find a solution.

Be sure to do two things: 1. Place a red check next to your picture of the solution using the listed analogy and 2. Find new solutions if you did not use the analogy listed

You will have up to 10 minutes to do this. Please raise your hand when you are finished. Go ahead and start. "

<u>11) Describe Features</u>

"For the analogies mentioned on the previous page, write a brief description of the features you used from the analogy to develop your solution.

12) End of the experiment:
Survey: **"This experiment is testing the effects on design by analogy of giving engineers either a very abstract description of a product or a very domain specific description. Due to the fact all descriptions are in English, how long you have spoken English and other languages you are fluent in may affect the results so the survey asks a few questions regarding your language skills."**

"Thank you for your participation. Please do not discuss this experiment with your classmates until after Saturday, April 29th since discussing the experiment could bias the data."

Criteria 1st design problems >=6 concept
Constrained >=4
New analogies >=5

RAW DATA

Final Data

		Design 1: Kayak				Design 2: Goggles				Design 3: Flour Sifter				
#	Part 1	S	A	V	VS	S	A	V	VS	S	A	V	VS	S
1	G	0	0	N	N	red	red	Y	Y	red	red	Y	Y	Y
2	G	green	green	Y	Y	green	green	Y	Y	green	green	Y	Y	N
3	G	black	purple	Y	Y	blue	blue	Y	Y	blue	green	Y	Y	Y
4	D	green	green	N	Y	green	green	Y	Y	blue	green	Y	Y	Y
5	D	green	green	N	Y	black	purple	Y	Y	green	green	Y	Y	Y
6	G	black	green	Y	Y	green	green	Y	Y	blue	green	Y	Y	Y
7	G	purple	purple	N	Y	green	green	N	Y	0	0	N	N	N
8	D	red	green	N	N	green	green	Y	Y	green	green	Y	Y	Y
9	D	black	purple	N	Y	red	red	Y	Y	blue	green	Y	Y	Y
10	G	black	green	N	Y	red	red	N	Y	red	red	N	Y	Y
11	G	blue	purple	N	Y	0	0	N	N	green	green	Y	Y	N
12	G	black	purple	Y	Y	blue	blue	Y	Y	green	green	Y	Y	Y
13	D	black	green	Y	Y	red	red	Y	Y	0	green	N	Y	N
14	D	blue	green	Y	Y	green	green	Y	Y	blue	green	Y	Y	Y
15	G	black	green	N	Y	black	green	N	Y	blue	green	Y	Y	N
16	D	black	red	Y	Y	black	black	Y	Y	green	green	N	Y	Y
17	D	black	green	Y	Y	green	green	Y	Y	blue	green	N	Y	Y
18	D	purple	green	N	Y	0	green	N	Y	blue	green	Y	Y	Y
19	G	purple	purple	Y	Y	red	red	Y	Y	green	green	Y	Y	Y
20	D	black	purple	N	Y	red	red	Y	Y	red	red	Y	Y	Y
21	G	green	green	Y	Y	black	green	Y	Y	red	red	Y	Y	Y
22	D	blue	red	Y	Y	black	green	Y	Y	green	red	Y	Y	Y
23	G	black	purple	N	Y	green	green	Y	Y	red	red	Y	Y	Y
24	G	black	green	Y	Y	blue	red	N	Y	0	0	N	N	N
25	G	black	purple	N	Y	green	green	Y	Y	red	red	Y	Y	Y
26	G	0	0	N	N	black	green	Y	Y	green	green	Y	Y	Y
27	D	red	red	Y	Y	red	red	Y	Y	red	red	Y	Y	Y
28	G	green	green	Y	Y	red	red	Y	Y	green	green	Y	Y	N
29	D	blue	purple	Y	Y	green	green	Y	Y	green	green	Y	Y	Y
30	D	blue	purple	Y	Y	black	green	N	Y	0	red	N	N	N
31	D	blue	green	N	Y	blue	purple	Y	Y	black	green	N	Y	N
32	G	green	green	Y	Y	blue	purple	Y	Y	green	green	Y	Y	Y
33	D	blue	blue	Y	Y	black	purple	Y	Y	red	red	N	Y	N

D= Domain, G=General, S=Color Solution was drawn in, A=Color target analogous product was written in, V=Valid solution by evaluator’s judgment, VS=Valid solution in the subject’s evaluation

Evaluator 2

	Design 1: Kayak				Design 2: Goggles				Design 3: Flour Sifter			
#	S	A	V	VS	A	V	VS	S	A	V	VS	S
1				N	red	red	Y	N	red	red	Y	N
2	green	green	Y	Y	green	green	Y	Y	blue	green	N	Y
3	purple	purple	Y	Y	blue	blue	N	Y	blue	red	Y	Y
4	green	green	N	Y	green	green	Y	Y	blue	green	N	Y
5	green	green	N	Y	black		Y	Y	blue	green	Y	Y
6	black	green	Y	Y	green	green	Y	Y	blue	green	Y	Y
7	purple	purple	N	Y	green	green	N	Y			N	N
8	green	green	N	Y	green	green	Y	Y	black	green	Y	Y
9	black	purple	N	Y	red	red	Y	N	blue	green	Y	Y
10	blue	green	N	Y			N	N			N	N
11	purple	purple	N	Y			N	N		green	N	Y
12	blue	purple	N	Y	blue	blue	Y	Y	blue	green	Y	Y
13	blue	green	Y	Y		red	Y	N		green	N	Y
14	blue	green	N	Y	green	green	Y	Y	blue	green	Y	Y
15		blue	N	Y		green	N	Y	blue	green	Y	Y
16	black	black	Y	Y	black	black	Y	Y			N	Y
17	black	purple	N	Y		green	Y	Y		green	N	Y
18		green	N	Y		green	N	Y	blue	green	Y	Y
19		purple	Y	Y	red	red	Y	N	blue	green	Y	Y
20		purple	N	Y	red	red	N	Y	red		N	Y
21	green	green	Y	Y	green	green	Y	Y	red	red	Y	N
22	blue	blue	N	Y	black	green	Y	Y	blue		Y	Y
23	black	purple	N	Y	green	green	Y	Y	red		N	N
24		green	N	Y		red	N	Y			N	Y
25	black	purple	N	Y	green	green	Y	Y	red		Y	N
26		red	N	N	black	green	Y	Y	green	green	Y	Y
27	red	green	Y	N			N	N	red	green	Y	Y
28		green	N	Y		red	N	N		green	N	Y
29	purple	purple	Y	Y	green	green	Y	Y		green	Y	Y
30	blue	blue	Y	Y		green	N	Y	red	red	N	N
31		green	N	Y	blue	purpl e	Y	Y		green	N	Y
32	green	green	Y	Y	blue	blue	Y	Y	green	green	Y	Y
33	blue	blue	Y	Y	black	black	Y	Y		green	N	N

RAW SURVEY DATA

							Seen Solution?		
Four Digit Code	English Years	Others Languages	Full Time	Part Time	Heard Exp.	Functional Models	D1	D2	D3
1126	23	E	1	0	N	1 to 3	N	N	N
3075	22	E	0	0	N	0	N	Y	N
0415	22	E	0	0	N	1 to 3	N	Y	N
0512	16	N/A	0	0	N	1 to 3	Y	N	N
1129	22	E	0.916	0.375	N	1 to 3	Y	Y	N
0726	22	E	0.25	0	N	1 to 3	N	N	N
0308	21	E, T, H	0.5	0	N	1 to 3	N	N	N
0605	5	E, S, P	0.5	0.3	N	1 to 3	N	N	N
0711	21	E	0	0	N	1 to 3	N	Y	N
0927	22	E	0.5	0.5625	N	1 to 3	N	Y	N
0919	27	E	0.58	0.15625	N	1 to 3	N	Y	N
0303	22	E	0.33	0	N	1 to 3	N	N	N
1107	22	E	0.5	0.875	N	1 to 3	Y	N	N
0909	22	E	0	0	N	0	N	N	N
8240	13	E, R	0	0	N	1 to 3	N	N	Y
0616	27	N/A	0	0	N	1 to 3	Y	Y	N
0504	22	E, J	0.25	0	N	0	N	N	N
1210	22	E	0	0.083	N	1 to 3	Y	N	Y
0724	21	E	0	0	N	1 to 3	N	N	N
0226	22	E	0	0	N	1 to 3	N	N	N
1006	22	E	0.166	0	N	1 to 3	N	N	N
0428	21	E	0	0	N	0	N	N	N
0415	22	E	0	0.020	N	1 to 3	N	N	N
0910	22	E	0.25	0	N	1 to 3	N	N	Y
1207	22		0.25	0.75	N	1 to 3	Y	N	N
1123	16	E, S	0.5	0	N	1 to 3	N	N	N
0213	22	E	0.5	0	N	0	N	N	N
0915	22	E, S, M	0.5	0	N	1 to 3	N	N	N
0609	18	E	0	0	N	1 to 3	N	N	N
0929	18	E, S	0	0	N	1 to 3	N	N	N
1123	22	E	0	0	N	4 to 6	N	N	N
0702	22	E, K, C	0.83	0	N	0	N	N	N
0902	23	E	0	0	N	0	N	Y	N
		E = English, T = Tamil, H = Hindi, S = Spanish, P = Portuguese, R = Russian, M = Malayalam, K = Korean, C = Chinese							

Four Digit Code	Comments
1126	
3075	
0415	
0512	
1129	
0726	I have heard of a type of water ski with this [hydrofoil]
0308	
0605	
0711	
0927	Participant actually rides. Mask fogs up
0919	
0303	Under Language: Spanish, but not fluently at all
1107	Too long for each design. Good Overall
0909	
8240	
0616	
0504	Under Language: Spanish (reading only)
1210	Used to kayak with friends discussed problem
0724	
0226	
1006	I really could not make a good connection between the toy and the mini-sifter (or the constrained problem solution)
0428	
0415	
0910	Some sugar or snacks would be nice
1207	
1123	
0213	
0915	
0609	Under Work: I don't know if it counts, but I have done FSAE for 3 years. Under Functional Models: I don't know exactly what counts as a functional model, but I have built 3 FSAE cars which included many parts that I designed
0929	
1123	
0702	
0902	

Appendix D: Analogy Experiment 3 Materials

PARTICIPANT INSTRUCTION SHEET: DAY 1, DOMAIN

Month and day of your birthday ☐☐ ☐☐
(or another 4-digit code you can remember)

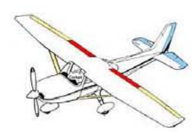
You will learn about a set of products. You will then be asked to **recall the verbal descriptions.**

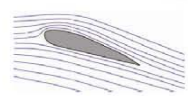
Please do not discuss this experiment with your classmates until after December 1st.

Multiple colors of pens are being used to keep track of when items are written. If you have any questions at any time during this experiment, please raise your hand.

Task 1: Read the descriptions for how the following five devices work. These devices may be familiar to you, but you may not have thought about the details of how they work. After studying how the devices work you will be asked to **recall the verbal description of each device.** You will have **30 minutes** to complete this task.

Airplane
An airplane flies through the air allowing rapid flights. The airfoil shape of the airplane's wings causes a lift force as the plane flies through the air. As the plane increases altitude there is less drag due to the air being less dense.





Section view of a Wing

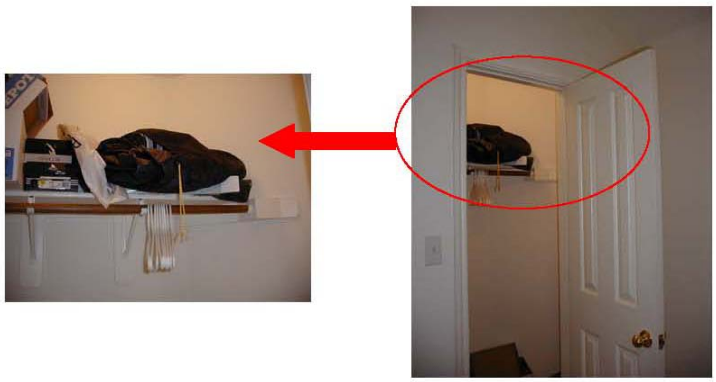
Kitchen flipper

This spatula meshes with the hand and slides between the pancake and the pan. It also supports the pancake and allows the pancake to be flipped.

Air Mattress

The air bed is inflated with air in the home where it will be slept on. The air required to cause the air bed to inflate is available in the home. The primary purpose of the air bed is to provide a comfortable bed for the person. The air bed accomplishes this by using the air to inflate and deflate the air bed. This allows the device to be easily put into a closet.





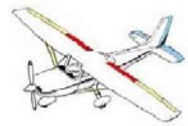
Shape-o-toy

This toy serves a number of purposes. The two halves contain the blocks allowing them to be carried. A child pulls the two halves apart and the blocks fall out.

Recall How the Device Works

From memory, **reproduce the verbal descriptions** of the devices that you just read.

Airplane



Kitchen flipper

Air Mattress

Travel Cart

The travel cart carries a large suitcase easily. The bottom and the wheels fold-up causing the travel device to have a smaller volume. The handle telescopes to fit in an overhead storage bin.

Shape-o-toy

Travel Cart

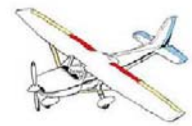
Solutions

Compare your descriptions to the ones shown on the following pages. What is different and what is similar? Look at the sentences you wrote. Give yourself one point for each of your sentences that are generally correct. Write the number of generally correct sentences on the following solution pages.

Number of Correct Sentences for this device: ________

Airplane

An airplane flies through the air allowing rapid flights. The airfoil shape of the airplane's wings causes a lift force as the plane flies through the air. As the plane increase altitude there is less drag due to the air being less dense.



Section view of a Wing

Number of Correct Sentences for this device: ________

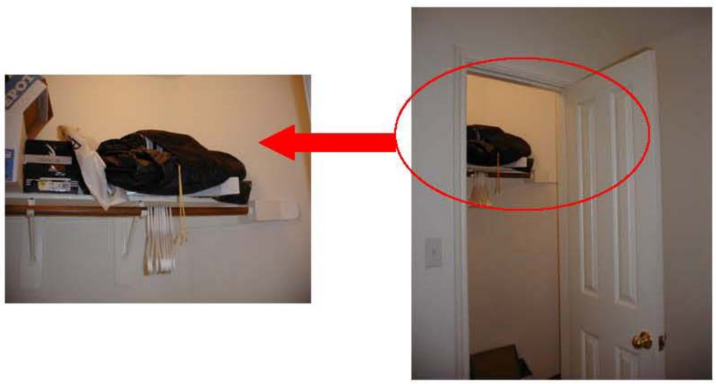
Kitchen flipper

This spatula meshes with the hand and slides between the pancake and the pan. It also supports the pancake and allows the pancake to be flipped.

Number of Correct Sentences for this device: ________

Air Mattress

The air bed is inflated with air in the home where it will be slept on. The air required to cause the air bed to inflate is available in the home. The primary purpose of the air bed is to provide a comfortable bed for the person. The air bed accomplishes this by using the air to inflate and deflate the air bed. This allows the device to be easily put into a closet.



Number of Correct Sentences for this device: ________

Shape-o-toy

This toy serves a number of purposes. The two halves contain the blocks allowing them to be carried. A child pulls the two halves apart and the blocks fall out.

Number of Correct Sentences for this device: ________

Travel Cart

The travel cart carries a large suitcase easily. The bottom and the wheels fold-up causing the travel device to have a smaller volume. The handle telescopes to fit in an overhead storage bin.

PARTICIPANT INSTRUCTION SHEET: DAY 1, GENERAL

Month and day of your birthday ☐☐ ☐☐

(or another 4-digit code you can remember)

You will learn about a set of products. You will then be asked to **recall the verbal descriptions.**

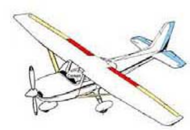
Please do not discuss this experiment with your classmates until after December 1st.

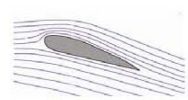
Multiple colors of pens are being used to keep track of when items are written. If you have any questions at any time during this experiment, please raise your hand.

Task 1: Read the descriptions for how the following five devices work. These devices may be familiar to you, but you may not have thought about the details of how they work. After studying how the devices work you will be asked to **recall the verbal description of each device.** You will have **30 minutes** to complete this task.

<u>Device for Rapid Travel</u>

This device moves through a fluid allowing rapid travel. The shape of the device's extensions causes a net force as the device moves through the fluid. As the device changes position there is less resistance due to the fluid being less dense.





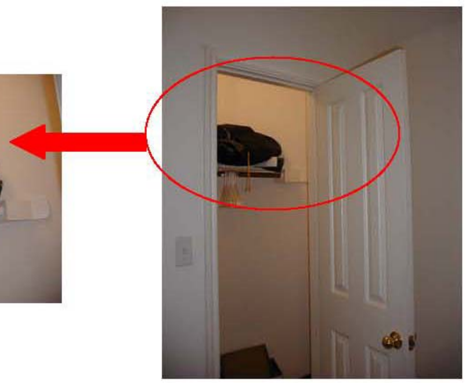
Section view of an extension

<u>Device to separate and move object</u>

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

Device to import and export a substance

The device is filled with a substance at the location where it will be used. The substance required to cause the device to function is available at the location. The primary purpose of the device is to distribute the force of the person during the task. The device accomplishes this by importing, storing and exporting the substance. This allows the device to be easily stored.



Device to hold and release substances

This device serves a number of functions. The two sections hold the substances allowing them to be moved. A force separates the sections and the substance is released.

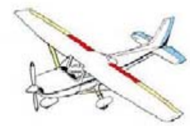
Load positioning device

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

Recall How the Device Works

From memory, **reproduce the verbal descriptions** of the devices that you just read.

Device for Rapid Travel



Device to separate and move object

Device to import and export a substance

Device to hold and release substances

Load positioning device

Solutions

Compare your descriptions to the ones shown on the following pages. What is different and what is similar? Look at the sentences you wrote. Give yourself one point for each of your sentences that are generally correct. Write the number of generally correct sentences on the following solution pages.

Number of Correct Sentences for this device: ________

Device for Rapid Travel

This device moves through a fluid allowing rapid travel. The shape of the device's extensions causes a net force as the device moves through the fluid. As the device changes position there is less resistance due to the fluid being less dense.

Section view of an extension

Number of Correct Sentences for this device: ________

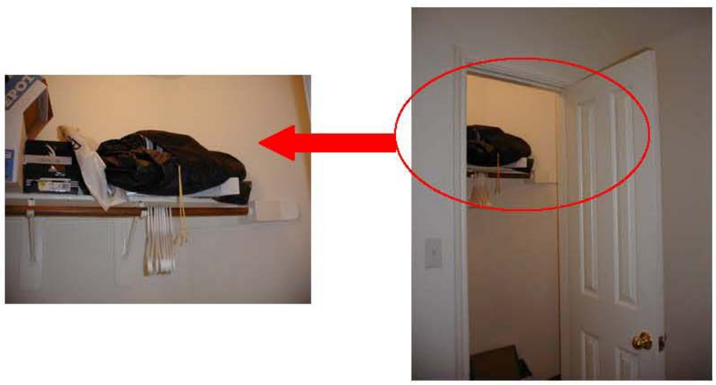
Device to separate and move object

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

Number of Correct Sentences for this device: ________

Device to import and export a substance
The device is filled with a substance at the location where it will be used. The substance required to cause the device to function is available at the location. The primary purpose of the device is to distribute the force of the person during the task. The device accomplishes this by importing, storing and exporting the substance. This allows the device to be easily stored.





Number of Correct Sentences for this device: ________

Device to hold and release substances

This device serves a number of functions. The two sections hold the substances allowing them to be moved. A force separates the sections and the substance is released.

Number of Correct Sentences for this device: ________

Load positioning device

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

PARTICIPANT INSTRUCTION SHEET: DAY 2, DOMAIN

Four Digit Code (Month and day of your birthday) ☐☐ ☐☐

Design Problems

- Generate as many solutions as possible in the allotted time to the following design problems.
- Write down everything you can think of even if it does not meet the constraints of the problem.
- The goal is to generate as many solutions with as high of quality and with as great of variety as possible.
- Wild, technically infeasible and far out ideas are also encouraged. This helps to generate unique feasible solutions.

Sketch and/or use words to describe your ideas.

Please do not discuss this experiment with your classmates until after December 1st

Design Problem 1

Design a piece of exercise equipment that can be carried in a suitcase. You will have 11 minutes.

Design Problem 1- Additional Constraints

Design a piece of exercise equipment that can be carried in a suitcase. Here are the additional requirements:

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

You have 11 minutes to **generate additional solutions** that meet these constraints.

Put a check mark next to all of your solutions that meet these constraints including the ones you generated previously.

Design Problem 2

Design a kitchen utensil to sprinkle flour over a counter.
You will have 11 minutes.

<u>Design Problem 2</u>- **<u>Additional Constraints</u>**

Design a kitchen utensil to sprinkle flour over a counter.

- The only material that is available to build the kitchen utensil from is various thicknesses of stainless steel wire.
- The entire kitchen utensil must be made from only **one** thickness of wire.
- The kitchen utensil must be **manufactured by bending** and cutting the wire only.
- The kitchen utensil must be capable of containing the flour and carrying the flour 1 meter without losing the flour.

You have 11 minutes to **generate additional solutions** that meet these constraints.

Put a **check mark next to all of your solutions that meet these constraints** including the ones you generated previously.

Analogies

1. On previous sheets write down a description of any analogies you used to help you generate ideas next to your solution. For example, a pair of scissors could be used as an analogy for designing a set of finger nail clippers. If you had used this analogy, you would write "scissors" **next to your solution.**

2. Try using analogies to help find solutions to the <u>constrained design problems</u>. Try to find at least one analogy and solution for each constrained design problem. You will have **10 minutes**.

3. Be sure to use sketches and/or words to describe your solution and write down a description of the analogy.

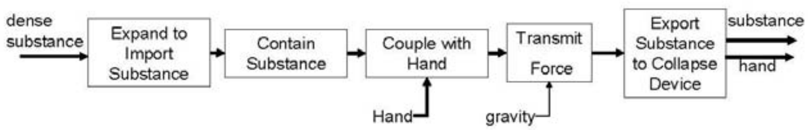
Functional Models

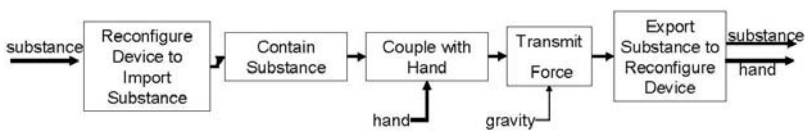
Use the following functional models for the design problems to help you find solutions to the **constrained design problems**. There are three different functional models for each design problem. You can use any or all of them to help you solve the design problem. You will have a **total of 15 minutes for the two design problems**.

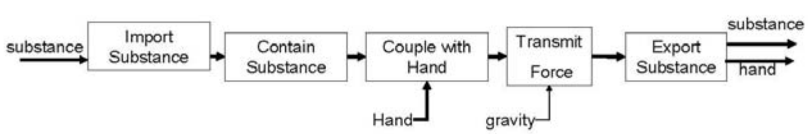
Design Problem 1

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

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



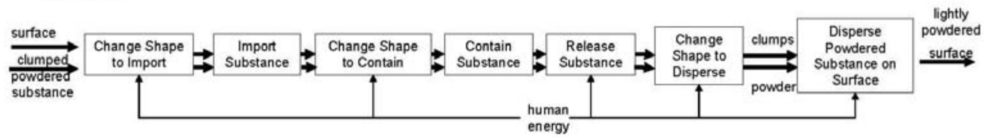


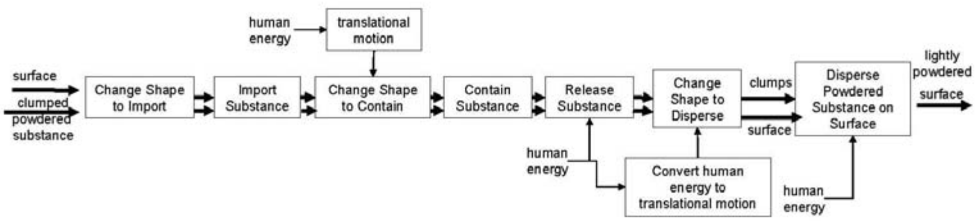


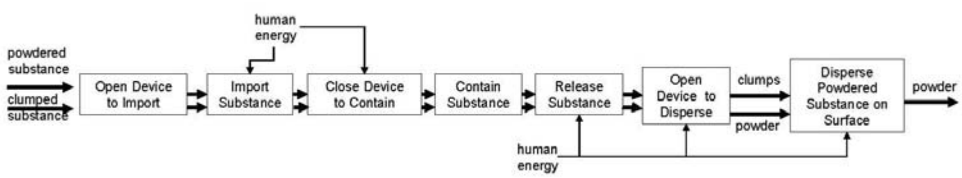
Design Problem 2

Design a kitchen utensil to sprinkle flour over a counter.

- The only material that is available to build the kitchen utensil from is various thicknesses of stainless steel wire.
- The entire kitchen utensil must be made from only **one** thickness of wire.
- The kitchen utensil must be **manufactured by bending** and cutting the wire only.
- The kitchen utensil must be capable of containing the flour and carrying the flour 1 meter without losing the flour.







Analogies part 2

1. Some of the products you saw in the experiment last week can be used as analogies to develop solutions to the **constrained design problems**. **Find solutions based on the products from the experiment last week.**

2. On previous sheets be sure to write down which product is analogous next to your solution and describe the solution.

You will have 6.5 minutes to do this.

Analogous Products from Last Week

Shown below is a list of the design problems and the product from the experiment last week or analogous products that can be used to find a solution to the constrained design problem. **If you found a solution to the <u>constrained design problem</u> using the product listed below place a check next to your solution on previous sheets.**

If you did not use the analogy listed, see if you can use the analogies given below to find a solution. You will have 7 minutes to do this. Please raise your hand when you are finished.

	Did you find a solution to the **<u>constrained problem</u>** based on the listed analogy?	
Design Problem 1- Analogy is an air mattress	☐ Yes	☐ No
Design Problem 2- Analogy is the toy	☐ Yes	☐ No

Post-Session Questions

For the analogies on the previous page, describe the features from the analogous product that you used in your solution.

Design Problem 1: air mattress
Features used in your solution from the air mattress:

Design Problem 2: the toy
Features used in your solution from the toy:

Post-Session Questions

1. How many years have you lived in an English-speaking country? _________ years

2. List all languages you read and/or speak fluently:

   ___________________________ ___________________________
   ___________________________ ___________________________
   ___________________________ ___________________________

3. How much engineering work experience (experience not part of a class) do you have?
   Full-time (35 + hrs/week) engineering work (internships or full-time work)
   _________months __________years

   Part-time (less than 35 hrs/week) engineering work _________hrs/week
   _________months __________years

4. Did you hear about **any of the design problems** prior to participating in the experiment? Please be honest, your reply will have no effect on the credit you are given.
   ☐ Yes ☐ No

5. How many functional models have you done?
   - ☐ 0 functional models: No experience or no idea what a functional model is.
   - ☐ 1-3 functional models: A little experience
   - ☐ 4-6 functional models: Some experience
   - ☐ 7+ functional models: A lot of experience

6. Have you seen or heard of any of the following products before this experiment?

AquaBells® Travel Weights ☐ Yes ☐ No

Precision Mini-Sifter ☐ Yes ☐ No

	Strongly Disagree	Disagree	Neither Agree Nor Disagree	Agree	Strongly Agree
I ran out of **time** before I ran out of ideas.					
I ran out of **ideas** before I ran out of time.					

Please state any additional comments you have about the experiment. Use the back of the paper if needed.

PARTICIPANT INSTRUCTION SHEET: DAY 2, GENERAL

Four Digit Code (Month and day of your birthday) ☐☐ ☐☐

Design Problems

- Generate as many solutions as possible in the allotted time to the following design problems.
- Write down everything you can think of even if it does not meet the constraints of the problem.
- The goal is to generate as many solutions with as high of quality and with as great of variety as possible.
- Wild, technically infeasible and far out ideas are also encouraged. This helps to generate unique feasible solutions.

Sketch and/or use words to describe your ideas.

Please do not discuss this experiment with your classmates until after December 1st

Design Problem 1

Design an exercise device that can be carried for long distances in a 3 ft^3 container. You will have 11 minutes.

Design Problem 1- Additional Constraints

Design an exercise device that can be carried for long distances in a 3 ft^3 container. Here are the additional requirements:

- Provides **at least 15 lbs of resistance**
- **Adds less than 4 lbs** to the 3 ft^3 container.
- **Maximum volume is 120 in^3** (~750 cm^3).
- It must be capable of being used for movements normally done with hand weights (see examples below).
- It **cannot use strips or cords of elastomer** (rubber) for resistance.

You have 11 minutes to **generate additional solutions** that meet these constraints.

Put a check mark next to all of your solutions that meet these constraints including the ones you generated previously.

Design Problem 2

Design a device to disperse a light coating of a powdered substance that forms clumps over a surface. You will have 11 minutes.

Design Problem 2- Additional Constraints

Design a device to disperse a light coating of a powdered substance that forms clumps over a surface.

- The only material that is available to build the device from is various thicknesses of stainless steel wire.
- The entire device must be made from only **one** thickness of wire.
- The device must be **manufactured by bending** and cutting the wire only.
- The device must be capable of containing the powdered substance and carrying the powdered substance 1 meter without losing the powdered substance.

You have 11 minutes to **generate additional solutions** that meet these constraints.

Put a **check mark next to all of your solutions that meet these constraints** including the ones you generated previously.

Analogies

1. On previous sheets write down a description of any analogies you used to help you generate ideas next to your solution. For example, a pair of scissors could be used as an analogy for designing a set of finger nail clippers. If you had used this analogy, you would write "scissors" **next to your solution.**

2. Try using analogies to help find solutions to the constrained design problems. Try to find at least one analogy and solution for each constrained design problem. You will have **10 minutes**.

3. Be sure to use sketches and/or words to describe your solution and write down a description of the analogy.

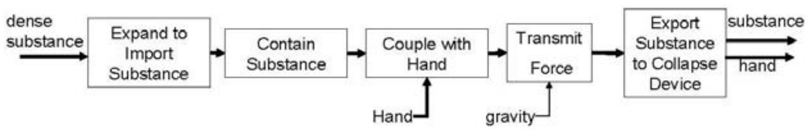
Functional Models

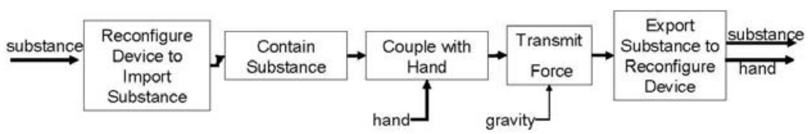
Use the following functional models for the design problems to help you find solutions to the **constrained design problems**. There are three different functional models for each design problem. You can use any or all of them to help you solve the design problem. You will have a **total of 15 minutes for the two design problems**.

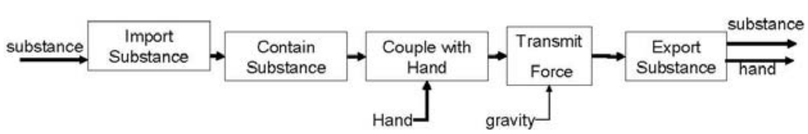
Design Problem 1-

Design an exercise device that can be carried for long distances in a 3 ft^2 container. Here are the additional requirements:

- Provides **at least 15 lbs of resistance**
- **Adds less than 4 lbs** to the 3 ft^2 container.
- **Maximum volume is 120 in^3** (~750 cm^3).
- It must be capable of being used for movements normally done with hand weights (see examples below).
- It **cannot use strips or cords of elastomer** (rubber) for resistance.



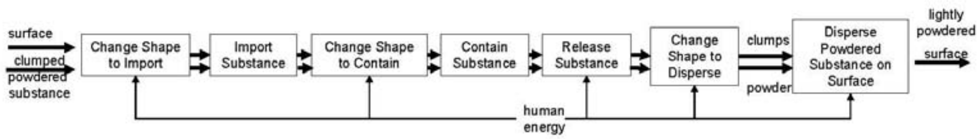


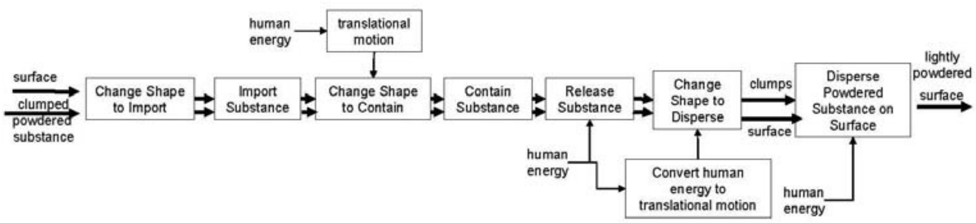


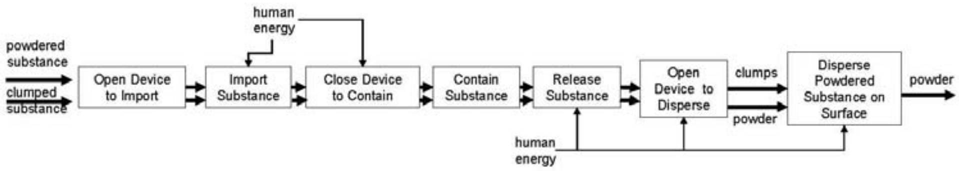
Design Problem 2-

Design a device to disperse a light coating of a powdered substance that forms clumps over a surface.

- The only material that is available to build the device from is various thicknesses of stainless steel wire.
- The entire device must be made from only **one** thickness of wire.
- The device must be **manufactured by bending** and cutting the wire only.
- The device must be capable of containing the powdered substance and carrying the powdered substance 1 meter without losing the powdered substance.







Analogies part 2

1. Some of the products you saw in the experiment last week can be used as analogies to develop solutions to the **constrained design problems**. **Find solutions based on the products from the experiment last week**.

2. On previous sheets be sure to write down which product is analogous next to your solution and describe the solution.

You will have 6.5 minutes to do this.

Analogous Products from Last Week

Shown below is a list of the design problems and the product from the experiment last week or analogous products that can be used to find a solution to the constrained design problem. **If you found a solution to the <u>constrained design problem</u> using the product listed below place a check next to your solution on previous sheets.**

If you did not use the analogy listed, see if you can use the analogies given below to find a solution. You will have 7 minutes to do this. Please raise your hand when you are finished.

	Did you find a solution to the **<u>constrained problem</u>** based on the listed analogy?	
Design Problem 1- Analogy is an air mattress	☐ Yes	☐ No
Design Problem 2- Analogy is the toy	☐ Yes	☐ No

Post-Session Questions

For the analogies on the previous page, describe the features from the analogous product that you used in your solution.

Design Problem 1: air mattress
Features used in your solution from the air mattress:

Design Problem 2: the toy
Features used in your solution from the toy:

Post-Session Questions

1. How many years have you lived in an English-speaking country? _________ years

2. List all languages you read and/or speak fluently:

   ___________________________ ___________________________
   ___________________________ ___________________________
   ___________________________ ___________________________

3. How much engineering work experience (experience not part of a class) do you have?
   Full-time (35 + hrs/week) engineering work (internships or full-time work)
   _________months __________years

   Part-time (less than 35 hrs/week) engineering work _________hrs/week
   _________months __________years

4. Did you hear about **any of the design problems** prior to participating in the experiment? Please be honest, your reply will have no effect on the credit you are given.
   ☐ Yes ☐ No

5. How many functional models have you done?
   - ☐ 0 functional models: No experience or no idea what a functional model is.
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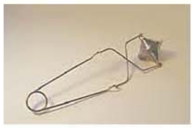
6. Have you seen or heard of any of the following products before this experiment?

AquaBells® Travel Weights ☐ Yes ☐ No



Precision Mini-Sifter ☐ Yes ☐ No

	Strongly Disagree	Disagree	Neither Agree Nor Disagree	Agree	Strongly Agree
I ran out of **time** before I ran out of ideas.					
I ran out of **ideas** before I ran out of time.					

Please state any additional comments you have about the experiment. Use the back of the paper if needed.

EXPERIMENTER SCRIPT: DAY 1, FOR GROUPS DOMAIN AND GENERAL

Experimenter script: **(1& 2) General Source & Domain Specific Source**
Items required for the experiment

- ☐ Participant Instruction Packets
- ☐ Consent forms
- ☐ Stop watch
- ☐ Multiple colored writing utensils (black, red)
- ☐ Extra paper
- ☐ Stapler

a) Give participants the consent form
b) Black pens

1) **"This study is evaluating various skills used in the design process. Your task today is to understand how a machine works. Next week you will generate ideas for some design problems. The total time required for this study is 3 hours, 1 hour today and two hours next week. If you agree to participate please sign the consent form. Any questions?"**

a) Collect signed form
b) Give participant a copy of the consent form

2) Encode the sources phase

"Write the Month and Day of your birthday or another four digit code you will remember next week in the upper right-hand corner. This will be used to match your results from this experiment to the results from the second experiment."

"You will have 30 minutes to study the following 5 products. At the end of the 30 you will be given a quiz requiring you to write down the product descriptions word for word. Multiple colors of pens are being used to keep track of when items are written. If you have any questions at any time during this experiment, please raise your hand."

"Read the descriptions for how the following five devices work. These devices may be familiar to you, but you may not have thought about the details of how they work. After studying how the devices work you will be asked to recall the verbal description of each device. You can use any memory tricks you know to help you remember the devices.

Remember the amount of extra credit you will receive depends on your performance.

Go ahead and start. If you have any questions please raise your hand."

At 15 minutes: **"You have only 15 minutes left to finish memorizing the verbal descriptions"**

a) Give participants Task 1a: Study the devices
    (1) make sure all participants are using black pen or pencil

3) Recall how the devices work
    i) Take the Encode the source sheets
    ii) give them the quiz "Recall the how the devices work"

"Please stop what you are doing. Turn over the sheets and place them off to the side. Be sure you can not read the information through the backside of the paper."

"For each of the five following products, as best as you can, please write down a word for word description of the device. You will have up to 15 minutes to do this. Please raise your hand when you are finished."

4) Evaluate your results:

"You are now being asked to evaluate your results. Give your self one point for each sentence that says pretty much the same thing as the solution sentence. Be sure to write the number of generally correct sentences on the following solution pages. You will have up to 10 minutes to do this. Bring me all of your sheets when you are finished."

a) Give back Study the devices.
b) Take away Black and give them **red.** Participants write down their scores

5) End of the experiment: **"Thank you for your participation. Please do not discuss this experiment with your classmates until after Saturday, Dec. 1st since discussing the experiment could bias the data. See you next week at this location at the same time to do some idea generation."**

EXPERIMENTER SCRIPT: DAY 2, DOMAIN

Experimenter script: **(1) Domain Specific Problem Description**

Items required for the experiment

- ☐ Participant Instruction Packets
- ☐ Stop watch
- ☐ Multiple colored writing utensils (black, blue, purple, pink (analogy extension), orange (function structures), green, red)
- ☐ Extra paper
- ☐ Stapler

a) Give participants the first design problem
b) Black pens

1) Black- Design Problem 1**-**
"This study is evaluating various skills used in the design process. Your task today is to generate ideas for a series of design problems. The time required for this study today is two hours. Please turn over the sheet. "

- **Generate as many solutions as possible in the allotted time to the following design problems.**
- **Write down everything you can think of even if it does not meet the constraints of the problem.**
- **The goal is to generate as many solutions with as high of quality and with as great of variety as possible.**
- **Wild, technically infeasible and far out ideas are also encouraged. This helps to generate unique feasible solutions.**

Sketch and/or use words to describe your ideas

You will have 11 minutes to generate solutions to the design problem.

Multiple colors of pens are being used to keep track of when items are written. If you have any questions at any time during this experiment, please raise your hand.

Design Problem 1: Design a piece of exercise equipment that can be carried in a suitcase. You will have 11 minutes."

a) make sure all participants are using black pen or pencil

2) Design Problem 1- Constrained
   a) Give them the next sheet.
   b) Take away black give them blue

"Please stop. Switch to the Blue pen and flip over the next sheet. Constrained design problem 1: Design a piece of exercise equipment that can be carried in a suitcase. The additional constraints are:

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

You have 11 minutes to generate additional solutions that meet these constraints.

Put a check mark next to all of your solutions that meet these constraints including the ones you generated previously."

   c) Check Blue.

3) Design Problem 2
   a) Give them the next sheet.

"Please stop. Switch to the Black pen and flip over the next sheet. Design Problem 2: Design a kitchen utensil to sprinkle flour over a counter. You will have 11 minutes. Go ahead and start. "

   b) Check **Black.**

4) Design Problem 3- Constrained
   a) Take away **Black** and give them **Blue.**
   b) Give them the next sheet.

"Please stop. Switch to the Blue pen and flip over the next sheet. Design Problem 2: Design a kitchen utensil to sprinkle flour over a counter.

- **The only material that is available to build the kitchen utensil from is various thicknesses of stainless steel wire.**
- **The entire kitchen utensil must be made from only one thickness of wire.**
- **The kitchen utensil must be manufactured by bending and cutting the wire only.**
- **The kitchen utensil must be capable of containing the flour and carrying the flour 1 meter without losing the flour.**

You have 11 minutes to generate additional solutions that meet these constraints.

Put a check mark next to all of your solutions that meet these constraints including the ones you generated previously. Go ahead and start. "

5) Break **"Please turn all of your sheets over and take a two minute break. Please do not discuss the experiment or your solutions during the break."**

6) Analogies
   a) Take blue give them purple
   b) Give them the next sheet.

"Step 1: On your previous sheets write down a description of any analogies you remember using to help you generate ideas next to the solution you generated. For example a pair of scissors could be used as an analogy for designing a set of finger nail clippers. If you had used this analogy, you would write "scissors" next to your solution.

If you did not use any analogies then do not write anything down.

Step 2: try using analogies to help find solutions to the <u>constrained design problems</u>. Try to find at least one analogy for each constrained design problem. Be sure to 1. Describe your solution. Just stating what the analogy is, is not enough. Describe the solution. and 2. Write down the analogous device next to the solution. You will have 10 minutes. Go ahead and start. "

Give a **Purple** pen. List any analogies you used. Use analogies.

7) **Analogies**—Extension
   a) Take purple give them pink

You now have 10 additional minutes to generate more solutions to the constrained design problems using analogies. Be sure to 1. Describe your solution and 2. Write down the analogous device next to the solution. You will have 10 minutes. Go ahead and start. "

8) **Functional Models**
   a) Next sheet
   b) Take pink **give them orange**

Use the following functional models for the design problems to help you find solutions to the constrained design problems. There are three different functional models for each design problem. You can use any or all of them to help you solve the design problem. You will have a total of 15 minutes for the two design problems.

9) **Analogies** part 2
   a) Give them the next sheet.
   b) Take light blue **give green**

"Some of the products you saw in the experiment last week can be used as analogies to develop solutions the <u>constrained design problems</u>. Find solutions based on the products from the experiment last week.

I will not tell you what the devices were last week. You will have to rely on your memory.

Be sure to write down which product is analogous. You may have already used some of the products for analogies. Please write these down also on your previous sheets.

Be sure to do two things: 1. describe the solution and 2. write down the analogous product.

You will have 6 and a half minutes to do this. Go ahead and start. "
   c) Give **Green** pen.

10) Tell them which devices are analogous
   a) Give **Red** pen.
   b) Give them the next sheet.

"Shown below is a list of the design problems and the product from the experiment last week that can be used to find a solution to the constrained design problem. If you found a solution to the <u>constrained design problem</u> using the product listed below place a check next to your solution on your previous sheets.

If you did not use the analogy listed, see if you can use the analogies given below to find a solution.

Be sure to do two things: 1. Place a red check next to your picture of the solution using the listed analogy and 2. Find new solutions if you did not use the analogy listed

You will have up to 6.5 minutes to do this. Please raise your hand when you are finished. Go ahead and start. "

<u>11) Describe Features</u>
"For the analogies mentioned on the previous page, write a brief description of the features you used from the analogy to develop your solution.

12) End of the experiment:
Survey: **"This experiment is testing the effects on design by analogy of giving engineers either a very abstract description of a product or a very domain specific description. Due to the fact all descriptions are in English, how long you have spoken English and other languages you are fluent in may affect the results so the survey asks a few questions regarding your language skills."**

"Thank you for your participation. Please do not discuss this experiment with your classmates until after December 1st since discussing the experiment will bias the data."

Criteria 1st design problems >=6 concept
Constrained >=4
New analogies >=8
Functional models >=6
Very unusual and unique solutions

EXPERIMENTER SCRIPT: DAY 2, GENERAL

Experimenter script: **(1) General Problem Description**

Items required for the experiment

- ☐ Participant Instruction Packets
- ☐ Stop watch
- ☐ Multiple colored writing utensils (black, blue, purple, pink (analogy extension), orange (function structures), green, red)
- ☐ Extra paper
- ☐ Stapler

a) Give participants the first design problem
b) Black pens

1) Black- Design Problem 1-
"This study is evaluating various skills used in the design process. Your task today is to generate ideas for a series of design problems. The time required for this study today is two hours. Please turn over the sheet. "

- **Generate as many solutions as possible in the allotted time to the following design problems.**
- **Write down everything you can think of even if it does not meet the constraints of the problem.**
- **The goal is to generate as many solutions with as high of quality and with as great of variety as possible.**
- **Wild, technically infeasible and far out ideas are also encouraged. This helps to generate unique feasible solutions.**

Sketch and/or use words to describe your ideas

You will have 11 minutes to generate solutions to the design problem.

Multiple colors of pens are being used to keep track of when items are written. If you have any questions at any time during this experiment, please raise your hand.

Design Problem 1: Design Problem 1: Design an exercise device that can be carried for long distances in a 3 ft^3 container
You will have 11 minutes."

a) make sure all participants are using black pen or pencil

2) Design Problem 1- Constrained
   a) Give them the next sheet.
   b) Take away black give them blue

   "Please stop. Switch to the Blue pen and flip over the next sheet. Design Problem 1: Design an exercise device that can be carried for long distances in a 3 ft^3 container. Here are the additional requirements:

   - **Provides at least 15 lbs of resistance**
   - **Adds less than 4 lbs to the 3 ft^3 container.**
   - **Maximum volume is 120 in^3 (~750 cm^3).**
   - **It must be capable of being used for movements normally done with hand weights (see examples below).**
   - **It cannot use strips or cords of elastomer (rubber) for resistance.**

   You have 11 minutes to generate additional solutions that meet these constraints.

   Put a check mark next to all of your solutions that meet these constraints including the ones you generated previously."

   c) Check Blue.

3) Design Problem 2
   a) Give them the next sheet.

"Please stop. Switch to the Black pen and flip over the next sheet. Design Problem 2- Design a device to disperse a light coating of a powdered substance that forms clumps over a surface.

You will have 11 minutes. Go ahead and start. "

   b) Check **Black.**

4) Design Problem 3- Constrained
   a) Take away **Black** and give them **Blue.**
   b) Give them the next sheet.

"Please stop. Switch to the Blue pen and flip over the next sheet.

<u>Design Problem 2-</u>

Design a device to disperse a light coating of a powdered substance that forms clumps over a surface.

- **The only material that is available to build the device from is various thicknesses of stainless steel wire.**
- **The entire device must be made from only one thickness of wire.**
- **The device must be manufactured by bending and cutting the wire only.**
- **The device must be capable of containing the powdered substance and carrying the powdered substance 1 meter without losing the powdered substance.**

You have 11 minutes to generate additional solutions that meet these constraints. Put a check mark next to all of your solutions that meet these constraints including the ones you generated previously. Go ahead and start. "

5) Break **"Please turn all of your sheets over and take a two minute break. Please do not discuss the experiment or your solutions during the break."**

6) Analogies
   a) Take blue give them purple
   b) Give them the next sheet.

"Step 1: On your previous sheets write down a description of any analogies you remember using to help you generate ideas next to the solution you generated. For example a pair of scissors could be used as an analogy for designing a set of finger nail clippers. If you had used this analogy, you would write "scissors" next to your solution.

If you did not use any analogies then do not write anything down.

Step 2: try using analogies to help find solutions to the <u>constrained design problems</u>. Try to find at least one analogy for each constrained design problem. Be sure to 1. Describe your solution. Just stating what the analogy is, is not enough. Describe the solution. and 2. Write down the analogous device next to the solution. You will have 10 minutes. Go ahead and start. "

Give a **Purple** pen. List any analogies you used. Use analogies.

7) **Analogies**—Extension
   a) Take purple give them pink

You now have 10 additional minutes to generate more solutions to the constrained design problems using analogies. Be sure to 1. Describe your solution and 2. Write down the analogous device next to the solution. You will have 10 minutes. Go ahead and start. "

8) **Functional Models**
   a) Next sheet
   b) Take pink **give them orange**

Use the following functional models for the design problems to help you find solutions to the constrained design problems. There are three different functional models for each design problem. You can use any or all of them to help you solve the design problem. You will have a total of 15 minutes for the two design problems.

9) **Analogies** part 2
   a) Give them the next sheet.
   b) Take light blue **give green**

"Some of the products you saw in the experiment last week can be used as analogies to develop solutions the constrained design problems. Find solutions based on the products from the experiment last week.

I will not tell you what the devices were last week. You will have to rely on your memory.

Be sure to write down which product is analogous. You may have already used some of the products for analogies. Please write these down also on your previous sheets.

Be sure to do two things: 1. describe the solution and 2. write down the analogous product.

You will have 6 and a half minutes to do this. Go ahead and start. "
   c) Give **Green** pen.

10) Tell them which devices are analogous
   a) Give **Red** pen.
   b) Give them the next sheet.

"Shown below is a list of the design problems and the product from the experiment last week that can be used to find a solution to the constrained design problem. If you found a solution to the constrained design problem using the product listed below place a check next to your solution on your previous sheets.

If you did not use the analogy listed, see if you can use the analogies given below to find a solution.

Be sure to do two things: 1. Place a red check next to your picture of the solution using the listed analogy and 2. Find new solutions if you did not use the analogy listed

You will have up to 6.5 minutes to do this. Please raise your hand when you are finished. Go ahead and start. "

11) Describe Features
"For the analogies mentioned on the previous page, write a brief description of the features you used from the analogy to develop your solution.

12) End of the experiment:
Survey: **"This experiment is testing the effects on design by analogy of giving engineers either a very abstract description of a product or a very domain specific description. Due to the fact all descriptions are in English, how long you have spoken English and other languages you are fluent in may affect the results so the survey asks a few questions regarding your language skills."**

"Thank you for your participation. Please do not discuss this experiment with your classmates until after December 1st since discussing the experiment will bias the data."

Criteria 1st design problems >=6 concept
Constrained >=4
New analogies >=8
Functional models >=6
Very unusual and unique solutions

RAW DATA

				Design 1: AquaBells		
			color of correct analogy	color of labeled	correct mapping?	Valid in Subject's evaluation
Person	P1 cond.	P2 cond.				
1	domain	general	black	green	yes	yes
2	domain	general	orange	green	yes	yes
3	domain	general	orange	green	yes	yes
4	domain	general	pink	green	yes	yes
5	general	general	black	red	no	yes
6	general	general	orange	green	yes	yes
7	general	domain	blue	green	yes	yes
8	domain	domain	blue	green	yes	yes
9	general	domain	blue	green	yes	yes
10	general	domain	blue	green	yes	yes
11	domain	domain	orange	green	yes	yes
12	domain	domain	black	0	no	no
13	domain	domain	black	red	yes	yes
14	domain	domain	black	red	yes	yes
15	domain	domain	black	green	yes	yes
16	domain	domain	blue	green	yes	yes
17	domain	domain	blue	green	yes	yes
18	domain	domain	orange	green	yes	yes
19	domain	domain	blue	green	yes	yes

20	general	domain	black	green	yes	yes
21	domain	domain	green	green	no	yes
22	general	domain	blue	green	no	yes
23	general	domain	blue	green	yes	yes
24	general	domain	blue	red	yes	yes
25	general	domain	red	red	no	no
26	general	domain	black	red	yes	yes
27	general	domain	black	pink	yes	yes
28	general	domain	blue	red	yes	yes
29	general	domain	orange	green	yes	yes
30	general	general	black	green	yes	yes
31	domain	general	orange	green	yes	yes
32	domain	general	red	red	no	yes
33	general	general	0	0	no	yes
34	general	general	orange	green	yes	yes
35	general	general	black	green	yes	yes
36	domain	domain	black	green	yes	yes
37	domain	domain	blue	0	no	no
38	general	domain	blue	green	yes	yes
39	domain	general	black	green	yes	yes
40	general	general	orange	red	yes	yes
41	general	general	blue	green	yes	yes
42	domain	general	black	green	yes	yes
43	general	general	blue	green	yes	yes
44	domain	general	red	red	yes	yes
45	general	general	orange	green	yes	yes
46	general	general	orange	green	yes	yes
47	general	general	blue	green	yes	yes
48	domain	general	blue	green	yes	yes
49	domain	general	0	0	no	no
50	domain	domain	green	green	no	no
60	domain	general	pink	green	yes	yes
61	domain	general	pink	green	no	no
62	domain	general	0	0	no	yes
63	domain	general	orange	green	no	yes
64	general	general	orange	green	yes	yes
65	general	general	orange	green	yes	yes
66	domain	general	0	0	no	no
67	domain	general	orange	green	yes	yes
68	general	general	purple	green	yes	yes
69	domain	general	blue	green	yes	yes
70	domain	domain	black	green	yes	yes
71	domain	domain	black	green	yes	yes
72	general	general	orange	green	yes	yes

73	domain	general	black	green	yes	yes
74	domain	domain	red	red	yes	yes
75	general	domain	black	green	yes	yes
76	general	domain	blue	green	yes	yes
77	domain	domain	blue	green	yes	yes
78	domain	domain	green	green	no	yes
79	general	domain	orange	green	no	yes
80	general	domain	black	purple	yes	yes
81	general	domain	blue	green	yes	yes
82	general	domain	black	green	yes	yes
83	domain	domain	blue	green	no	no
84	domain	domain	black	green	yes	yes
85	general	domain	orange	green	yes	yes
86	domain	domain	red	red	no	yes
87	domain	general	orange	green	yes	yes
88	general	general	blue	red	no	yes
89	general	general	blue	green	no	yes
90	general	general	orange	green	yes	yes
91	general	general	orange	red	yes	no
92	domain	general	0	0	no	no
93	domain	general	orange	green	yes	yes
94	domain	general	0	0	no	no
101	general	domain	orange	green	yes	yes
102	domain	domain	black	green	yes	yes
103	general	domain	black	red	no	yes
105	domain	general	black	green	no	yes
106	general	general	blue	green	yes	yes
107	general	general	black	red	yes	yes
108	domain	general	orange	green	yes	yes
109	general	general	red	red	yes	yes

		Design 2: flour sifter			
	color of correct analogy	color of labeled	Valid solution	correct mapping?	Valid in Subject's evaluation
Person					
1	green	green	yes	yes	yes
2	red	red	no	no	yes
3	orange	red	no	no	yes
4	orange	green	yes	yes	yes
5	blue	green	yes	yes	yes
6	red	red	no	yes	yes
7	blue	red	yes	yes	yes

8	red	red	yes	yes	yes
9	pink	green	yes	yes	yes
10	orange	green	yes	yes	yes
11	black	red	no	no	yes
12	green	green	yes	yes	yes
13	green	green	yes	yes	yes
14	blue	green	yes	yes	yes
15	red	red	yes	yes	yes
16	blue	green	yes	yes	yes
17	green	green	yes	yes	yes
18	orange	green	yes	yes	yes
19	orange	red	yes	no	yes
20	orange	red	yes	yes	yes
21	blue	green	yes	yes	yes
22	blue	green	yes	yes	yes
23	blue	green	yes	no	yes
24	blue	red	yes	yes	yes
25	green	green	yes	yes	yes
26	blue	red	yes	no	yes
27	red	red	yes	yes	yes
28	blue	green	yes	yes	no
29	0	0	no	no	no
30	0	0	no	no	no
31	red	red	no	no	yes
32	orange	green	yes	yes	yes
33	green	green	yes	yes	yes
34	orange	green	yes	yes	yes
35	red	red	yes	yes	yes
36	orange	green	yes	yes	yes
37	red	red	yes	no	yes
38	0	0	no	no	no
39	red	red	no	no	no
40	blue	green	yes	yes	yes
41	blue	green	yes	yes	yes
42	blue	green	yes	yes	yes
43	red	red	yes	yes	yes
44	red	red	yes	yes	yes
45	orange	green	yes	yes	yes
46	blue	green	yes	yes	yes
47	green	green	yes	yes	yes
48	green	green	yes	yes	yes
49	green	green	yes	no	yes
50	blue	green	yes	yes	yes
60	green	green	yes	no	yes

61	green	green	yes	yes	yes
62	green	green	no	no	yes
63	blue	green	yes	yes	yes
64	blue	green	yes	yes	yes
65	blue	red	yes	yes	yes
66	0	0	no	no	no
67	orange	green	yes	no	yes
68	blue	red	yes	yes	yes
69	orange	red	yes	yes	yes
70	blue	green	yes	yes	yes
71	green	green	yes	yes	yes
72	orange	green	yes	yes	yes
73	blue	green	no	yes	yes
74	green	green	yes	yes	yes
75	blue	green	yes	yes	yes
76	red	red	yes	no	no
77	blue	green	yes	yes	yes
78	black	red	no	no	no
79	green	red	no	no	no
80	blue	green	yes	yes	yes
81	blue	green	yes	yes	yes
82	pink	pink	yes	yes	no
83	blue	green	yes	yes	yes
84	blue	green	yes	yes	yes
85	green	green	yes	yes	yes
86	blue	green	yes	yes	yes
87	red	red	yes	yes	yes
88	red	red	yes	yes	yes
89	red	red	yes	yes	yes
90	blue	green	no	no	yes
91	blue	green	yes	yes	yes
92	green	green	no	no	no
93	blue	green	no	no	no
94	0	0	no	no	no
101	orange	green	yes	yes	yes
102	orange	green	yes	yes	yes
103	green	red	yes	yes	yes
105	blue	green	yes	yes	yes
106	red	red	yes	yes	yes
107	green	green	yes	yes	yes
108	0	0	no	yes	no
109	green	green	yes	yes	yes

Appendix E: WordTree Method Experiment Materials

CASE STUDY: LAUNDRY FOLDER WORDTREE

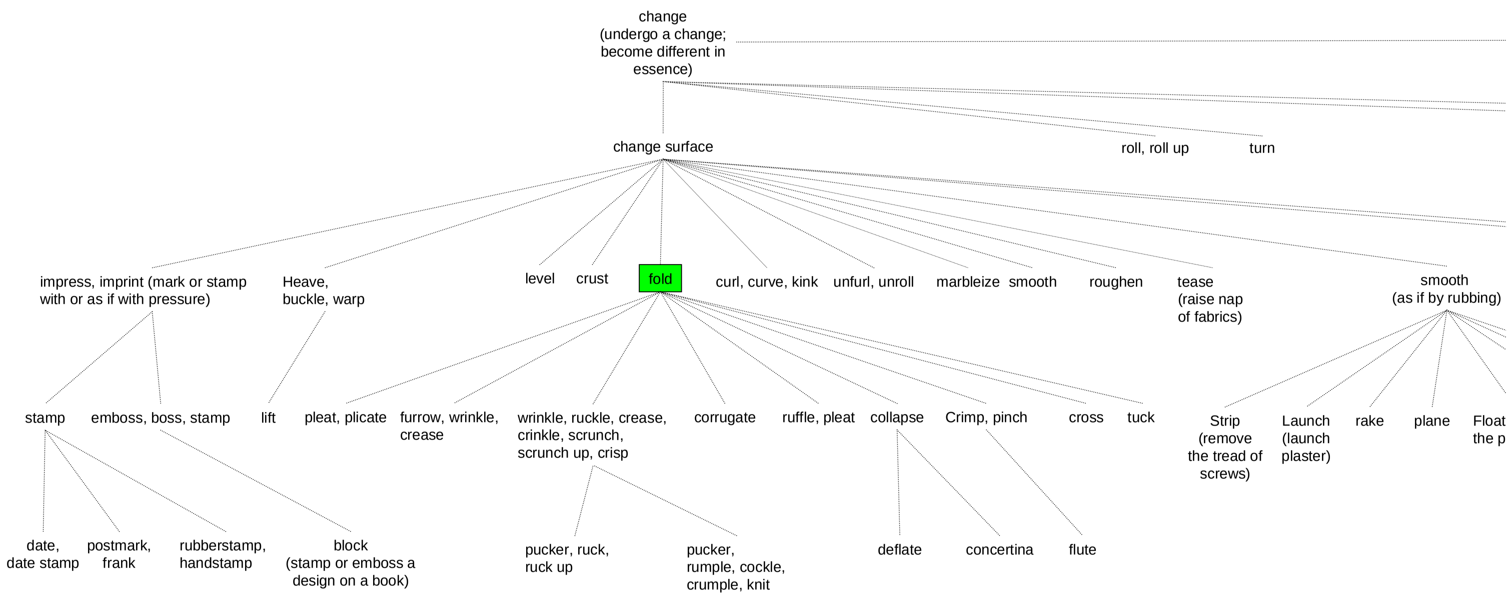


FIGURE 101: LEFT HALF OF "FOLD" WORDTREE

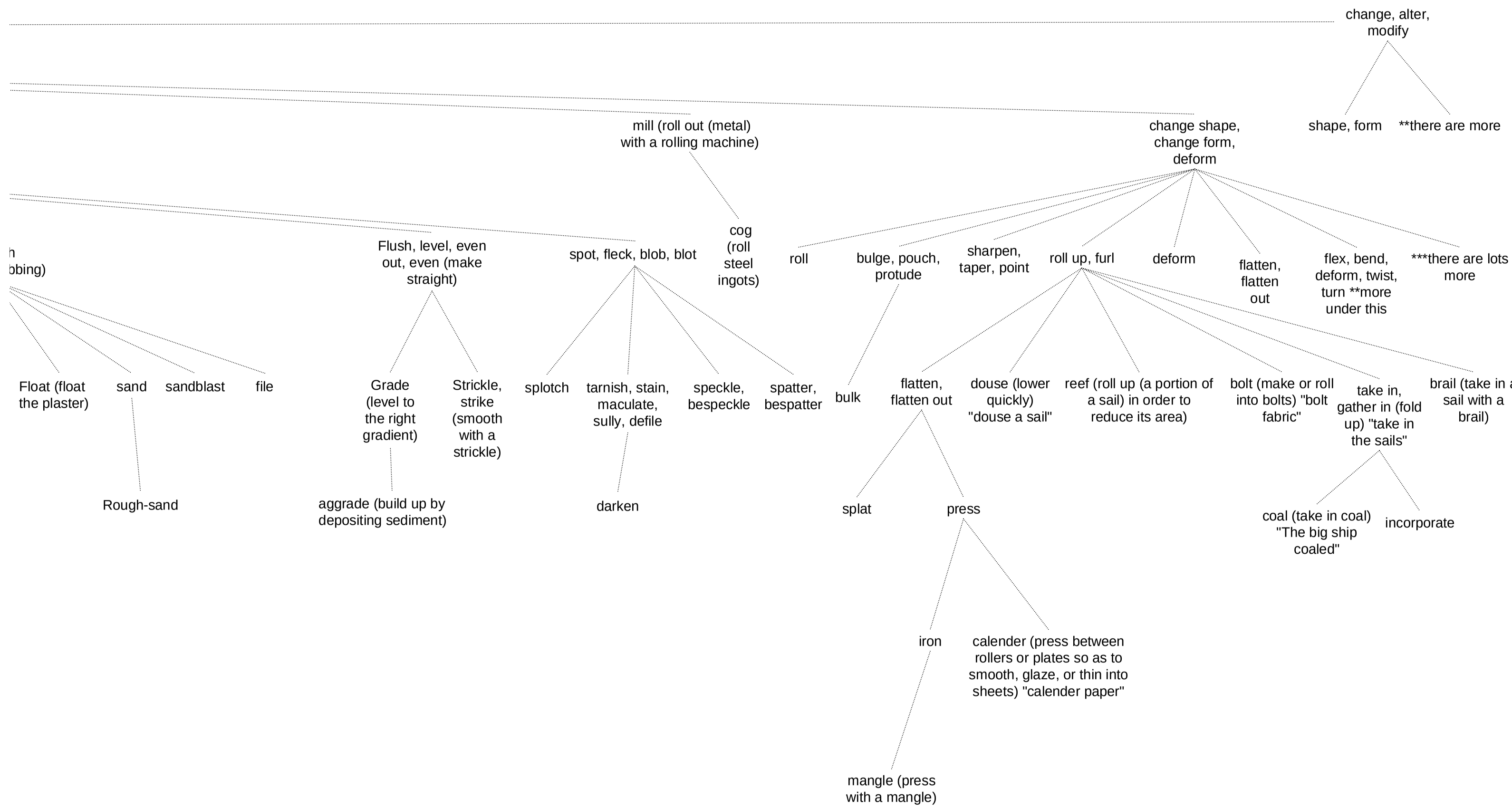
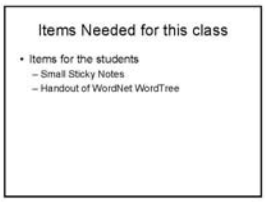
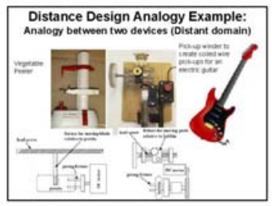


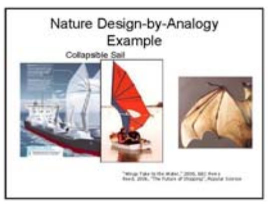
FIGURE 102: RIGHT HALF OF "FOLD" WORDTREE.

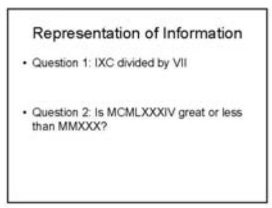
SLIDES ILLUSTRATING THE METHOD

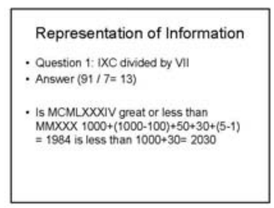
A very similar presentation was used for the Senior Design Methods class, Application to Industry Sponsored Projects and the Controlled Experiment.

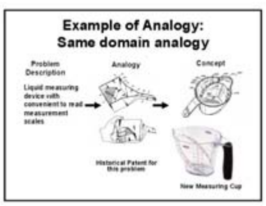


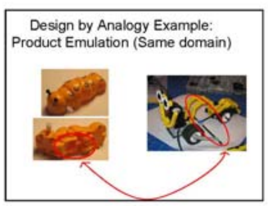


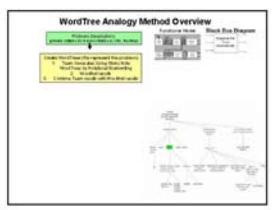


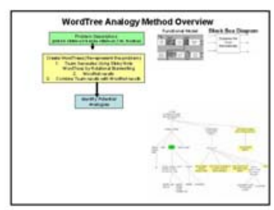


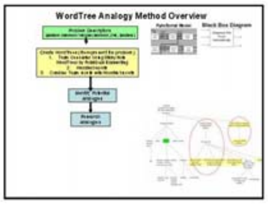


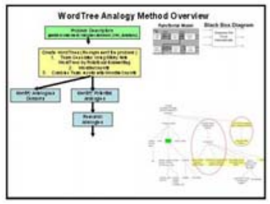












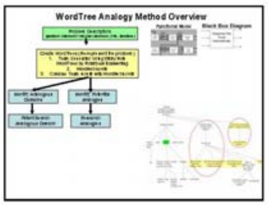
Step 1: Find Key Problem Descriptors (list at least 6)

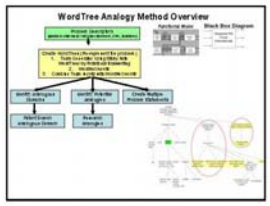
- **single word action verbs**
- Key functions of the device
- Key customer needs

Step 1: Find Key Functions (list at least 4)

- Key functions of the device are **single word action verbs**
  1. Single action verb that summarizes black box or mission statement

Example: Device that aims and delivers water to plants →





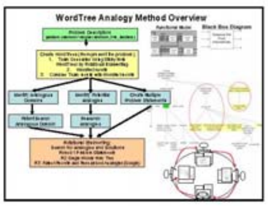
Step 1: Find Key Functions (list at least 4)

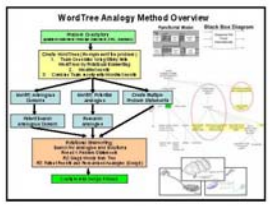
- Key functions of the device are **single word action verbs**
  1. Single action verb that summarizes black box or mission statement

Example: Device that aims and delivers water to plants → watering

Step 1: Find Key Functions (list at least 4)

- Key functions of the device are **single word action verbs**
  1. Single action verb that summarizes black box or mission statement (e.g. Device that aims and delivers water to plants → watering)
  2. Functions in black box
  3. Functions in the mission statement





Example: Key functions of the device (Automatic Pet Feeder)

Mission Statement

Product Description: "Feed small pets automatically without requiring human intervention."

Black Box Diagram

Dispense Pet Food Automatically

Example: Key functions of the device (Automatic Pet Feeder)

Mission Statement

Product Description: "Feed small pets automatically without requiring human intervention."

Black Box Diagram

Dispense Pet Food Automatically

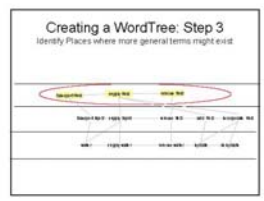
Key Functions of Device
1. Feed [Feed Pet]
2. Dispense [Dispense Food]
3. Provide [Provide Food]

Summary Step 1: Find Key Problem Descriptors (list at least 4)

- Key functions of the device are **single word action verbs** (list at least 4)
  1. Single action verb that summarizes black box or mission statement (e.g. Device that aims and delivers water to plants → watering)
  2. Functions in black box
  3. Functions in the mission statement
  - **Other functions of the device can also be used**
  1. Functions that most important constraints are tied to or
  2. Function of the device that most needs improvement
  3. Particular function you are having difficulty finding solutions for
  4. Any functions from functional model

Critical CN (select 3-4)

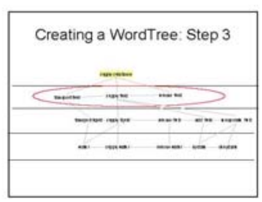
- Good Examples
  - CNs that can be model using a function structure. Must have a clear flow that can be modeled.
  - Words that are or have **imaginable action verbs** associated with them (e.g. easily repairable→ repair)
  - action verb + material flow (remove shell, holds variable quantity of water)
- Other Options
  - Very Context dependent
    - rugged / portable / compact
- Don't use the follow CNs
  - safe (you need instead what causes the harm, e.g. does not reflect laser, no pinch points, etc.)
  - easy to use
  - CNs that are constraints
    - light weight / low force / cost or closely related concepts
  - solution based (e.g. switch-activated)

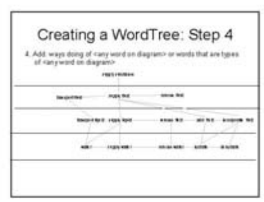


Good CNs to Expand**add

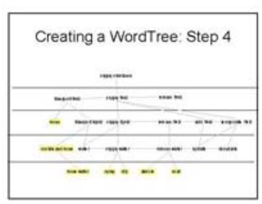
Good CNs
- easily repairable
- grip tabletop
- inside can be cleaned easily
- fingers are not pinched easily (things that pinch fingers)
- lockable
- holds variable quantity of water

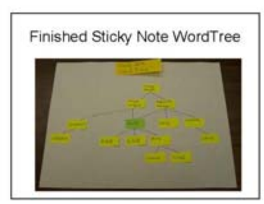
Activity: As a Team Define 1-2 of your Project's Key Problem Descriptors

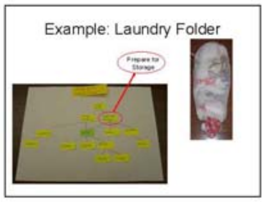


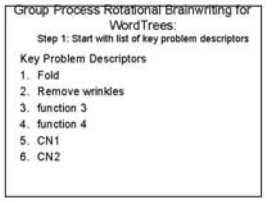


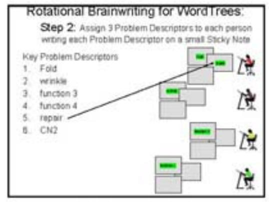
Creating the Sticky Note WordTree Method

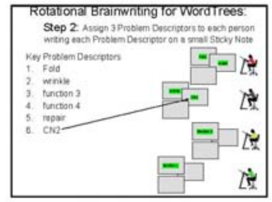





Example: Laundry Folder
Prepare for Storage


Group Process Rotational Brainwriting for WordTrees:
Step 1: Start with list of key problem descriptors
Key Problem Descriptors
1. Fold
2. Remove wrinkles
3. function 3
4. function 4
5. CN1
6. CN2


Rotational Brainwriting for WordTrees:
Step 2: Assign 3 Problem Descriptors to each person writing each Problem Descriptor on a small Sticky Note
Key Problem Descriptors
1. Fold
2. wrinkle
3. function 3
4. function 4
5. repair
6. CN2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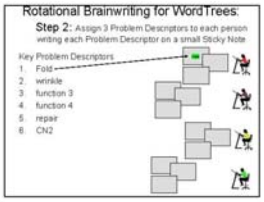
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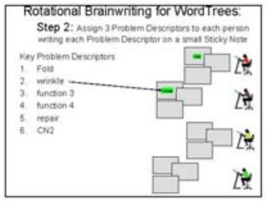
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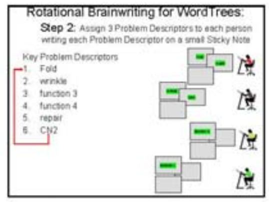
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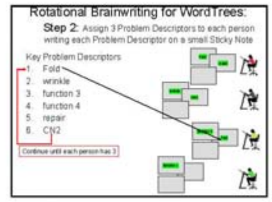
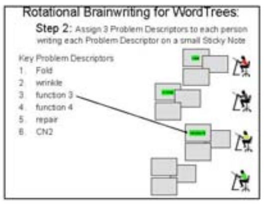

Rotational Brainwriting for WordTrees:
Step 2: Assign 3 Problem Descriptors to each person writing each Problem Descriptor on a small Sticky Note
Key Problem Descriptors
1. Fold
2. wrinkle
3. function 3
4. function 4
5. repair
6. CN2
Continue until each person has 3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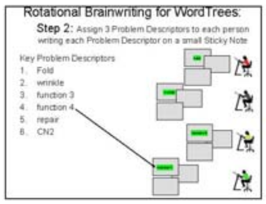
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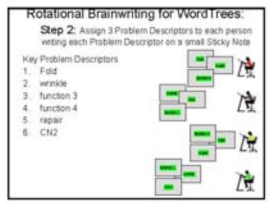
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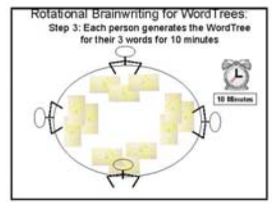
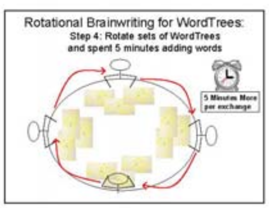
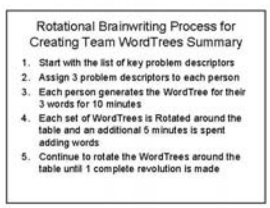
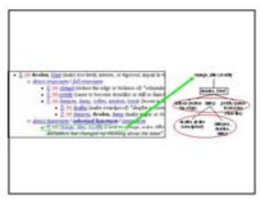
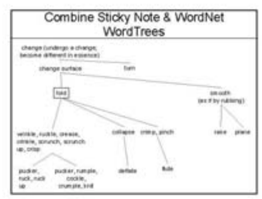
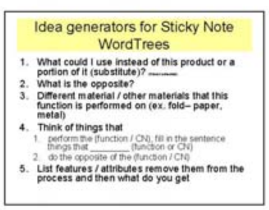

Rotational Brainwriting for WordTrees:
Step 3: Each person generates the WordTree for their 3 words for 10 minutes
10 Minutes

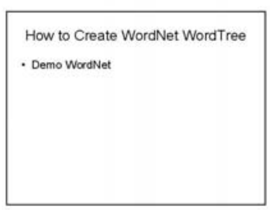

Rotational Brainwriting for WordTrees:
Step 4: Rotate sets of WordTrees and spent 5 minutes adding words
5 Minutes More per exchange

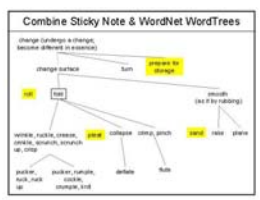

Rotational Brainwriting Process for Creating Team WordTrees Summary
1. Start with the list of key problem descriptors
2. Assign 3 problem descriptors to each person
3. Each person generates the WordTree for their 3 words for 10 minutes
4. Each set of WordTrees is Rotated around the table and an additional 5 minutes is spent adding words
5. Continue to rotate the WordTrees around the table until 1 complete revolution is made

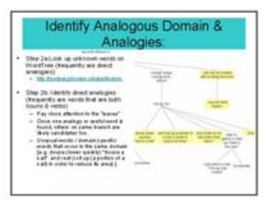


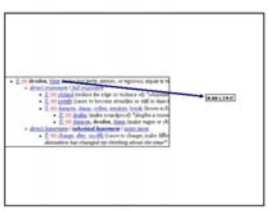

Combine Sticky Note & WordNet WordTrees

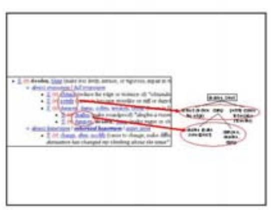

Idea generators for Sticky Note WordTrees
1. What could I use instead of this product or a portion of it (substitute)?
2. What is the opposite?
3. Different material / other materials that this function is performed on (ex. fold– paper, metal)
4. Think of things that
1. perform the (function / CN), fill in the sentence things that ________ (function or CN)
2. do the opposite of the (function / CN)
5. List features / attributes remove them from the process and then what do you get

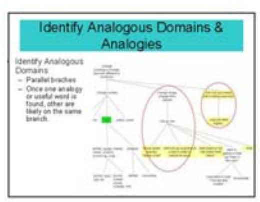

How to Create WordNet WordTree
• Demo WordNet

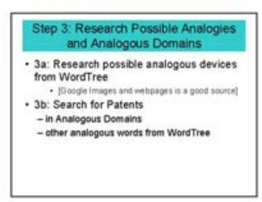

Combine Sticky Note & WordNet WordTrees
prepare for storage

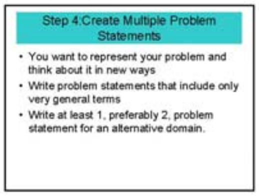

Identify Analogous Domain & Analogies:

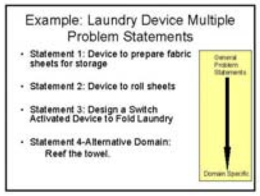




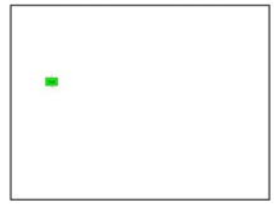

Identify Analogous Domains & Analogies

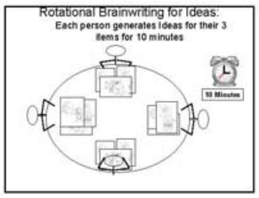

Step 3: Research Possible Analogies and Analogous Domains
• 3a: Research possible analogous devices from WordTree
• [Google Images and webpages is a good source]
• 3b: Search for Patents
– in Analogous Domains
– other analogous words from WordTree

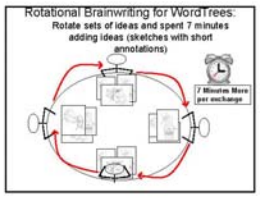

Step 4:Create Multiple Problem Statements
• You want to represent your problem and think about it in new ways
• Write problem statements that include only very general terms
• Write at least 1, preferably 2, problem statement for an alternative domain.

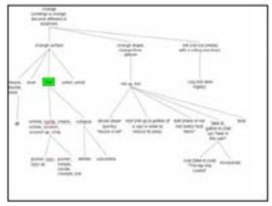

Example: Laundry Device Multiple Problem Statements
• Statement 1: Device to prepare fabric sheets for storage
• Statement 2: Device to roll sheets
• Statement 3: Design a Switch Activated Device to Fold Laundry
• Statement 4-Alternative Domain: Reef the towel.
General Problem Statements
Domain Specific

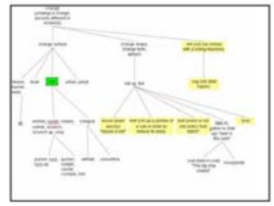

• Step 1: Create the WordTrees [Re-Represent the Design Problem]
– 1a: Identify at least 4 key functions and 2-4 key Customer Needs
– 1b: Team generates Sticky Note WordTrees using Rotational Brainwriting
– Submit Sticky Note WordTrees to receive WordNet results?
– 1c: Combine Sticky Note WordTrees with WordNet results
• Step 2: Identify Analogous Domains and analogies from the WordTrees
– 2a: Look up any unknown words on the WordTree using WordNet
– 2b: Identify possible analogous devices on the WordTree (frequently words that are both verbs and nouns)
– 2c: identify analogous domains
• Step 3: Research Possible Analogies and Analogous Domains
– 3a: Google for information about the analogous devices
– 3b: Search for Patents in analogous domains
• Step 4: Create Multiple Problem Statements
• Step 5: Rotational Brainwriting for Ideas and More Analogies
• Step 6: Continue with Design Methods [Summarize [Morph Matrix]]

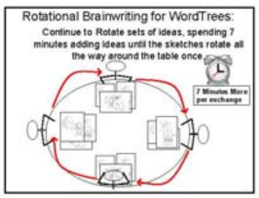


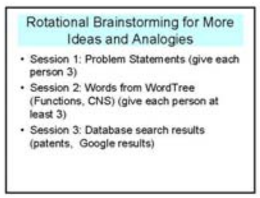

Rotational Brainwriting for Ideas:
Each person generates Ideas for their 3 items for 10 minutes
10 Minutes

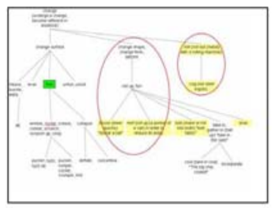

Rotational Brainwriting for WordTrees:
Rotate sets of ideas and spent 7 minutes adding ideas (sketches with short annotations)
7 Minutes More per exchange

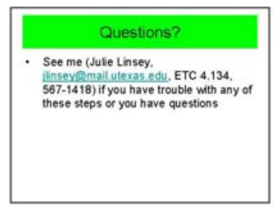





Rotational Brainwriting for WordTrees:
Continue to Rotate sets of ideas, spending 7 minutes adding ideas until the sketches rotate all the way around the table once.
7 Minutes More per exchange


Rotational Brainstorming for More Ideas and Analogies
• Session 1: Problem Statements (give each person 3)
• Session 2: Words from WordTree (Functions, CNS) (give each person at least 3)
• Session 3: Database search results (patents, Google results)




Questions?
• See me (Julie Linsey, jlinsey@mail.utexas.edu, ETC 4.134, 567-1418) if you have trouble with any of these steps or you have questions

SURVEYS FOR APPLICATION TO INDUSTRIAL SPONSORED PROJECTS

Any Four digit number (e.g. month and day of birthday) _______

Did your team use the following for your K project:		
	Yes	**No**
Mission Statement		
Quality Function Deployment (QFD, House of Quality)		
Customer Needs Analysis		
Specification Sheet		
Black Box Model		
Activity Diagram		
Function Structure		
Subtract and Operate		
Energy Flow Diagram (Force Flow)		
Brainstorming		
6-3-5		
Mind Mapping		
Design by Analogy		
TRIZ/TIPS		
Morph Matrix		
Patent Search		
Background Research / Literature Review		
Search by Physical Principle		
Other (please list):		

Have you use any of the following Search Engines?					Which project?					
	Yes	No			K	J	Other			
U.S. Patent Office Search Engine										
Patent Search										
Google Patent Search										
Freepatentsonline.com										
Other (please list):										

SENIOR DESIGN METHODS CLASS EVALUATION SURVEY

WordTree Method

1. IRB APPROVED ON 10/23/2007 EXPIRES ON 10/21/2008

Engineering Conceptual Design IRB PROTOCOL #2005-08-0031
Conducted By: Julie Linsey, Arthur Markman, Ph.D. and Kristin Wood, Ph.D.
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You are being asked to participate in a research study. This form provides you with information about the study. The person in charge of this research will also describe this study to you and answer all of your questions. Please read the information below and ask questions about anything you don't understand before deciding whether or not to take part. Your participation is entirely voluntary and you can refuse to participate without penalty or loss of benefits to which you are otherwise entitled. You can stop your participation at any time by simply telling the researcher.

The purpose of this study is to understand the ways in which engineers understand products and the conceptual design process. About two hundred people will participate in this study.

If you agree to be in this study, you will be asked to do the following things:
• Generate concepts for a design problem (WordTree Method)
• A very brief, 15 minute survey

Total estimated time to participate in study is 3 hours. 15 minutes for the on-line survey.

Risks and Benefits of being in the study
• The risk associated with this study is no greater than everyday life.
• You will practice your engineering concept generation skills.

Compensation:
• You will receive extra credit in your design class.

The records of this study will be stored securely and kept private. Authorized persons from The University of Texas at Austin, members of the Institutional Review Board, and (study sponsors, if any) have the legal right to review your research records and will protect the confidentiality of those records to the extent permitted by law. All publications will exclude any information that will make it possible to identify you as a subject.

Contacts and Questions:
If you have any questions about the study please ask now. If you have questions later or want additional information, call the researchers conducting the study. Their names, phone numbers, and e-mail addresses are at the top of this page. If you have questions about your rights as a research participant, please contact Jodi Jensen, Ph.D., Chair of The University of Texas at Austin Institutional Review Board for the Protection of Human Subjects, (512) 471-8871 or email: orsc@uts.cc.utexas.edu.
Please print a copy of this information to keep for your records.
Statement of Consent:

I have read the above information and have sufficient information to make a decision about participating in this study. I consent to participate in the study.

I agree to participate: *

(•) yes

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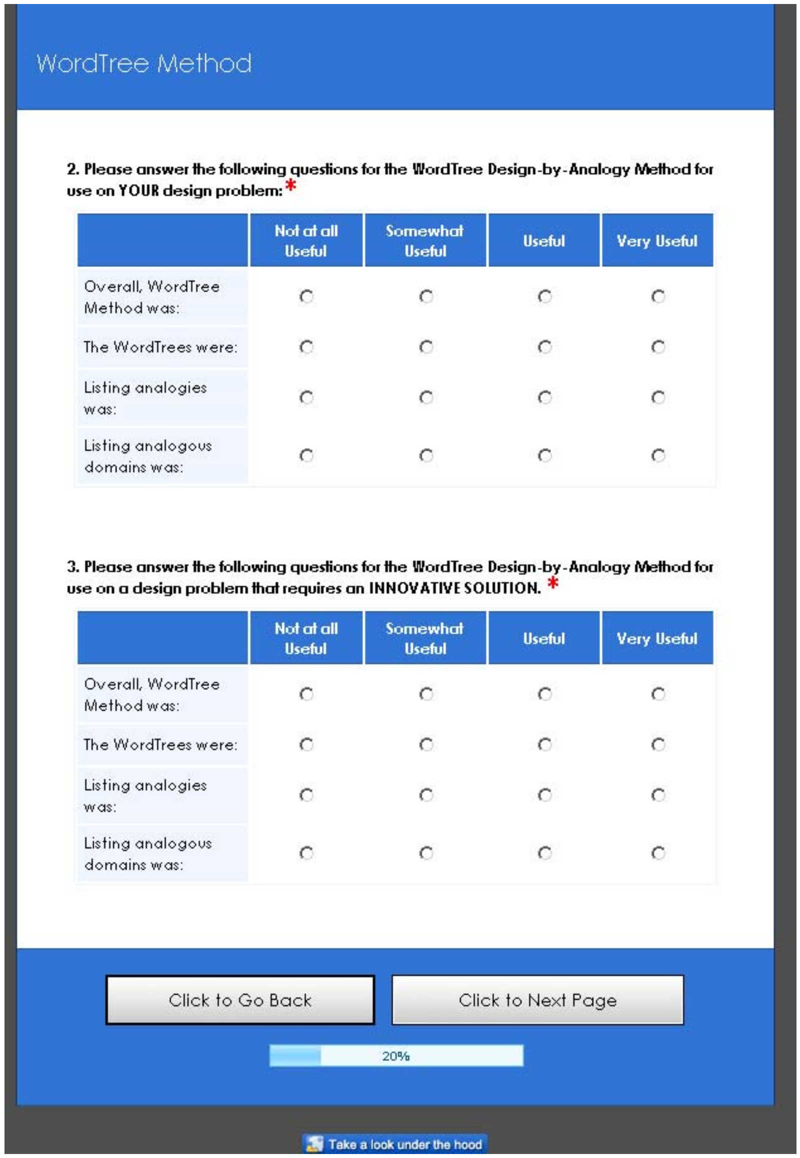

WordTree Method

2. Please answer the following questions for the WordTree Design-by-Analogy Method for use on YOUR design problem: *

	Not at all Useful	Somewhat Useful	Useful	Very Useful
Overall, WordTree Method was:	○	○	○	○
The WordTrees were:	○	○	○	○
Listing analogies was:	○	○	○	○
Listing analogous domains was:	○	○	○	○

3. Please answer the following questions for the WordTree Design-by-Analogy Method for use on a design problem that requires an INNOVATIVE SOLUTION. *

	Not at all Useful	Somewhat Useful	Useful	Very Useful
Overall, WordTree Method was:	○	○	○	○
The WordTrees were:	○	○	○	○
Listing analogies was:	○	○	○	○
Listing analogous domains was:	○	○	○	○

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20%

Take a look under the hood

WordTree Method

4. What is the value of each of the following methods for use on YOUR design problem: *

	Zero value	A little value	Medium value	High value	Extremely valuable	Did not use method
Background research / Literature review	○	○	○	○	○	○
Mission Statement	○	○	○	○	○	○
Quality Function Deployment (QFD, House of Quality)	○	○	○	○	○	○
Black Box diagram	○	○	○	○	○	○
Activity Diagram	○	○	○	○	○	○
Function Structure	○	○	○	○	○	○
Patent Search	○	○	○	○	○	○
6-3-5	○	○	○	○	○	○
Mind Maps	○	○	○	○	○	○
TRIZ/TIPS	○	○	○	○	○	○
Morph Matrix	○	○	○	○	○	○
Pugh Charts	○	○	○	○	○	○
WordTree Method	○	○	○	○	○	○

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30%

WordTree Method

5. What is the value of each of the following methods for a DESIGN PROBLEM THAT REQUIRES AN INNOVATIVE SOLUTION?*

	Zero value	A little value	Medium value	High value	Extremely valuable	Did not use method
Background research / Literature review	○	○	○	○	○	○
Mission Statement	○	○	○	○	○	○
Quality Function Deployment (QFD, House of Quality)	○	○	○	○	○	○
Black Box diagram	○	○	○	○	○	○
Activity Diagram	○	○	○	○	○	○
Function Structure	○	○	○	○	○	○
Patent Search	○	○	○	○	○	○
6-3-5	○	○	○	○	○	○
Mind Maps	○	○	○	○	○	○
TRIZ/TIPS	○	○	○	○	○	○
Morph Matrix	○	○	○	○	○	○
Pugh Charts	○	○	○	○	○	○
WordTree Method	○	○	○	○	○	○

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40%

WordTree Method

6. How likely are you to use each of the methods in the future?

	Very Unlikely	Unlikely	Neutral	Likely	Very Likely
Background research / Literature review	○	○	○	○	○
Mission Statement	○	○	○	○	○
Quality Function Deployment (QFD, House of Quality)	○	○	○	○	○
Black Box diagram	○	○	○	○	○
Activity Diagram	○	○	○	○	○
Function Structure	○	○	○	○	○
Patent Search	○	○	○	○	○
6-3-5	○	○	○	○	○
Mind Maps	○	○	○	○	○
TRIZ/TIPS	○	○	○	○	○
Morph Matrix	○	○	○	○	○
Pugh Charts	○	○	○	○	○
WordTree Method	○	○	○	○	○

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50%

Take a look under the hood

WordTree Method

7. Please answer the following questions for the WordTree Method:

*

	Strongly Disagree	Disagree	Neither Agree Nor Disagree	Agree	Strongly Agree
This method helped me to find analogies for my design problem.	○	○	○	○	○
This method helped me to generate more ideas.	○	○	○	○	○
This method helped me to generate higher quality ideas.	○	○	○	○	○
This method was a waste of time.	○	○	○	○	○
The presentation of this method was easy to understand.	○	○	○	○	○
The method was easy to use.	○	○	○	○	○
I expect to use this method in the future.	○	○	○	○	○
This method needs improvements.	○	○	○	○	○
This method was useful.	○	○	○	○	○
I liked using the method.	○	○	○	○	○
I expect to use this method in the future for design problems that require an innovative solution.	○	○	○	○	○

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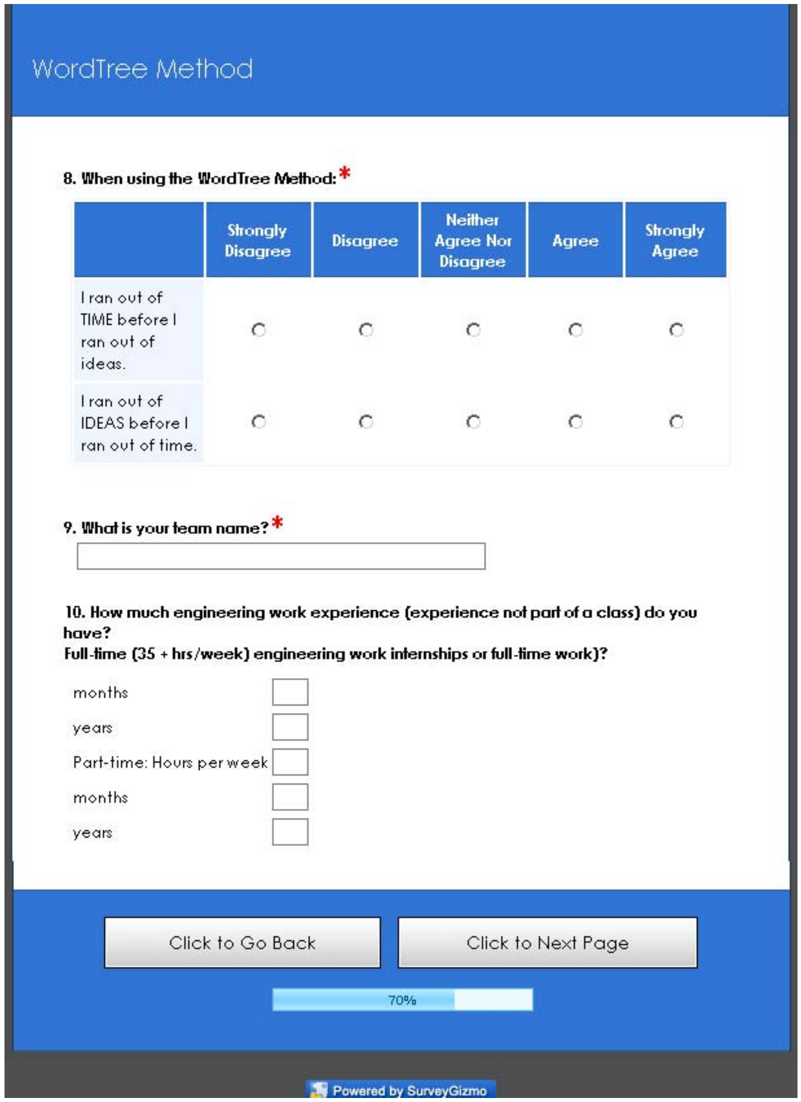
60%


WordTree Method

8. When using the WordTree Method: *

	Strongly Disagree	Disagree	Neither Agree Nor Disagree	Agree	Strongly Agree
I ran out of TIME before I ran out of ideas.	○	○	○	○	○
I ran out of IDEAS before I ran out of time.	○	○	○	○	○

9. What is your team name? *

10. How much engineering work experience (experience not part of a class) do you have?
Full-time (35 + hrs/week) engineering work internships or full-time work)?

months

years

Part-time: Hours per week

months

years

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70%

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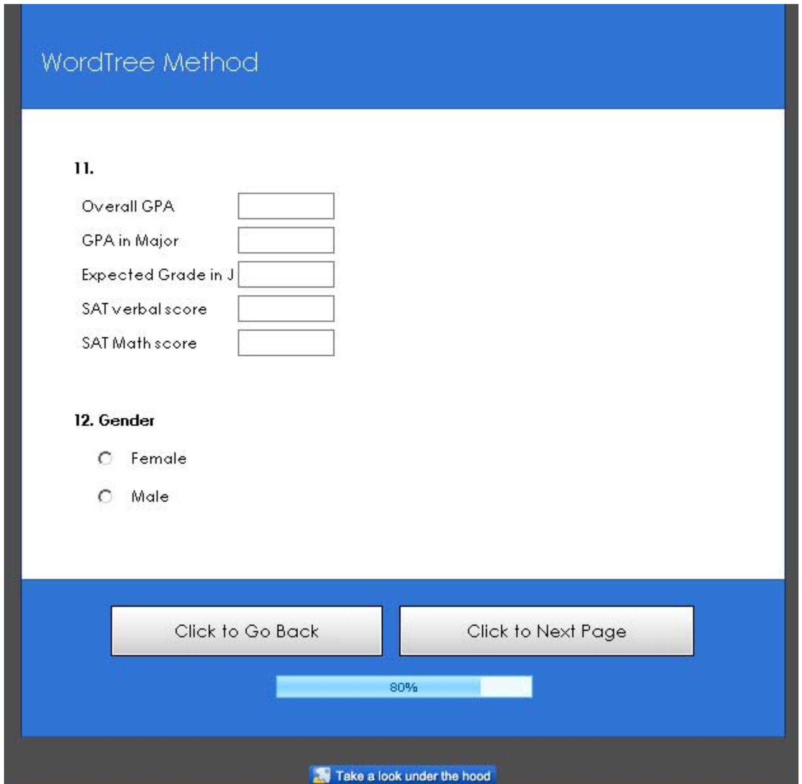
WordTree Method

11.

Overall GPA
GPA in Major
Expected Grade in J
SAT verbal score
SAT Math score

12. Gender

Female
Male

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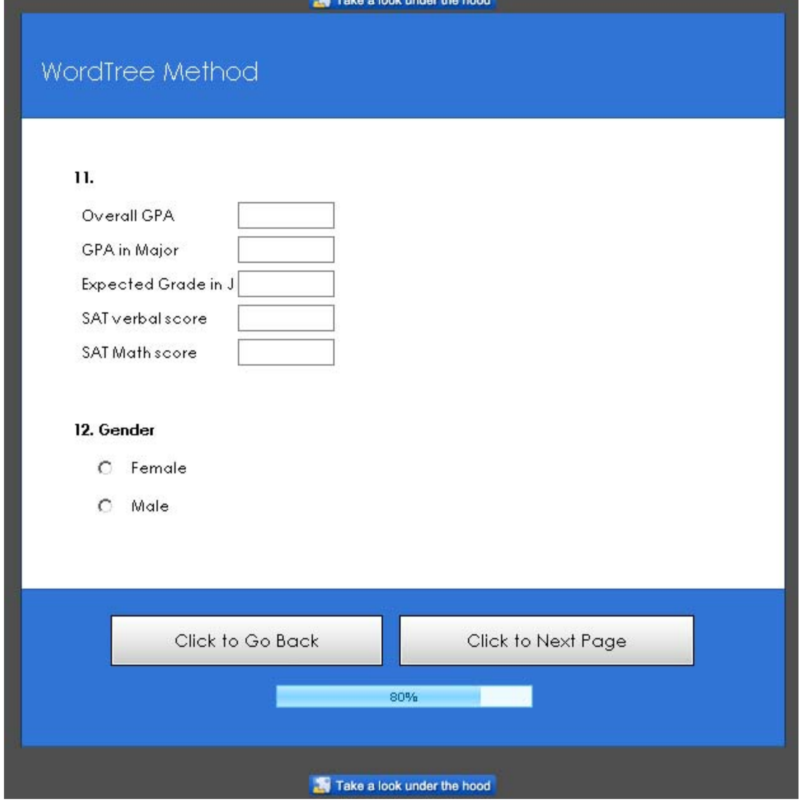
80%

Take a look under the hood


WordTree Method

11.

Overall GPA
GPA in Major
Expected Grade in J
SAT verbal score
SAT Math score

12. Gender

Female
Male

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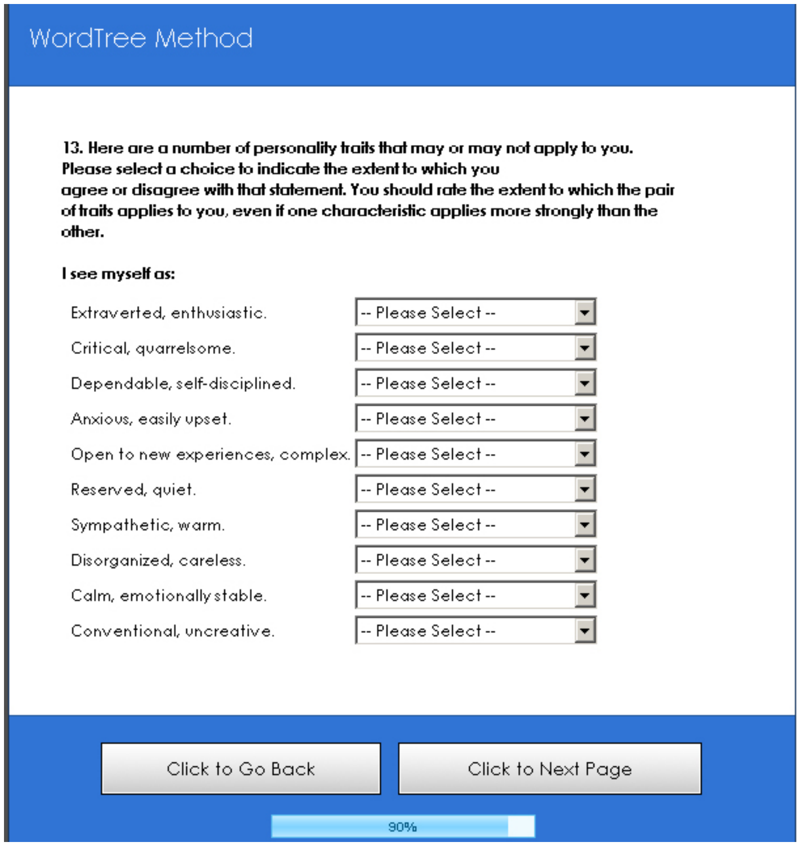
80%

Take a look under the hood


WordTree Method

13. Here are a number of personality traits that may or may not apply to you. Please select a choice to indicate the extent to which you agree or disagree with that statement. You should rate the extent to which the pair of traits applies to you, even if one characteristic applies more strongly than the other.

I see myself as:

Extraverted, enthusiastic.	-- Please Select --
Critical, quarrelsome.	-- Please Select --
Dependable, self-disciplined.	-- Please Select --
Anxious, easily upset.	-- Please Select --
Open to new experiences, complex.	-- Please Select --
Reserved, quiet.	-- Please Select --
Sympathetic, warm.	-- Please Select --
Disorganized, careless.	-- Please Select --
Calm, emotionally stable.	-- Please Select --
Conventional, uncreative.	-- Please Select --

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90%

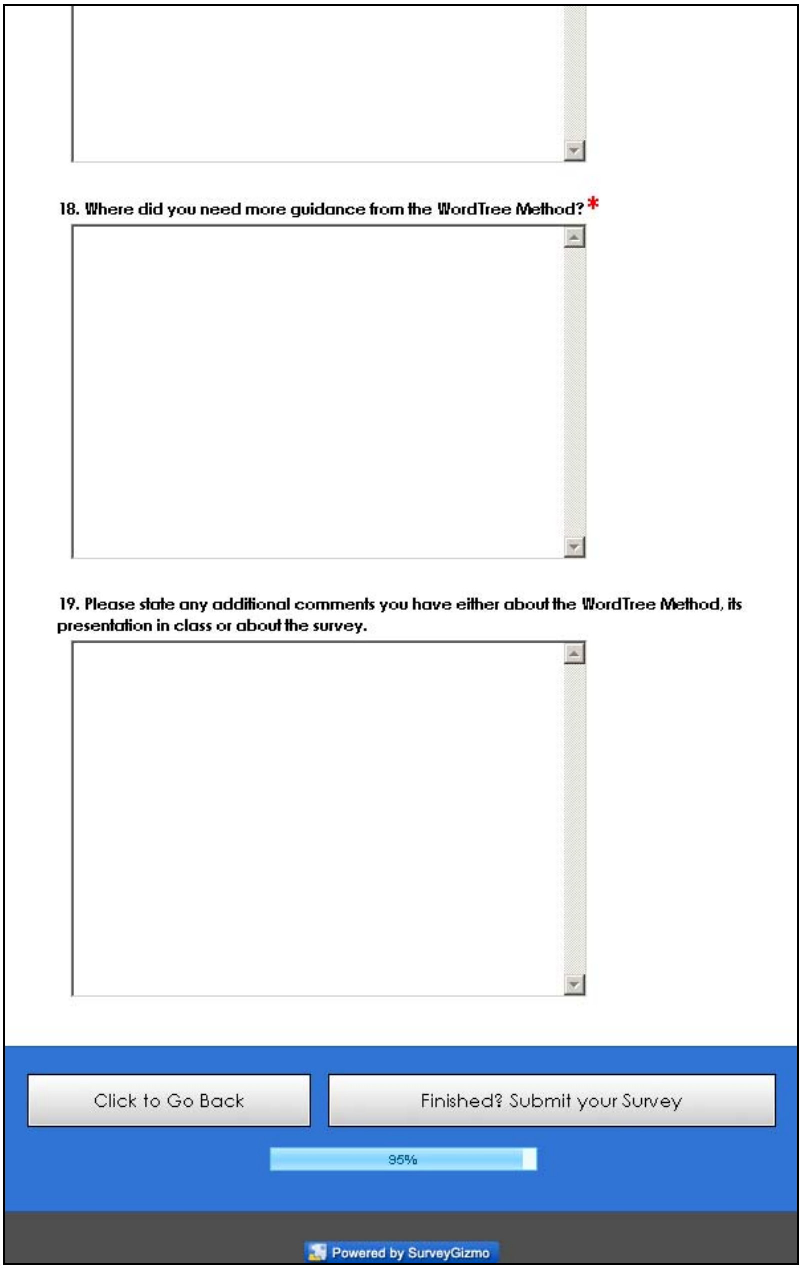
WordTree Method

14. What did you like about the WordTree Method? *

15. What steps in the WordTree Method were most useful? *

16. How could the WordTree Method be improved? *

17. What difficulties did you have when using the WordTree Method? *



18. Where did you need more guidance from the WordTree Method?*

19. Please state any additional comments you have either about the WordTree Method, its presentation in class or about the survey.

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Finished? Submit your Survey

95%

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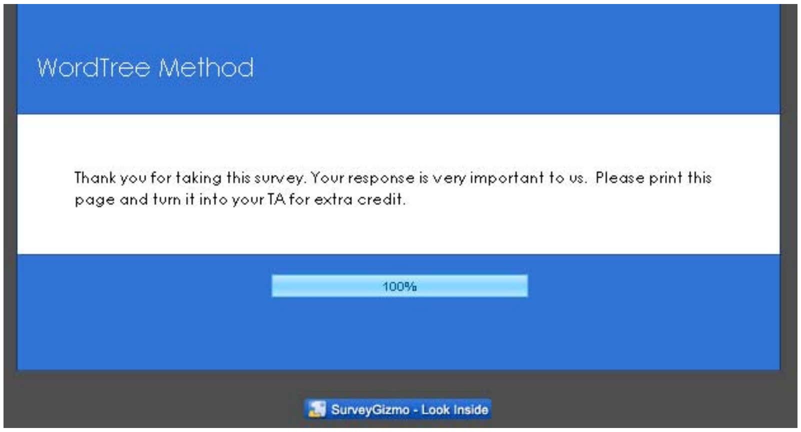


CONTROLLED EXPERIMENTAL EVALUATION OF THE WORDTREE METHOD MATERIALS

Participant Instruction Sheets: Control

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

Why did you decide to end the idea generation session? One or more reasons may be given.

1.

2.

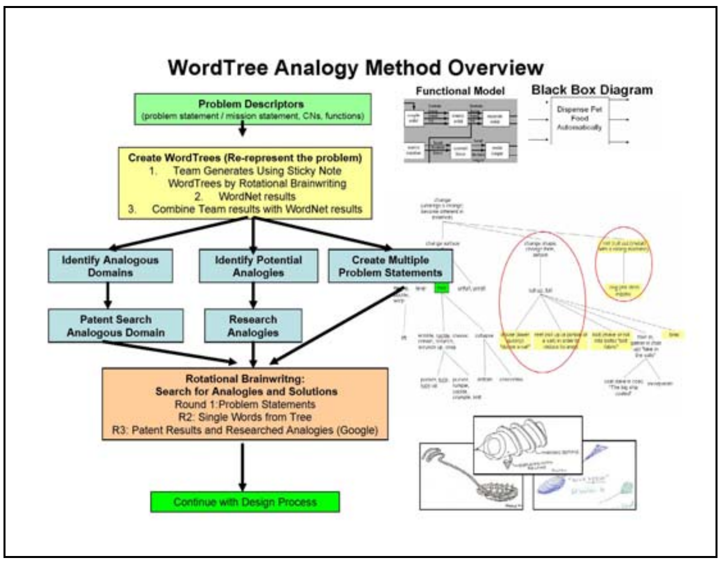
3.

4.

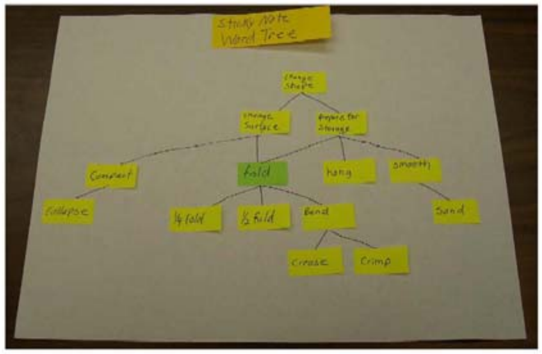
5.

Continue to generate ideas. Most people can continue to generate new ideas even after they think they have run out of ideas.

Participant Instruction Sheets: WordTree

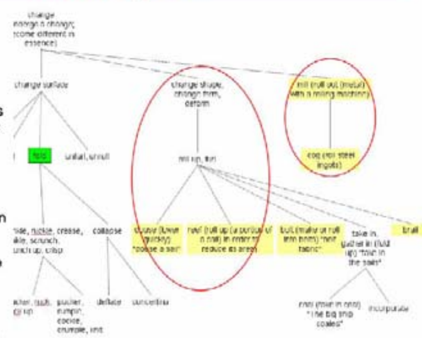


Finished Sticky Note WordTree



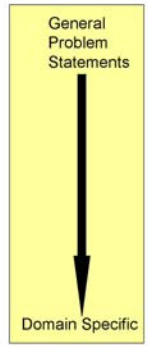
Identify Analogous Domains & Analogies

- Identify Analogous Domains
  - Parallel braches
  - Multiple potential analogies in the same domain
- Identify potential analogies (frequently, words that are both nouns & verbs)
  - Unusual words / domain specific words
  - [e.g. douse (lower quickly) "douse a sail" and reef (roll up (a portion of a sail) in order to reduce its area)]
  - Pay close attention to the "leaves"
  - Once one analogy or useful word is found, others on same branch are likely candidates too.



Example: Laundry Device Multiple Problem Statements

- Statement 1: Device to prepare fabric sheets for storage
- Statement 2: Device to roll sheets
- Statement 3: Design a Switch Activated Device to Fold Laundry
- Statement 4-Alternative Domain:
  Reef the towel.



Generating Ideas and Analogies

1. Problem Statements
2. Words from WordTree

Generating Ideas and Analogies

1. Problem Statements
2. Words from WordTree
3. Researched Potential Analogies (Google) from list and search for patents in the analogous domains you identified

Provided WordTrees for Peanut Shelling Device

Figure 103: "Remove / Shell" WordTree (left half).

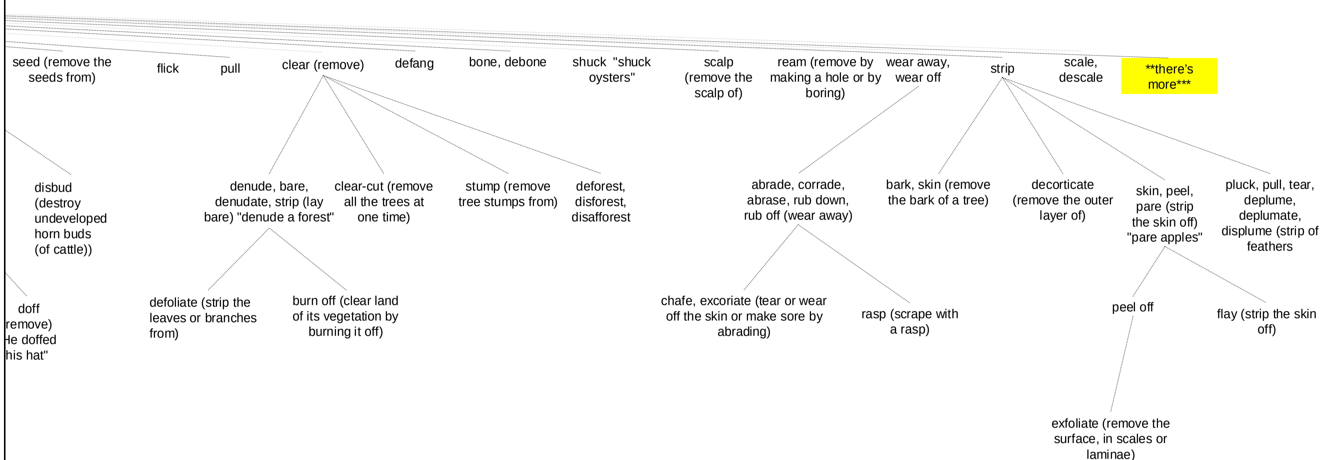


FIGURE 104: "REMOVE / SHELL" WORDTREE (RIGHT HALF).

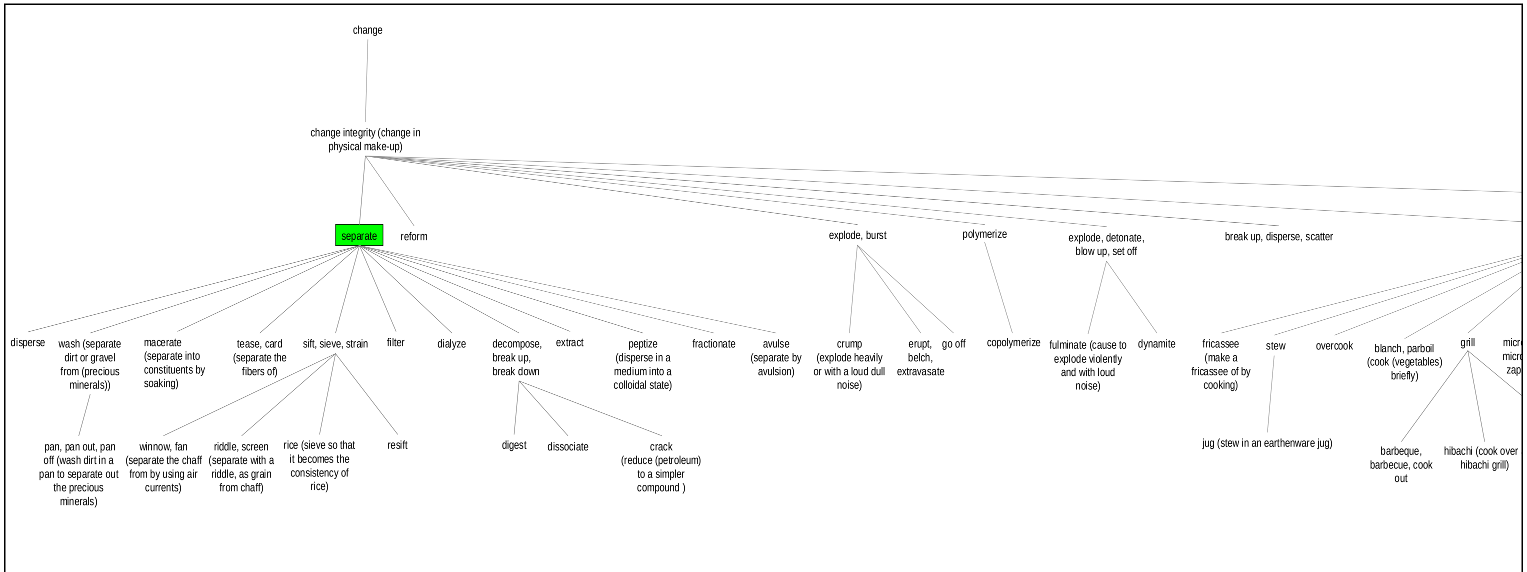


Figure 105: “Separate” WordTree (left half).

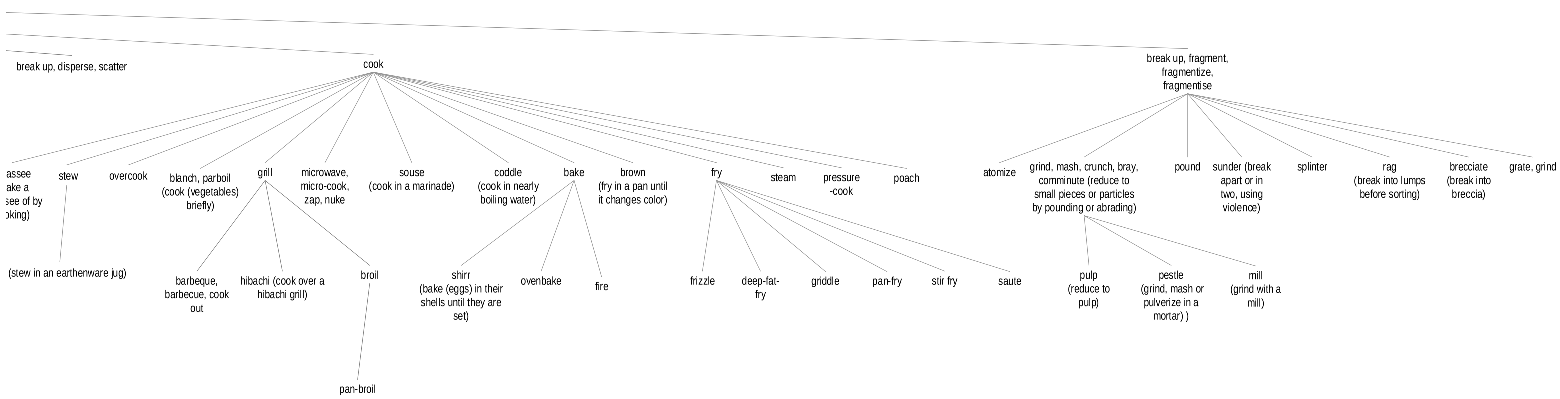


Figure 106: “Separate” WordTree (right half).

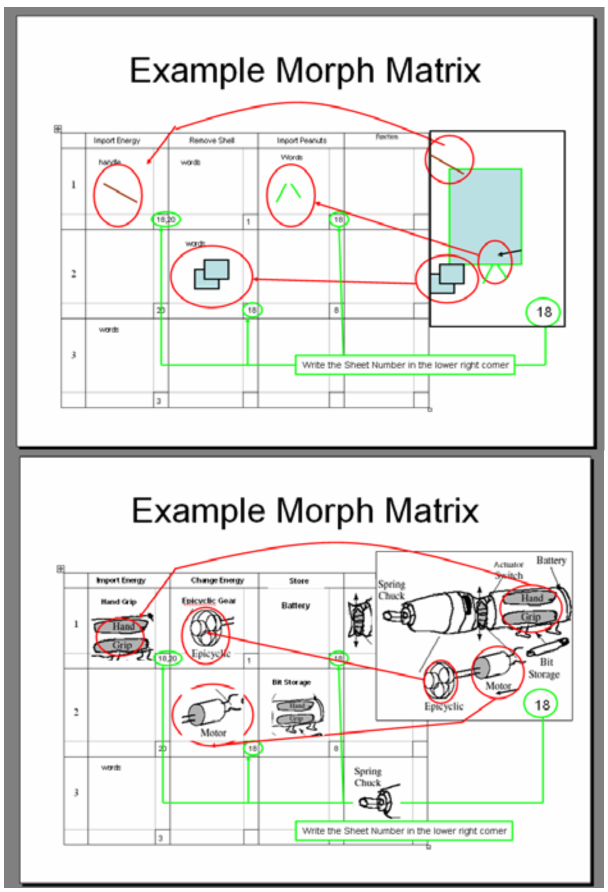
Participant Instruction Sheet: Day 2, Morph Matrix

Day 2: Provided Morph Matrices

	Remove shell	Separate (shells & nuts	Store peanuts	Import peanuts

Other functions included on the morph matrices were: Import energy, Change energy, Transmit energy, distribute, Store energy, Allow DOF, Guide, Other?

Morph Matrix Overhead Example



EXPERIMENTER SCRIPT: DAY 1, CONTROL

Experimenter script: **Control**

Items required for the experiment

- ☐ Participant Instruction Packets
- ☐ Slides
- ☐ Consent forms
- ☐ Stop watch
- ☐ Multiple colored writing utensils (black, blue, green, pink maroon, light blue pen, light blue marker)
- ☐ Numbered paper (40 sheets)
- ☐ Stapler

a) Give participants the consent form
b) Black pens

0-15: black
15-30: blue
30-40: green
40-45: pink
45-60: maroon
**break
60-1:15: purple
1:15-1:30: light blue pen

1) **"This study is evaluating different idea generation methods. Your task today is to generate ideas and analogies for a design problem. The total time required for this study is 3 hours, 2 hours today and 1 hour during a second session. If you agree to participate please sign the consent form. Any questions?"**

a) Collect signed form
b) Give participant a copy of the consent form

2) <u>Problem</u>
"Write the Month and Day of your birthday or another four digit code you will remember at the next session in the upper right-hand corner. This will be used to match your results from this experiment to the results from the second session. If you have any questions at any time during this experiment, please raise your hand."

Multiple colors of pens are being used to keep track of when items are written. I will be asking you to switch colors periodically throughout the experiment.

***show analogy examples

You are being asked to generate ideas and analogies for a peanut shelling machine. Flip over the sheet.

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

This is a real problem from a website called Thinkcycle.org. Thinkcycle.org presents designs needs from underserved populations. An efficient, low-cost solution does not exist for this problem. Your ideas may be given to a design team working on this problem.

You may individually use any method you learned in your design methods class (J). You must work individually.

The goal is to generate as many solutions as possible with as high of quality as possible and with as great of variety as possible. Technically infeasible, wild, non-standard and far out ideas are also encouraged. This helps to generate unique feasible solutions.

This experiment contains multiple tasks that will require the entire two hours. You may choose when to end the idea generation session and move on to the next tasks. When you are ready to move on to the next task please raise your hand.

You can use the entire two hours for idea generation

Remember the amount of extra credit you will receive depends on your effort and performance.

Go ahead and start."

Pen Colors **"Switch to the X pen."**

Time	Color	Start	End
0-15	black		
15-30	blue		
30-40	Green		
40-45	Pink		
**computer			
45-60	Maroon		
Break			
60-1:15	Purple		
1:15-1:30	light blue pen		

****Make sure I write down what time they want to end the activity ********

<u>At 45 Minutes</u>

"If you want to us them, computers with internet access are available to assist you in solving the peanut shelling device problem. You do not need to use them. If you gain ideas from using the web, be sure to write down the reference information (the website address or other appropriate information). Please raise you hand if and when you want to use one of the computers. "

****Make sure I write down what time they start using the computer********

Break at 60 minutes

"Please turn all of your sheets over and take a two minute break. Close the computers. Please do not discuss the experiment or your solutions during the break."

After break

Please continue to generate ideas. Remember your extra credit is based on your effort.

End of session

Thank you for your participation.

Make sure you noted any analogies you used to help you find solutions. Please go ahead and add these if you have not already done so.

If you used the computer to search for ideas, write down a short description of how you searched. What search engines did you use? What terms did you search for?

There are multiple conditions being evaluated for this experiment. It is critical that you do not discuss the experiment or the design problem with your classmates until after Saturday, Dec. 1st or when I present the results in class. Also do not discuss if you liked or disliked the experiment since this will also bias the data. The second session is about 45 minutes long, includes a survey and will not focus on idea generation for the peanut sheller. I can schedule the second session at this time."

Experimenter Script: Day 1, WordTree

Experimenter script: **WordTree**

Items required for the experiment

- ☐ Participant Instruction Packets
- ☐ Slides
- ☐ Consent forms
- ☐ Sticky Notes
- ☐ Stop watch
- ☐ Multiple colored writing utensils (black, blue, green, pink maroon, light blue pen, light blue marker)
- ☐ Numbered paper (40 sheets)
- ☐ Stapler
- ☐ Camera
- ☐ Print out of WordTree Method Reminder

a) Give participants the consent form
b) Black pens

1) **"This study is evaluating different idea generation methods. Your task today is to generate ideas and analogies for a design problem. The total time required for this study is 3 hours, 2 hours today and 1 hour during a second session. If you agree to participate please sign the consent form. Any questions?"**

a) Collect signed form
b) Give participant a copy of the consent form
c) Give black pen

d) problem statement sheet
e) sticky notes

2) <u>Problem</u>
"Write the Month and Day of your birthday or another four digit code you will remember at the next session in the upper right-hand corner. This will be used to match your results from this experiment to the results from the second session. If you have any questions at any time during this experiment, please raise your hand."

Multiple colors of pens are being used to keep track of when items are written. I will be asking you to switch colors periodically throughout the experiment.

***show analogy examples

You are being asked to generate ideas and analogies for a peanut shelling machine. Flip over the sheet.

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

This is a real problem from a website called Thinkcycle.org. Thinkcycle.org presents designs needs from underserved populations. An efficient, low-cost solution does not exist for this problem. Your ideas may be given to a design team working on this problem.

For the session today, you are being asked to use the WordTree Design-by-Analogy Method that was presented in class on Monday.

Spend 20 minutes creating sticky note WordTree for the following Key Problem Descriptors:

- **Shell**
- **Remove**
- **Separate**
- **Import energy**

Give black pen

Please stop. Switch to the blue pen. I need to record your WordTrees before you move on.
take picture of sticky note WordTrees***

hand out WordNet wordtree, blue pen, analogy list sheet*
Combine your sticky note WordTrees with the WordNet results for the shell and separate trees. You have five minutes. Go ahead and start."

Please stop. Now using the WordTrees identify and list potential analogies and analogies domains. Write down every possible analogy or analogous domain, even if it is not directly from your WordTree or it is technically infeasible, wild, or crazy. You have ten minutes to do this. Go ahead and start.
****

green pen, problem statement sheet*

The next step in the WordTree method is to write multiple problems statements that range from very general to very domain specific. Use your WordsTrees to create a series of problem statement. Make sure some are very general and some are domain specific language that is from one of the analogous domains you. You have ten minutes to do this.

*****

"Please turn all of your sheets over or cover all your sheets and take a two minute break. Please do not discuss the experiment or your solutions during the break."

****

maroon pen, problem statement sheet*

Now you are being asked to generate solutions and continue generating analogies for the peanut shelling problem. Begin by using your Problems Statements and then move to using single words from the WordTree.

The goal is to generate as many solutions as possible with as high of quality as possible and with as great of variety as possible. Technically infeasible, wild, non-standard and far out ideas are also encouraged. This helps to generate unique feasible solutions.

Use sketches and words to describe your ideas.

This experiment contains multiple tasks that will require the rest of the time. You may choose when to end the idea generation session and move on to the next task. When you are ready to move on to the next task please raise your hand.

You can use the rest of the time for idea generation.

Begin generating ideas by using your Problems Statements and then move to using single words from the WordTree.

Remember the amount of extra credit you will receive depends on your effort and performance.

Go ahead and start."

Pen Colors **"Switch to the X pen."**

Time	Color	Start	End
0-15	maroon		
15-30	Light blue pen		
30-40	Light blue marker		
40-45	pink		
**computer			
45-60	purple		

****Make sure I write down what time they want to end the activity ********

Remember you can use your WordTrees and Problems Statements to help you generate ideas.

<u>At 45 Minutes</u>

"If you want to us them, computers with internet access are available to assist you in solving the peanut shelling device problem. You can use them to researched the potential analogies you identified in previous sets and search for patents in the analogous domains. You do not need to use them. If you gain ideas from using the web, be sure to write down the reference information (the website address or other

appropriate information). Please raise you hand if and when you want to use one of the computers. "

****Make sure I write down what time they start using the computer********

End of session
Thank you for your participation.

Make sure you noted any analogies you used to help you find solutions. Please go ahead and add these if you have not already done so.

If you used the computer to search for ideas, write down a short description of how you searched. What search engines did you use? What terms did you search for?

There are multiple conditions being evaluated for this experiment. It is critical that you do not discuss the experiment or the design problem with your classmates until after Saturday, Dec. 1st or when I present the results in class. Also do not discuss if you liked or disliked the experiment since this will also bias the data. The second session is about 45 minutes long, includes a survey and will not focus on idea generation for the peanut sheller. I can schedule the second session at this time."

Experimenter Script: Day 2, Both Conditions

Experimenter script: **Morph Matrix Summary**

Items required for the experiment

- ☐ Morph matrices
- ☐ survey
- ☐ Stop watch
- ☐ pencils
- ☐ Stapler
- ☐ Analogy list
- ☐ Explanation slides

First go through all your concepts you generated in the last session and write down a description of any analogies you thought of or that you used to help you generate solutions. All the pages in your packets are numbered. Please write down the page number of where the analogy or solution occurs.

Next, take all your solutions and break them down into a morph matrix. Use words and pictures in the morph matrix. Here is an example on the overhead (laptop). In the lower right corner of each cell, be sure to include the page number for where the concept occurs. Some cells will have multiple page numbers since the same idea occurs on multiple pages.

The morph matrix does not include a complete list of functions. Only the most common functions are included so add additional functions as needed on the blank sheets.

Make sure all of your ideas are captured somewhere in the Morph Matrix. If one of your ideas does not fit under functions please put it in the other column. For example, genetically engineered peanuts would be placed in the other column. Be careful to list all of the analogies you used to assist in generating solutions and also list any other analogies you thought of even if you did not use them to generate solutions. It is very important that I get an accurate count of all the ideas and analogies you generated.

When you finish listing all of your analogies and the morph matrix, please fill out the survey.

After finishing the morph matrix, list of analogies and survey please spend any reminding time generating ideas. Be sure to include them in the morph matrix and analogy list.

******

"There are multiple conditions being evaluated for this experiment. It is critical that you do not discuss the experiment or the design problem with your classmates until after Saturday, Dec. 1st or when I present the results in class. Also do not discuss if you liked or disliked the experiment since this will also bias the data. If you have any questions regarding this experiment I can answer them at this time.

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