EVALUATING METHODS OF BIO-INSPIRED DESIGN AND

PROBLEM EQUIVALENCY

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EVALUATING METHODS OF BIO-INSPIRED DESIGN AND PROBLEM EQUIVALENCY

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SUMMARY

Bio-Inspired Design is becoming an increasingly popular approach that uses nature as a source of inspiration in order to develop innovative designs. Currently, tools and methods are being examined to determine how designers may generate innovative designs through leveraging biological systems. This thesis first presents a study that was performed in an engineering elective course and aims to explore the effects of five different existing methods for Bio-Inspired Design: Directed, Case Study, AskNature.org, BioTRIZ, and Bio-Keyword search. These methods were evaluated based on the quality, quantity, novelty, and variety of the ideas that students generated, the students' self-efficacy, and the feedback from the students. Multiple short design problems were employed in order to test each method with the participants. To account for differences among problems, such as varying levels of difficulty and complexity, the Linear Equating method was applied to the metric results. This attempted to effectively render the problems equivalent. The results demonstrated each method's ability to produce numerous effective and creative concepts, with high quality and novelty, and large quantity of ideas. It is also shown, through the use of Self-Efficacy surveys, that the methods utilized to teach Bio-Inspired Design positively affected the students' design confidence, outcome expectancy and anxiety, while also preserving students' high motivation towards engineering design. The Linear Equating method assumes a linear relationship between participants' performance on different problems and that there is no significant interaction between the design problem and method. This study originally planned to counterbalance the problems in order to account for problem differences, but this ended up not being possible due to course availability. From qualitative observation

of the participants' ideas, it was clear that there is significant interaction between the problems chosen and the design method. Therefore, more research was completed to understand the influence of different characteristics of the design problems.

A considerable portion of design theory research seeks to create, evaluate, improve or optimize design methods such as Bio-Inspired Methods. Developing a set of standardized design problems that can be used for within-subjects designs and can effectively compare the impacts of various design methods is an on-going challenge. This thesis used the scaling factors from an initial, large scale attempt to create a set of equivalent design problems. Due to unaccounted characteristic differences in the design problems used, some noticeable irregularities were qualitatively observed, despite the proper application of the Linear Equating Formula. In turn, this fueled the initiative to explore the characteristics of the design problems. These differences in characteristics may influence design outcomes that a linear relationship may not account for: experience and exposure to the design problems vary between participants, and certain problems may be easier to solve depending on the method that is being used.

This thesis proposes a small set of design problem characteristics that may influence the consistency between design problems, and presents two experiments targeted at uncovering these influences. In a first between-subject experiment, differences in quantity, quality, novelty and variety evaluation metrics were examined between two different design problems: an alarm clock and a device that shucks corn. This exploratory experiment identified the metrics the two problems were comparable or different, in order

to provide a basis for the proposed characteristics influence. An alarm clock is more familiar to students thus instigating a higher quality and greater number of concepts. The metric results confirmed this hypothesized difference in quality and number of concepts. To further support this hypothesis and explore the influence of familiarity, a follow up within-subject experiment was conducted to reduce variance due to participants and attempted to determine linear correlation consistency in metric results between the two problems. A different, but more commonly employed set of problems in design research were used: designing a device to shell peanuts and designing a measuring cup for the blind. This within-subject experiment displayed that a linear correlation between the two problems for the quantity and variety metrics was present, but absent for the quality and novelty metrics. In other words, the Linear Equating method is effective to scale these two problems under the same conditions for the quantity and variety metric, and not for quality and novelty. In addition, through the use of surveys, two of the hypothesized characteristics were correlated and compared: familiarity of the participants to existing solutions, and the number of analogies they were able to draw from nature. The survey results displayed a positive correlation for the number of concepts participants were familiar with for the two different problems. In other words, participants have a similar level of familiarity for both problems. However, a greater number of Bio-Inspired analogies are observed for the peanut shelling problem. These preliminary results support the possible existence of interaction between the design method and the design problem, especially when testing Bio-Inspired Design methods. For example, in this study, Blind Measuring Cup resulted in a greater variety of concepts. But when coupled with a Bio-Inspired Method like the Directed method (using the extent of one's knowledge), one's

ability to draw a greater number of analogies in nature may favor the Peanut problem. In that case, the Linear Equating method may be ineffective. Thus, demonstrating the necessity to further explore and improve design problem characteristics and linear equivalence to better evaluate and test methods of design.

CHAPTER 1: INTRODUCTION

1.1 Context and Motivation

Studying creativity in the hopes of improving innovation has been sought for decades, since it is essential to ensure competitiveness among industries and to solve engineering problems. Thus, the need to foster and enhance creativity and innovation has been highly solicited and continues to escalate. With prior work that confirms the ability to foster and enhance creativity and innovation in individuals, many researchers are encouraged and driven to seek ways of exploring that possibility [1-3]. Through exploring different approaches that aim to feed creativity and innovation, Analogy, which includes Bio-Inspired Design, has been found to be highly effective to achieve that goal [4-14].

1.2 Research Scope

Bio-Inspired Design, also called biomimetic design, biologically inspired design, or biomimicry, is a growing field that leverages biological organisms and systems to inspire the design of engineering systems [14]. Means of applying biological analogies to engineering concepts have previously been employed such as the Directed method, as termed by Glier *et al.* (2012), which simply directs one to use nature as source of inspiration, and Case Study which exposes one to successful cases of Bio-Inspired design to inspire ideas [14-21]. Subsequently, various tools of Bio-Inspired Design have been developed to assist designers with limited biological knowledge. Three of these tools are AskNature, BioTRIZ and Bio-Keyword Search [22-26]. A senior level elective design course at Texas A&M University was created to teach student designers how to use each

of these methods and tools to solve engineering problems. These methods were selected as they were five primary schools of thought available at the time that the class was created. In order to evaluate these methods, students were instructed to individually solve design problems and develop concepts for a group project, using these methods. Within the context of this course and the design problems given, this thesis investigates the similarities and differences between each method towards generating creative, numerous, and innovative concepts. It further explores student's feedback on each method and how learning these methods affected their engineering design self-efficacy.

This study was motivated by multiple inquiries: Previous research shows that drawing analogies has great impact on innovation during the design process, so one of this study's motives is to determine the effectiveness of these formalized Bio-Inspired methods [10, 12, 27, 28]. There are various Bio-Inspired Design methods that have been developed [29-34]. Unfortunately, there are few empirical studies that compare them. Pertaining to the final motive, this study seeks to determine the best ways to facilitate learning how to innovate using nature. Some courses have recently been developed to teach students Bio-Inspired Design, but there is ample room for improvement [35-38]. Determining the areas for refinement will contribute in the formulation of forthcoming Bio-Inspired courses.

Previous studies compared the effects of using nature as inspiration in contrast to non-biologically inspired methods of inspirations and also compared pairs of Bio-Inspired methods in order to determine advantages of one over another [9, 20, 39, 40]. No

study has simultaneously compared the five aforementioned methods in a course environment and tested the methods using similar design problems. While each of these five Bio-Inspired methods have been previously evaluated individually and shown effective, they have not been tested utilizing a within subjects design. Additionally, this study employs a design self-efficacy instrument to determine the effect of teaching and learning Bio-Inspired methods on students' design self-confidence. It is expected that the set of formalized Bio-Inspiration tools will outperform the Directed method since they provide better guidelines and databases, rather than relying only on the current biological knowledge of the students.

The design problems utilized in this study were developed and selected to be familiar to the students, while preserving a sense of challenge to solve. Moreover, they were employed as relatively similar problems. When testing multiple methods with design problems, using the same participants, one needs more than one design problem or else the participants would be tempted to fixate on concepts that they generated the first time around. It is recognized that no two problems are equivalent [41]. However, while these problems are different, researchers need for them to output comparable results under the same conditions. Thus, a method called Linear Equating will be implemented in this thesis to explore means of re-scaling problem outputs, under the assumption that the different problems have a linear relationship.

While analyzing the resulting design problem concepts that the students generated in the Bio-Inspired Design methods study, it was noticed that the design problems,

although intended to be similar and relatively interchangeable, may require further attention and improvement in creating the problems in order to ensure effective similarity and relative interchangeability. Directing the attention to the design problems is pertinent beyond the scope of the work presented in this thesis. Much research in creativity often involves providing predetermined design problems to subjects in an experiment and asking them to generate designs which may then be compared across a variety of factors [20, 39, 42-46]. Experiment designers craft these design problems to generate a range of designs across the measured variables while also limiting the introduction of potential confounds into the experimental setup. The design experiment settings, subjects and methods are highly variable, and thereby cause variability in the design problems that researchers create (or borrow) to address certain design needs. In order to evaluate the effects of multiple methods of design, subjecting the same participant to the same design problem multiple times will prove ineffective since the participant will already be familiar to the problem and may adhere to similar concepts that they generated during the first time around. Thus, utilizing different but equivalent design problems is highly desired in this genre of experiments. After analyzing these problems during the Bio-Inspired methods evaluation experiment, it was noticed that some participants' results were random and inconsistent (for some of the design problems).Some tended to produce on average more designs of lower quality, while others produced fewer designs with higher quality, regardless of the method used. Thus, this prompted the investigation to search for means of developing equivalent problems that would reduce randomization per participant, to be effectively utilized in this experiment. To do so, the differences between the current design problems must be understood and characterized.

This thesis offers the first steps in identifying those differences and characteristics. To do so, a proposed list of twelve design problem characteristics that may influence design outcome is hypothesized. Then, two exploratory experiments will be presented in which each compares the quantity, quality, novelty and variety metrics between two pairs of design problems: an alarm clock compared to a corn shucking device and a measuring cup for the blind compared to a peanut shelling device. In the latter comparison, the linear relationship of the metric results and possible effects of two of the twelve design characteristics (design solution familiarity in two domains) are further explored.

1.3 Thesis Organization

The following chapters of this thesis are structured as follows: I will begin by providing a background in Chapter 2, which will pertain to the topics and experiments that will be presented in later chapters, by introducing the context and various prior studies motivating this thesis. In Chapter 3, there will be a description of tools that were used in the studies, including the set of design problems, evaluation metrics, and the Linear Equating method. In Chapter 4, a study that tests and evaluates the various Bio-Inspired design methods will be presented as the Bio-Inspired Design (BID) Evaluation study. Chapter 5 will present a background and context for the second study which seeks to identify differences and relationships between problems: this study will be referred to as the Problem Equivalency study. The latter is comprised of two parts: Problem Effects, comparing the Alarm and Corn problems, Solution Familiarity, comparing Blind Cup vs Peanut. Finally, Chapter 6 will provide a comprehensive conclusion for both the BID Evaluation and Problem Equivalency studies, and impart on future work.

CHAPTER 2: LITERATURE REVIEW

This chapter provides a literature review that will help the readers of this thesis to have a better context and idea of what the thesis offers. It will demonstrate prior work that led to the motivation of the thesis, as well as works that are similar but serve to highlight and contrast the benefits and significant contributions of the thesis.

2.1 Teaching Creativity and Innovation

In the last decade, our ability to innovate and produce technology is increasing exponentially, resulting in increases in competition in engineering exploits [47]. While creativity research has been ongoing for many decades and proved effective, there is still a need to pursue further means of improving creative and innovative abilities in engineers and designers in order to maintain a competitive edge. Defining "Creativity" has been a never ending argument short of a finalized consensus [48, 49]. Most descriptions fit along the ability to intentionally produce novel, appropriate, non-traditional, and useful outcomes [48-52].

The ability to teach engineers and designers to think more creatively, opens the possibility to enhance their ability to be creative [3]. It can be cultivated and further developed through curriculums, practice, conditioning and various stimuli [2, 53, 54]. Various studies have demonstrated that the possibility to foster and improve creativity exists, through activities such as creativity lectures and mentoring [1] and creativity training [53]. Thus, countless researchers seek the ability to improve and foster creativity in designers. To tackle this drive earlier on in one's career, we must start through the

education of engineers, to output a highly creative and superior workforce. Starting at the source, school and education, we can prepare the future generations of engineers.

Many universities seek to improve the education of their students to make them more creative, not only in the United States, but all over the world [55-57]. Among the various research pursuits to improve creativity in university students, some studies examined ways to better engage students during courses, such as higher interaction between teams and instructor feedback [58], hands on building and testing [59, 60], problem based learning [61], and design curriculums that focus on creative problem solving skills, communication and teamwork via class projects and exercises [58, 62-64]. While these programs have proven to be effective towards fostering creativity, they are constantly being improved, redesigned, and new ones emerge.

2.2 Methods of Idea Generation

Creativity is most useful during idea generation process. Thus, various methods have been proposed and developed to help designers generate ideas and concepts in these initial phases of product design. Some of these methods include Brainstorming, TRIZ, SCAMPER and Functional Analysis, which can be used by a single individual, and 6-3-5, C-Sketch and Gallery method, which are team based methods [24, 25, 65-71].

Brainstorming was developed by Osborn to exploit one's imagination and improve the quantity of ideas or concepts generated during a group problem solving process [67]. He suggested suspending judgment and criticism to allow the extraction of a larger pool of ideas; the more ideas produced, the higher the chances of obtaining a successful one. This idea resulted in the following four rules:

1. *Criticism is ruled out.* Adverse judgment of ideas must be withheld until later.

2. *"Free-wheeling" is welcomed.* The wilder the idea, the better; it is easier to tame down than to think up.

3. *Quantity is wanted.* The greater the number of ideas, the more the likelihood of winners.

4. *Combination and improvement are sought.* In addition to contributing ideas of their own, participants should suggest how ideas of others can be turned into better ideas; or how two or more ideas can be joined into still another idea [67]

Though follow-up studies by other researchers found that the quantity of ideas generated through the combination of individual brainstorming sessions have been greater than a group brainstorming session [72-74]. Thus, if one's goal is to generate as many ideas as possible, it would be preferable to initiate individual brainstorming to maximize output and increase the "likelihood of winners", and then discuss the ideas as a group to combine and improve the best ones.

SCAMPER is another ideation method developed by Erberle which makes use of several ideas introduced by Osborn's Brainstorming, such as suspending judgment, large quantities, combining, improving and building upon ideas, and introducing wilderness [67-69]. This method suggests a series of actions or questions that can be posed to create new or improve upon existing ideas. These actions or questions fall under a set of categories that form the acronym S.C.A.M.P.E.R: Substitute, Combine, Adapt, Modify, Put to other use, Eliminate and Rearrange/Reverse [68]. For example, under the substitute

category, one could ask "What can I substitute component A with, that could maintain functionality but reduce weight?". While theoretically, the use of this method should improve creativity, it was shown by Mijares-Colmenares *et al.* that it displayed no significant improvement in figural creativity [75], as measured by Torrance's Figural Form A test [76]. However, a recent study shows that while the use of SCAMPER may induce fixation, it significantly improves the novelty of ideas generated when compared to a control group that uses no method of assistance [77].

The "Theory of Inventive Problem Solving" (TIPS or TRIZ) is built on the study of millions of patents to identify and classify repeatable patterns of innovation and thus create a theory, or at least algorithm, for innovation [24, 70, 71]. A contradiction matrix was developed that contains principles of innovation for 39 system parameters. Once a specific conflict is recognized, a look-up table is used to identify the specific principles of innovation that can overcome the conflict. TRIZ has been extensively studied and found to be an effective method to generate novel, useful and creative solutions [78-80].

The 6-3-5 method is a method developed by Rohrbach that uses similar principles as those of Osborn's Brainstorming, such as suspending criticism and combining and improving others ideas, to assist in idea generation sessions of groups [81]. According to Rohrbach, the group would consist of 6 participants, where each one would be given a piece of paper to write down 3 ideas for 5 minutes, thus the name "6-3-5". After each 5 minute interval, the each member of the group would rotate and pass along their piece of paper to the person next to them. During another 5 minutes, each

member will add onto the existing solution or create new ones. After those 5 minutes, the group rotates again and repeats the latter process until each paper returns to the original owner, for a grand total of 5 rotations. While this can be an effective method to generate a large quantity of ideas simultaneously and is preferred over the conventional brainstorming method, other researchers have developed extended or variations of the 6-3-5 method [82-85]. One extensively used variation is the C-Sketch method. It is very similar to the 6-3-5 method, however, instead of writing down ideas, they are sketched [82]. Linsey and Becker show that the use of C-Sketch is less effective than the 6-3-5 method when using sketches only [66, 86]. However, when using sketches along with annotations, it is more effective than using the 6-3-5 method, as the use of sketches can be more ambiguous, thus cause misinterpretations that lead to new ideas [82, 86, 87]. While these methods of idea generation may be effective in some ways, they do not provide sources of inspiration beyond one's existing knowledge.

2.3 Design by Analogy

An analogy, in the context of design, is described as the identification of similarities between two domains [88]; these similarities could be features, functions, or structures, depending on the objective. Gentner suggests the analogy between a battery and a reservoir; The similarities are not necessarily regarding the shape nor the build materials, but by their overall function of holding potential energy that is to be released a power systems [88]. Analogies, or taking ideas from existing systems, are often found to be useful during the idea generation process [89]. These analogies or sources of inspiration, serve as a guideline that facilitates the "known" aspects of inventive and

innovative creativity, from Taylor *et al*. [90], and allows one to apply these in novel ways or to develop new ideas. Using analogy as a source of inspiration is proven to be effective at fostering creativity and innovation [91]. Several methods have been developed to facilitate the use of Design-by-Analogy, including Synetics [92] and the WordTree method [93, 94],

2.4 Bio-Inspired Design Methods

Nature is a great resource of inspiration in engineering innovation [4-8, 14]. Drawing analogies from nature for design, frequently referred to as Bio-Inspired Design, has kindled many researchers' aspiration to explore such techniques. It is also referred to as Biomimetic Design, Biologically Inspired Design, or Biomimicry. In Bio-Inspired Design research, there are four core units, as suggested by Jamal Wilson: Biological and Engineering Research, Representation of Biological systems, Analogical Translation (Identification, transfer), Design Utilization [95]. At the dawn of Bio-Inspired design, there was limited formal framework other than simply directing designers' attention to nature. This thesis will refer to this Bio-Inspired design method as *Directed*. In other words, the designer is directed to reflect on or search biology for inspirations and analogies. This is consistent with prior work by Glier *et al.* [20]. Since most designers and engineers do not have a readily available database of natural inspirations, using the Directed method is limited by the extent of their biological knowledge. Some Bio-Inspired design methods attempt to mitigate these issues. Researchers have initiated the development of formal Bio-Inspired Design methods and tools in order to guide and assist engineers and designers in drawing ideas from nature [32, 33, 36, 96, 97].

Fu *et al.* offers a very comprehensive audit of the then-current state-of-the-art Bio-Inspired Methods and tools that had been developed, summarizes the characteristics of each, and provides a correlation that serves to highlight their alignments with findings in Design-by-Analogy factors [98]. These methods and tools include Biomimetic Design Through Natural Language Analysis, DANE, Idea Inspire, Engineering-to-Biology Thesaurus and the Four-Box Method. Essentially, through extensive literature research, each method was evaluated and classified by the degree to which it addressed cognitive and implementation factors that have been found through prior Design-by-Analogy research. Some of these factors include fixation, incubation, expertise, modality of representation, accessibility, computational synthesis and problem-solution approach. Thus, they subsequently provide an overview of opportunities that exist for future research that may improve these methods and tools to better address these factors. For example, none of the methods were found to address the factor of incubation. Hence, highlighting the opportunities of exploring the effects of incubation on these Bio-Inspired design methods [98]. Accounting for and mitigating these limiting cognitive and implemental factors in the development or improvement of Bio-Inspired design methods and tools, their use will be more efficient and increase the chances of success [98].

The Biomimetic Design Through Natural Language Analysis was developed as a systematic approach to retrieve a multitude of biology keywords that are more relevant to the target engineering application [99, 100]. These keywords facilitate the search for biological phenomena from journals and books that can inspire engineering design. Chiu

& Shu used WordNet as their lexical database, and found that while the method was used successfully in some cases, they encountered differences between engineering and biology lexicons which led to the necessity of future improvements [99]. Nonetheless, the search with action words like "remove", "encapsulate" and "release" resulted in a high return of significant biological keywords. Cheong *et al.* adapted this tool and refined it so that it utilizes keywords found in the Functional Basis developed by Stone and Wood [25, 100]. They systematically related relevant biological keywords with those found in the Functional Basis. The use of the Functional Basis keywords led to improved resulting biological keywords that an engineer can then utilize to find more relevant biological phenomena. This enhancement upon Chiu and Shiu's work displayed a useful application through a study with senior undergraduate in mechanical engineer students. They were to use the words "Prevent" and "Inhibit" in order to generate concepts for a device that is used for protection in sports or hobbies, and resulted in creative concepts [100]. Though this use of improved language analysis tool provided meaningful results, it showed the necessity of better guidance and strategies to better use the system.

The Engineering-to-Biology Thesaurus is mostly used as a tool in conjunction with a form of functional modeling [9, 101, 102]. It utilizes the Functional Basis as developed by Stone and Wood [25], but instead of the mechanical synonyms found in the "correspondents" column, they are replaced by biological function words found in nature [101]. These biological words were determined through the combined accumulation of biological discoveries done by Oregon State University, University of Toronto and Indian Institute of Science. Using these biological terminologies, one can more easily search

biological databases and build functional models that lean towards biological inspirations. This method was tested with a group of mechanical engineering students by having them read various biological sentences that contained Engineering-to-Biology Thesaurus keywords, and rate how relevant and useful these sentences were to inspire solutions to a design problem [9]. The results pointed to the need of improving student's training at using biological inspirations, and better testing environments and methods.

DANE and IDEA INSPIRE are two very similar computational tools, but have some differences [103, 104]. They are both comprised of models of biological and engineering systems that can be found through the search of their fundamental function [103]. They both also represent their biological systems in various visual forms and texts [103]. IDEA INSPIRE, on one hand, makes use of a functional method called SAPPhIRE (State-Action-Part-Phenomenon-Input-oRgan-Effect), and was tested using focus groups in a laboratory environment [104, 105]. DANE classifies its models in their library using a Stucture-Behavior-Function (SBF) modeling scheme, and was tested in a classroom setting, focused on teaching Bio-Inspired Design. Although the latter study displayed a lower usage and efficacy of DANE when compared the studies that tested IDEA-INSPIRE, it was shown to be useful. The differences, as pointed out by Vattam *et al.* could be associated to the type of environment in which the two tools were tested; One was in a laboratory setting where professional designers were directed to use IDEA INSPIRE in a limited period of time, whereas DANE was tested in a classroom setting where the students had more time and freedom to use alternative methods [103].

From observation of past studies [106], Helms and Goel noticed that students had trouble formulating problems and detecting relevance of biological passages or text in order to draw useful analogies from nature [107]. Subsequently, they sought to address these issues through their introduction of the Four-Box Method [107]. It is a quick-to-use tool that guides users to better represent, formulate and evaluate design problems and possible biological passages. Most prior methods mostly focused on finding similarities between problem descriptions and analogies in nature, however, the Four-Box methods serves to also account for the differences. Acknowledging the differences sometimes helps to determine new parameters in problem solving [107]. The Four-Box method draws its name from the simple four components the user must complete. The four components are Operational Environment, Function, Specifications and Performance Criteria. For each component, the user must describe the corresponding criteria for the problem description, and repeat the process for a possible biological phenomenon. Using a T-Chart, the users would be able to compare the four categories of the problem and those of the analogical passage. The T-Chart will help highlight the similarities and differences between the two. To assess the usability and effectiveness of the Four-Box method, Helms and Goel conducted a study in a Bio-Inspired course and integrated the method into the course material. Assignments were given to the students and were directed to use the method to better formulate design problems and determine their relationship with biological passages. The results of this study demonstrated the ease of use of the method and the accuracy in which the students employed it. Although, further research needs to be conducted in order to evaluate the effectiveness of using the Four-Box method to generate creative and novel solutions [107].

The selected methods employed in the undergraduate Bio-Inspired Engineering Design elective course at Texas A&M University were the Directed, Case Study, AskNature, BioTRIZ and Bio-Keyword Search method. Most of the methods described previously were not available at the time this course was planned. The five methods used are briefly discussed below.

2.4.1   *Directed*

The Directed Method simply directs a designer to use nature as a source of inspiration since biology has been recommended by many, as a valuable inspirational resource [14-17]. It uses existing knowledge of biology to apply it to a design problem. No formal structural tool is used, so with this method, the range of biologically inspired solutions relies on, and is limited to the designer's extent of biological knowledge. Glier *et al.* conducted a study to determine the effectiveness of using the Directed approach to solve design problems by prompting a group of novice designers to use the Directed method to generate ideas, while another was not prompted to use any formal methods [20, 21]. It was found that the Directed approach did not provide any significant advantages over using no specific method, in terms of quantity of ideas, quality, novelty and variety. This lack of difference was concluded to be a result of the designer's limited biological knowledge, therefor they suggested the use of formal methods to conduct Bio-Inspired Design [20, 21].

2.4.2   Case study

The Case Study Method of Bio-Inspired Design allows designers to search for inspiration through nature via existing Bio-Inspired designs. The course instructor would also expose the students to existing natural principles and show various phenomena that occur in nature (e.g. strong spider silk, gliding animals). The principle idea is that the designers will be exposed to different cases of Bio-Inspired Designs and will then develop an ability to recognize analogies used to transfer knowledge to engineering solutions. Thus, a collection of existing Bio-Inspired design solutions will be displayed and discussed in lectures. Many case studies can be found in various collection databases [14, 18, 19, 108]. University of Maryland and Montana State University have both developed courses that utilize this method [37, 96, 108]. The University of Maryland was able to test run the concept of Bio-Inspired design in a brand new course and exposed the students to multiple cases using their accumulated repository of case studies [96]. The initial evaluation outcomes, based on sole observation of the students and feedback surveys, were positive. They were able to grasp and utilize biological concepts in their resulting products, they demonstrated high engagement and attraction to Bio-Inspired Design, and over 90% of the students' feedback showed strong interest in the subject and the acquisition of new skill sets [96]. Montana State University also exposed their students in their Bio-Inspired Design course, to multiple case studies and reverse engineering [37]. Thus far, there is no documentation of the direct student feedback or evaluation on this course, to the author's best knowledge. However, Jenkins provides best practices based on the experiences, and offers insights to develop a Bio-Inspired Design course in a following text [108]. The demonstration of successful Bio-Inspired Design

cases may be helpful to a designer who is be able to apply the same analogical transfer found in that case, to their existing problem.

2.4.3 AskNature

Asknature.org is a curated database and website launched in 2008, that inventories nature's discovered solutions or phenomenon [109]. For each phenomenon, AskNature provides descriptions, pictures, diagrams, history, application ideas, similar natural systems, or existing designs that have applied said phenomena. This allows users to search for phenomena by keyword, function name, strategy, existing solutions, and organisms. Within the context of this database, function is defined by Asknature.org as "a speficic challenge met by nature", and strategy is defined as a means to address more than one challenge, thus serve multiple functions [22]. The information is free of charge for anyone, and there are currently over 1,800 natural phenomena available in the database, as of April 2015 [22]. This database essentially provides access to relevant biological information as they are continuously being discovered, studied and extracted from peer-reviewed journals [23]. The creators allowed users to create profile and hoped for communication, sharing and social activity, however this objectives were not observed in satisfactory levels [23]. As it is still an experiment relying on user feedback, it is constantly being improved by its developers [23]. Though there have not been any empirical studies, as of today, exploring the effectiveness of using AskNature.org to promote creativity, it has been found to be a useful resource [109].

2.4.4 BioTRIZ

The BioTRIZ Method is derived from the TRIZ method mentioned earlier [71]. BioTRIZ, is very similar to TRIZ, however, instead of using successful principles found from technological patents, the principles are derived from nature [24]. Similarly to TRIZ, BioTRIZ principals were developed through the study of around 500 biological principles which resulted in the documentation of 270 functions, leading to 2500 contradictions with their associated biological resolutions [24]. The system parameters were updated to six fields of operation for BioTRIZ (Substance, Structure, Space, Time, Energy, and Information), making it easier to use than the 36 system parameters found in TRIZ [24]. The use of BioTRIZ has been shown to be useful through direct application [110, 111]. Craig *et al.*, through the utilization of BioTRIZ, have successfully developed a Bio-Inspired solution to anengineering problem. They were able to design a roof structure that allowed for cooling of buildings with limited passage restriction to longwave infrared. Such a solution would not have been attainable through the sole use of the original TRIZ method [111]. Glier *et al.* has also evaluated the use of BioTRIZ through a study with a group of 12 graduate-level mechanical engineering students [112]. The students were taught to use TRIZ, BioTRIZ, Functional Modeling and bio-keyword search, and were then given a simple design problem to solve using TRIZ, then with BioTRIZ. It was found that both methods were well applied and rated higher, through student survey feedback,than Functional Modeling and bio-keyword search. While the two methods generated different concepts, there were no apparent advantages of using one over the other [112]. There were also some minor difficulties when using BioTRIZ after having used TRIZ. The fields of operation of BioTRIZ are more abstract than those

of TRIZ, which led to ambiguous problem conflict definitions and some confusion [112]. In general, the use of BioTRIZ was found to be simple and easy, however using the inventive principles to generate concepts was somewhat of a challenge for some.

2.4.5   *Bio-Keyword Search*

Functional Modeling enables a thorough understanding of the requirements and use of a product, while decreasing the tendency of designers to fixate on a particular physical solution for the problem [113]. Using Functional Modeling, designers deconstruct a problem so that an analogous function in nature can be more easily found. From there, one can use function terms to search for analogies in a bio-keyword-based database. Several of these curated databases have been created to facilitate the search for appropriate biological sources of inspiration, such as AskNature, DANE and IDEA INSPIRE [31, 105]. The method evaluated in this thesis, Bio-Keyword search, makes use of Functional Modeling in combination with black box models, Glier's Engineering-to-Biology Thesaurus, and the use biological journals and textbooks as databases [9, 101, 102]. During the functional modeling phase, the user would create a black box model to identify the core functions of the system, then decompose the system into more detailed functions using terminologies from the functional basis [25], then translate these terms into biological words via the Engineering-to-Biology thesaurus, and use those "bio" terms to search the journals and textbooks [9, 101, 102]. Several examples of functional models can be found here [26, 97, 114]. By developing such models using bio-keywords from the Engineering-to-Biology Thesaurus, it facilitates the individual functions in the models to be explored through analogies in nature, and also allows one to compare the

full functional models of mechanical problems to those found in nature. Subsequently, black box models can also be compared to facilitate direct inspiration matching. Furthermore, the functional modeling of biological systems allows engineers to better understand the phenomena occurring in the said system; mitigating the need for engineers to comprehend biological language. Such a repository of biological phenomena functional models has been developed [113]. Through the use of four case studies, results of a preliminary studies showcases the successful use of functional modeling coupled with repositories to effectively enhance problem formulation, and further transfer principles from biology to engineering systems, leading to the development of uniquely creative solutions [97, 113]. In all four cases, the biologically inspired solution function flows and components were compared to those of the engineered solutions on a, and were regarded to be relatively unique, novel, functional and effective [97, 113].

2.5 Teaching Bio-Inspired Design Methods

Various universities like Georgia Institute of Technology, Montana State University and University of Maryland have developed courses through which students are taught methods of Bio-Inspired design [37, 96, 115]. The studies at Montana State University and University of Maryland were discussed previously in the Case Study section. The instructors and designers of the courses are still investigating better methods and structures by trial and error, course evaluation experiments and student feedback. Whilst progressing, these universities have published descriptions of their course structures to inspire other universities, provided data for extensive research, and have conducted their own studies and evaluations of the courses [33, 36, 96, 116-118]. Georgia Institute of

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Technology nurtures the Center for Biologically Inspired Design (CBID), and has introduced a multidisciplinary Bio-Inspired Design course. The curriculum and methods of teaching have been modified with every new semester since it was first introduced in 2006, in order to explore various effects and the best practices. It typically involves a mix of undergraduate and graduate mechanical engineers, biologist, biomedical engineers, industrial engineers, architecture, material science and a mixture of other disciplines. It also involves readings, assignments and group projects. As other universities have done, this course catches the student's interest in Bio-Inspired design by familiarizing them with successful case studies. Then, they were taught how to assess and reframe engineering problems presented to them in terms of functional analysis, how to draw analogies from nature and allow them to solve small group exercises. It is predominantly focused on novel design techniques, interdisciplinary communication and collaboration, and exploration of topics beyond one's core domain [118].

This course has been the subject of many studies conducted by Helms *et al.*, including the implementation and testing of DANE (discussed earlier) [106, 107, 117-120].Some those findings include the identification of key challenges when teaching students to perform Bio-Inspired design. Some of those challenges include searching, identifying, understanding and evaluating biological systems and good design problems, mapping, transferring and communicating analogies and complex systems, and interacting in interdisciplinary team environments [118]. Additionally, they were able to use the course to evaluate two high-level processes of performing Bio-Inspired Design: Solution-Driven and Problem-Driven. It was found that a Solution-Driven starting point

more readily drives the design process, as opposed to a Problem-Driven starting point, since it incites more structural focus [106, 120]. Furthermore, they suggest from observation that using interdisciplinary teams allows an expansion of one's horizons and domain since each student is pushed to examine problems from different point of views and communicate ideas to diverse disciplines. This promotes creativity and innovation [118].

Texas A&M University developed a similar elective course to introduce undergraduate Mechanical Engineering students to Bio-Inspired design. Prior studies were conducted to develop the course and determine the methods that would be incorporated into the curriculum [115]. The teaching methods and curriculum will be discussed in Section 4.1.

2.6 Evaluating and Comparing Methods Studies

With the development of formalized methods and tools come the inevitable studies that test, evaluate, and compare the effectiveness of each method. Most of the studies briefly discussed in the previous section test the effectiveness of each singular method when compared to a "no-method" control group. For some traditional, non-Bio-Inspired methods, such as TRIZ, SCAMPER, 6-3-5, C-Sketch, BrainSketching, and Gallery Method, there have been a few comparative studies to determine advantages of one method over the other, to the author's best knowledge.

Chulvi *et al.* compares the TRIZ, SCAMPER, Osborn's Brainstorming and no method by assigning four different groups of design PhD students a specific method, with

which they were to solve design problems [78]. The results were analyzed using a multidisciplinary panel of judges that rated each concept on novelty and utility. Results show that the use of TRIZ helps to generate more novel solutions than SCAMPER. Unexpectedly, brainstorming result in more novel solutions than both, however, those were rated as less useful than those generated by both TRIZ and SCAMPER [78]. However, the use of the three formal design methods showed advantages on both criteria when compared to no formal method.

In another study by Linsey *et al.*, equivalent methods to Brainstorming, 6-3-5, C-Sketch, BrainSketch and the Gallery Method were compared by assigning various senior level mechanical engineers a design problem to solve with each method [66, 86]. The resulting concepts were analyzed using the formalized Quantity, Quality, Novelty and Variety evaluation metrics (discussed later), and displayed greater advantages in quantity and quality metrics when using methods that involve both sketching and text [66, 86].

Similar styles of studies are also applied to evaluate the effectiveness of Bio-Inspired Design methods. For example, as discussed earlier, testing the effectiveness of using nature through the Directed approach, or the Engineering-To-Biology Thesaurus approach [9, 20]. These studies observed each method individually but were not compared to other Bio-Inspired design methods. Glier *et al.* evaluated the use of Bio-Keyword Search (similar to the one in this thesis) and BioTRIZ, by teaching them to working professionals, through a weekend-long workshop [39, 112]. The comparison was made possible through the analysis of a three-part activity given during the weekend, a

long-term design project, and feedback surveys. It was found that the designers were able to learn and quickly apply each method, and they aided to generate concepts that were inspired by nature. Some difficulties using each method were discovered. As discussed earlier under the BioTRIZ section, the BioTRIZ inventive principles were easily found but difficult to apply. Furthermore, Glier *et al.*'s version of Bio-Keyword search facilitated the search for biological analogies for those that were familiar with Functional Modeling. Thus, since most were unfamiliar, they were unable to generate useful models, whereasthose who better grasped the concepts of functional modeling were able to generate more useful models [112].

CHAPTER 3: EXPERIMENTAL TOOLS

In this thesis, various tools were used to test participant's creative and innovative skills, and assess their self-efficacy to evaluate to degree to which the elective course impacted the participant's perceived engineering design skills. This chapter will present those various tools, where they came from, how they are used and applied.

3.1 Design Problems

As many prior studies, engineering design problems are used to assess one's creativity and ability to generate concepts. To develop design problems, researchers often began by brainstorming potential problem ideas as a lab group when applicable design problems are not available in the literature. Currently, in the design literature there are a limited number of problems available.   In this study, several problems were selected and used to evaluate subjects' outputs. These include Alarm, Corn, Coconut, Blind Cup, Peach, Towel Ironing, and Peanut Sheller [20, 39, 42-45, 121, 122].These problems are described in Table 1. Each problem presents an engineering query within their context and environment of operation, followed by a set of customer needs that concepts should satisfy.

Table 1: Design Problems Descriptions

Corn
Corn is currently the most widely grown crop in the Americas with the United States producing 40% of the world's harvest. However, only the loose corn kernels are used when bought canned or frozen in grocery stores. An ear of corn has a protective outer covering of leaves, known as the husk, and strands of corn silk threads run between the husk and the kernels. The removal of husk and silk to clean the corn is known as shucking corn. Design a device that quickly and cheaply shucks corn for mass production.
Customer Needs:
• Must remove husk and silk from corn cob with minimal damage to kernels.
• A large quantity of corn must be shucked quickly.
• Low cost.
Alarm
Alarm clocks are essential for college students, however often times they will wake up a roommate and those around them as well. Design an alarm clock for individual use that will not disturb others. The clock should be portable for use in a variety of situations such as on the bus, in the library, or in a classroom.
Customer Needs:
• Must wake up individual with no disturbance to others.
• Must be portable and lightweight.
• Electrical outlets are not available as a constant power source.
• Low cost.
Blind Cup
Design a volume-measuring apparatus for use while cooking by a person who is blind. It needs to be easy to operate and able to be used for both powders and liquids without splattering during operation. The apparatus needs to measure graduated quantities from 1/4 to 2 cups.
Customer Needs:
• Prevent waste of food products.
• Easy to clean.
• Low cost.
Towel Ironing
Design an automatic wrinkle removing device for use for towels in high-end hotels. The purpose of the device is to remove wrinkles from freshly laundered towels and to fold the towels. At this stage of the project, there is no restriction on the types and quantity of resources consumed or emitted.
Customer Needs:
• Remove wrinkles and fold towels quickly.
• Consistently remove all of the wrinkles and fold towels to the same size.

Table 1: Design Problems Descriptions (Continued)

Coconut

In certain places like the Philippines, Indonesia, and India, coconut harvesting is a major practice. The current process requires a skilled person to climb the tree and cut down the coconuts. The average height of a coconut tree is 35-40 feet and though there are grooves along the tree that make it easier to climb, the tree surface becomes very slippery during the rainy seasons. The process may take as long as 12 hours for large farms that average 150 trees. The goal of this problem is to design a low-cost product to improve the coconut harvesting process so that it is safer and can be done more quickly. The target throughput is at least 500 pounds per hour.

Customer Needs:

• Must climb tree and remove coconut with little damage to fruit.

• Electrical outlets are not available as a power source.

• Low cost

Peach

Peaches have a pit in the center of the fruit that should not be eaten. Ripe peaches are delicate, soft, and bruise easily. For certain types of peaches, the flesh of the peach clings tightly to the pit. Design an automated device that can cleanly remove the pits of all ripe peaches while keeping the fruit intact and without wasting much of the fruit. The peaches cannot be genetically modified. The target throughput is approximately 50 pounds per hour.

Customer Needs:

• Must remove entire peach pit with minimal damage to the peach.

• A large quantity of peaches must be quickly pitted.

• Low cost.

Peanut

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 of this project is to design and build a low-cost, easy to manufacture peanut shelling machine that will increase the productivity of the African 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 quantity of peanuts must be quickly shelled.

• Low cost.

• Easy to manufacture

The Alarm problem was adapted from the design problem created by Genco *et al.* to compare freshman undergraduate engineering students' innovative capability to those of seniors [42]. Their version asked the participants to design an alarm clock that could be disabled by a user with oven mitts, earmuffs, and blindfolds, whereas Glier *et al.* modified it to the description shown in Table 1 [20]. No reason was given for the changes. The modified Alarm problem was used in conjunction with the Corn problem by Glier *et al.* to study the effectiveness of the Directed method's use [20]. The Coconut problem was developed by Glier *et al.*'s for a Bio-Inspired workshop study [39]. It was adapted from Atilola *et al.*'s "Coconut Husking", for their study to compare the effects of representations of examples [43]. The Blind Cup problem was taken directly from Janson and Smith's study to test the ability of measuring design fixation [44]. Jansson and Smith asked participants to design a measuring cup for individuals with visual impairments. It was chosen because it would be less familiar to participants, thus avoiding fixation. The Peanut (or Peanut Shelling) problem is the most used in various prior design studies that test creativity and innovative capabilities of designers [45, 121, 122].

The Peach and Towel Ironing problems were developed for the purpose of the course presented in this thesis. There was a need to find a problem that students would be familiar with but did not have obvious known solutions, thus creating an engineering challenge.

3.2 Idea Evaluation Metrics

To measure the effectiveness of experimental conditions, four formal ideation metrics have been used in prior studies: quantity of ideas, quality of concepts, novelty and variety. These metrics were first proposed by Shah *et al.* [123], which were then adapted and supplemented by Linsey *et al.* [121, 122]. The procedures for assessing these metrics were recently further refined to increase reliability by Helms *et al.*, which are documented and formalized in a comprehensive Training Packet [124]. When a participant generates conceptual sketches as possible solutions for a particular design problem, these metrics are used to quantitatively analyze, evaluate and compare these resulting concepts.

To better explain these metrics, one must understand the context in which they are used. Participants are typically asked to sketch and annotate several concepts for a particular design problem. The concepts are then analyzed and coded by graduate students that have been trained using the coding Training Packet developed by Helms *et al.* [124]. For each metric, there are structured procedures to follow to ensure consistency in coding. The Training Packet ensures that all trainees will evaluate problems similarly, following the same guidelines. It offers a full description of each metric, along with multiple example concepts that a trainee may use for practice. The purpose and process of each metric are described as follows.

3.2.1   Quantity

The Quantity of Ideas, or simply referred to as "Quantity", is an ideation metric that determines the number of non-redundant ideas found in a set of concepts provided by one participant. An single "idea" is a part of the design that satisfies a function in the Functional Basis [125]. Each concept usually encompasses several ideas in order to complete a task or set of tasks. In order to calculate the number of these non-redundant ideas, each concept provided by a subject is initially analyzed individually and all the ideas present each concept is listed. If any idea is used by one individual participant more than once within the same concept, or duplicated in another concept, then that idea is only counted once. However, if there was a component that was used to accomplish different functions, the component was counted for each function. For example, in the example concept for the Peanut Shelling problem in Figure 1, the concept uses a human being to perform two separate functions: to position the peanuts and to supply energy. Thus, "Human" is counted twice as a non-redundant idea for that participant's set of concepts. Furthermore, if this same participant were to generate 3 more concepts that also utilized a "Human" as an idea that satisfies the functions Supply and Position, then the pair of "Human-Position" and "Human-Supply" would only be counted once for all four concepts, since they would be redundant ideas for all four concepts. In the end, the total number of non-redundant ideas for a set of concepts is counted and recorded. To ensure reliability amongst coders that analyze these concepts, a Pearson Correlation is often used between two different raters that count the number of non-redundant ideas.
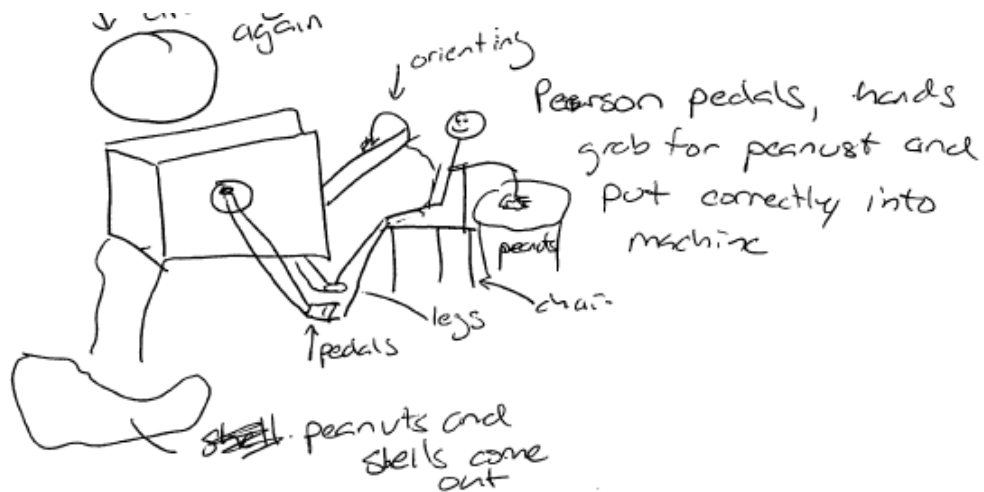
Figure 1: Example Concept to Peanut Problem Demonstrating the "Position" and "Supply" functions performed by a human [124].

3.2.2   Quality

Quality is a measure of the feasibility of a concept and how well it meets the problem specifications or customer needs [126]. This metric uses a three-point rating scale, which was developed by Linsey *et al.* [121, 122]. A quality score of zero is given to concepts that are not technically feasible or do not meet any of the customer needs. A score of one is given to concepts that are technically feasible and partially meet the customer needs. A score of two is given to concepts that are both technically feasible and also meet all the customer needs. To better represent this though process, the 3 levels of quality are represented in the flowchart in Figure 2.
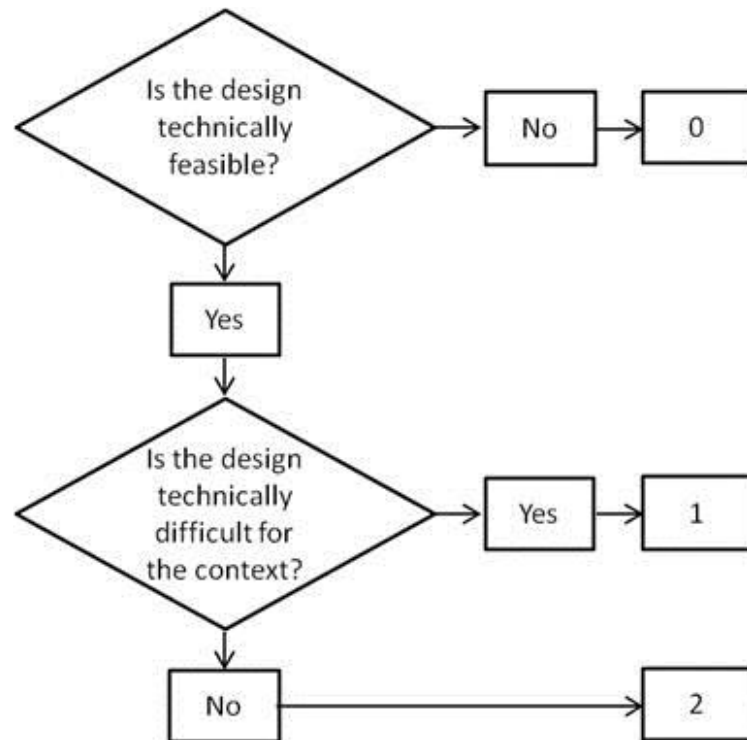
Figure 2. Flow chart process for quality rating.

Two examples of quality ratings are shown in Figure 3. The first shows a concept involving genetically modified or bio-engineered worms that will only eat the shell but leave the peanut intact. While this concept may be considered to be very creative and out of the ordinary, it received a quality score of 0 due to its lack of technical feasibility. The second concept utilized human feet to crack the peanut shells, which is feasible and low cost, however it may cause damage to the peanuts, the output number would be lower than what is demanded, and there would be a lack of consistency in the pressure applied to each peanut. That concept would receive a score of 1.
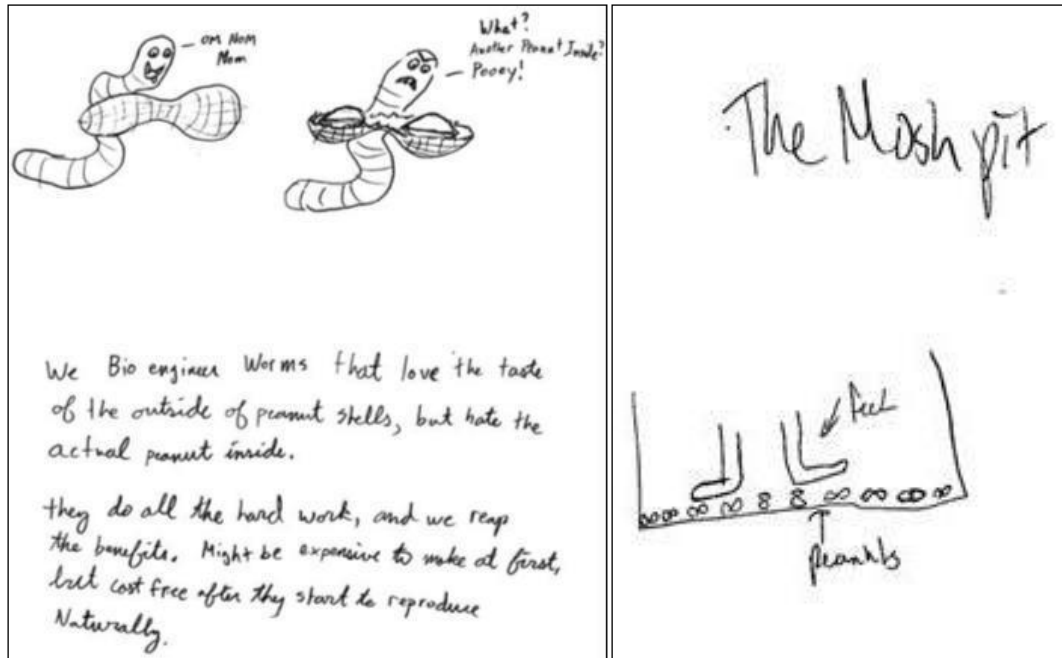
Figure 3: Concepts that have quality score of 0 (left) and 1 (right)

A concept with a score of 2 would be found to be technically feasible, fitting to the context of the problem, and fulfilling most of the customer needs. A concept receiving a score of 2 is shown in Figure 4 because it is simple, consistently removes the shells, uses a low cost source of power and has a high rate of shelling.
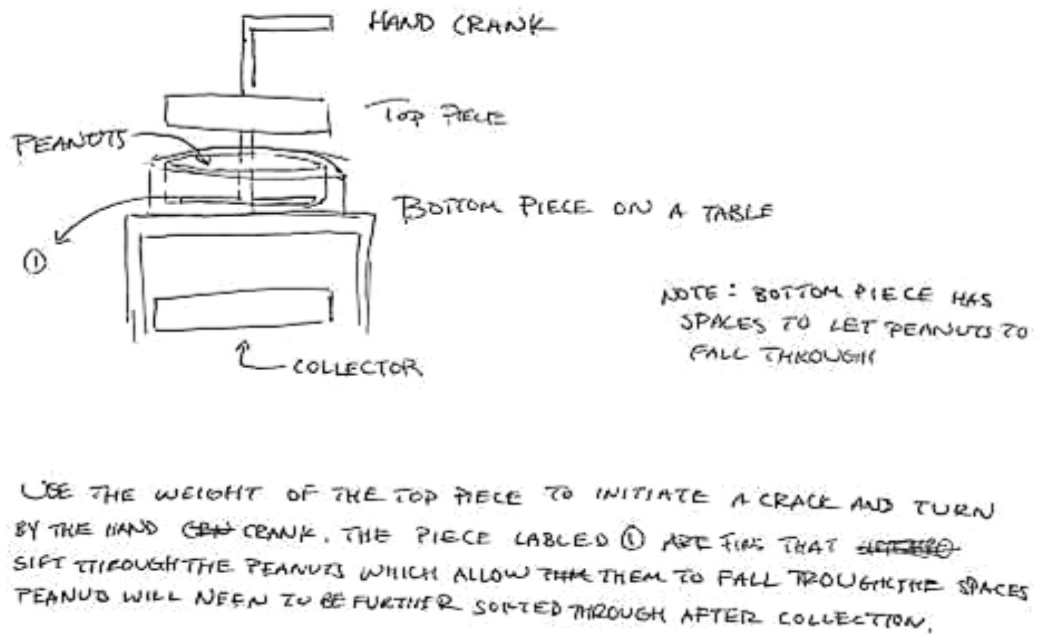
Figure 4: Concept that has a quality score of 2

For each participant, the average quality score of their Concept set is averaged. This allows the comparison of each participant's levels of output quality. Of course, different raters may determine different quality scores for the same concepts, thus to ensure reliability of this metric among raters, the use of Cohen's Kappa is used for at least half the data being rated, as it is a measure of inter-rater agreement for qualitative data analysis [127].

3.2.3   *Novelty and Variety*

The Novelty metric measures the frequency of occurrence of concepts given a solution space generated by the participants, while the Variety metric measures the size of that solution space [126]. In order to measure Novelty and Variety, a "Bin" list is developed for each design problem solution space. These bins consist of a list of concepts that have been used by different participants. For example, since the peanut shelling problem has been the most used, it has the most coherent and reliable bin's list. Some of these bins include cylindrical roller, blade, filter, press, centrifuge, vibration, etc. For each individual concept, one point is added to a bin, or if the concept is composed of multiple bin concepts, a point will be added to a multiple of bins. Thus far, after multiple studies and use of the peanut shelling problem, a coherent bin's list consisting of 45 bins has been established, accounting for a wide variety of concepts that have been generated by over thousands of participants [65, 128, 129]. A full bin list and description is provided in Appendix B for the peanut shelling problem. The Alarm and Corn problem, which have been used by a few studies [20, 21, 130], consists of 39 and 43 Bins thus far, respectively (Shown in Appendix C). A lesser used problem, Blind Cup, consists of 33 bins thus far (Appendix C). For newer problems such as Coconut, and Towel Ironing, and Peach, well established bins have not yet been developed, but thus far consist of 45, 38, and 30 bins, respectively (also shown in Appendix C). Once a bin's list is established, the concepts at hand can now be entered into an excel sheet as shown in APPENDIX D. For each particular concept, the individual ideas in that concept are cross listed with the corresponding bin. The number of occurrences of each bin across the pool of concepts leads to the calculation of the Novelty and Variety metric as follows.

For each bin and a given solution space, the novelty score is calculated by taking one minus the ratio of number of concepts in a bin to the number of total number of concepts. The mean novelty score for each participant is then found by averaging the novelty scores of their concepts. This would result in a score between 0 and 1. The closer the score is to 1, the more novel it is. The variety metric employs the same bin counts that were utilized for Novelty. For each individual participant, the variety score is the ratio of total bins used by that participant to the total number of bins. Similar to the novelty metric, the score can vary between 0, for not developing any concepts, to 1, for generating concepts that fall within every bin. For reliability and consistency of novelty and variety results, a Pearson correlation is used between two raters' results.

3.2.4   Number of Concepts

This metric shows the number of single product solutions provided by each participant for a given problem. A single product solution is defined as all the ideas contained on a single page unless participants made a clear indication that the product solution is continued onto another page [121]. This metric is evaluated by counting the number of single product solutions generated by each participant, and obtaining a total number. To not be confused with "Quantity of Ideas", a participant can provide many concepts. For example, the student-generated solution set in Appendix B shows 4 concepts generated by one student. Thus the number of concepts for that student is 4, and each of these 4 concepts contains multiple "Ideas" as described by the Quantity of Ideas metric.

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3.3 Linear Equating

Design problems vary in difficulty to solve, participant familiarity, solution space size and many other factors. To account for between-problem evaluation metric differences, a method of linear equating was introduced in order to scale resulting metrics to make different problem metric results "equivalent". The reasoning behind this method can be explained by the following example: If Problem A is always twice as hard as Problem B under one specific condition, then for future evaluation and alternate testing conditions, we always want to take into account that hardness factor of 2. But to determine that "2" factor, both problems need to be evaluated under the same situation to serve as a baseline.

To determine the baselines in the context of this study, the multiple design problems were given to freshman engineering students under the same conditions. It is assumed that all freshmen have similar knowledgeability and with a large enough sample size, different groups can essentially be treated as equals. The peanut sheller problem was used as the reference. In other words, from the previous example, the peanut sheller problem represents Problem A, and the subsequent problem factors (B, C, D, etc...) are relative to Problem A. This Peanut problem was particularly chosen for this purpose as it was the most used, developed and well evaluated by Linsey *et al.* [121, 122]. It served as a solid baseline reference. Thus, within the same parameters and level of knowledge, the resulting evaluated metrics for the different problems can be correlated back to those of the Peanut Sheller. Ideally, after using these factors and the method of linear equating to

rescale Problems B (C, D, etc…), they can essentially be treated as equivalent to Problem A (or the Peanut Sheller problem in this case).

To obtain these ratios or factors between each problem's metrics and those of the Peanut Sheller, the resulting metrics obtained from the analysis of the concepts generated by the participants are recorded. These factors are then used to calculate the equivalent scores, assuming the relationship between groups were linear, thus using the Linear Equating equation from ETS [131]. With this scaling, there are three parameters to take into account. The data set of the reference problem, Problem A (in this case being Peanut Sheller), referred to as A_1, the data set of the problem (B, C, D, etc.) which was collected under the same conditions as that of the Peanut Sheller, referred to as B_1, and the data set of the new scores (under the new conditions being tested) that need to be scaled (Problem B, C, D, etc.), referred to as B_{2i}. The new equivalent or scaled scores were calculated using Equation 1

$$\textbf{\textit{Scaled B}}_{2i} = \left(\frac{SD(A_1)}{SD(B_1)}\right) \textbf{\textit{B}}_{2i} + \left[\textbf{\textit{mean}}(A_1) - \left(\frac{SD(A_1)}{SD(B_1)}\right) \textbf{\textit{mean}}(B_1)\right] \quad (1)$$

Where B_{2i} is the input of the equation, representing the metric score to be scaled, $SD(A_1)$ and $SD(B_1)$ are the standard deviations of the A_1 and B_1 data set respectively. $mean(A_1)$ and $mean(B_1)$ are the means of the A_1 and B_1 data sets, respectively. $Scaled\ B_{2i}$ is the new, scaled score which should be equivalent to that of A_1, which in this case is the Peanut Sheller problem.

The Alarm, Corn, Blind Cup, Towel Ironing and Coconut problems were given to freshmen engineering students under the same conditions: 50 min to generate as many concepts as possible, without using any particular method of problem solving. This data was mainly collected for the purpose of a longitudinal study by Kim *et al.* but with the secondary purpose of these equivalency factors. For more detailed experimental setup, please refer to [132]. For this thesis, the available resulting average and standard deviation values for the quantity, quality were pulled and acquired from Kim *et al.*'s study and are displayed in Table 1 to facilitate the use of Equation 1. Since the Peach Pitter problem used in this thesis is different from the Peach Transport problem in Kim *et al.*'s study, the equivalency factors are yet to be available. Additionally, the Novelty and Variety factors were not recorded due to differences in bins and rating training of these respective metrics from the time the freshman data was analyzed to this thesis' analysis.

Table 2: Equivalency Factors

	Quality		Quantity	
	Mean	**SD**	**Mean**	**SD**
Peanut	1.29	0.28	15.3	4.92
Alarm	1.62	0.29	12.4	4.99
Corn	1.06	0.23	9.85	3.56
Blind Cup	1.29	0.42	13.0	4.71
Towel Ironing	1.32	0.36	9.63	4.73
Coconut	0.93	0.29	17.0	6.31
Peach	Not Avail.	Not Avail.	Not Avail.	Not Avail.

3.4 Self-Efficacy

Bandura defined self-efficacy as one's beliefs in their own level of ability to successfully perform domain-specific tasks [133]. It was shown that as one's self-efficacy increases, one is more likely to wield greater effort towards an activity in the domain of that self-assessment [134]. Subject-specific self-efficacy can be improved through additional education, as well as increased experience[135]. Thus, one's self-efficacy can be increased through the learning of material pertaining to one's goal and gaining the motivation to succeed [136]. Thus, a higher self-efficacy drives one's behavior towards higher achievements.

The ability to measure an individual's self-efficacy allows researchers to measure the effectiveness of experimental variables such as training programs, curriculums, experiential learning, etc. Carberry *et al.* developed a self-efficacy instrument to study people's self-efficacy towards engineering design tasks [135]. These engineering tasks follow the eight steps of the engineering design process as proposed by the Massachusetts Department of Education: Identify the need or problem, research the need or problem, develop possible solution(s), select the best possible solution(s), construct a prototype, test and evaluate the solution(s), communicate the solution(s), and redesign [137].

This instrument examines four task-specific self-concepts, which are defined as "any variables concerning the understanding an individual has of him or herself for a given task" [135]. The four task-specific self-concepts in the survey are self-efficacy, motivation, expectancy of success, and anxiety towards the task. For each of the four

self-concepts, a set of nine questions, of which the last eight of the steps correspond to the eight steps of the engineering design process, is posed. The first question is a comprehensive question (soon to be explained). The user must select a degree, on a scale of 0 to 100, to which they think they can perform the specific tasks. The example questions are presented in the structure presented in Figure 5.

Rate your degree of (FILL IN TASK-SPECIFIC SELF-CONCEPT OF INTEREST) (i.e. belief in your current ability) to perform the following tasks by recording a number from 0 to 100. (0 = low; 50 = moderate; 100 = high)

	0	10	20	30	40	50	60	70	80	90	100
Conduct engineering design											
Identify a design need											
Research a design need											
Develop design solutions											
Select the best possible design											
Construct a prototype											
Evaluate and test a design											
Communicate a design											
Redesign											

Figure 5: Carberry *et al.*'s Generic Scale that represent the engineering design domain [135]

The very first task, "Conduct Engineering Design" is referred to as one's Engineering Design (ED) score, which in theory encompasses one's self-concept of performing the entirety of the eight subsequent tasks of the engineering process. The eight individual tasks are the steps that construct the overall design process, and their entirety is referred to as the Engineering Design Process (EDP). Ultimately, the survey asks a subject to complete the set of nine tasks shown in Figure 5 for the four self-concepts: Their confidence, their motivation, expectancy of success, and their level of

anxiety. Thus, an individual with high self-efficacy would be confident in their abilities to complete the task, would have high motivation and expectancy of success, and have low levels of anxiety.

This self-efficacy instrument, or modified versions, has been employed by various studies to measure subjects' improvement or lack thereof, of their self-efficacy from experimental processes, courses, design methods, or training [138-141]. To clarify, this self-efficacy instrument reports one's self-reflected abilities to conduct traditional engineering design, not the ability to conduct Bio-Inspired Design. Though this thesis examines the use of Bio-Inspired Design, it employs this self-efficacy instrument to evaluate the effects of learning various Bio-Inspired Design methods on the student's self-reflected ability to conduct a traditional engineering design processes. It is hoped that learning these new methods provides new perspective and insights in the students' future application of the traditional engineering process.

CHAPTER 4 – BID EVALUTION STUDY

BIO-INSPIRED DESIGN METHODS

This chapter will present the quantitative and qualitative evaluation of the five Bio-Inspired Design methods using the tools from Chapter 3, with additional analysis of surveys and student feedback.

4.1 Experimental Methods and Analysis

A between-subject experiment was run with students from a senior level Bio-Inspired design course at Texas A&M University, during two different semesters, one year apart. The participants consisted of 32 students in Semester 1, and 42 students in Semester 2. Since the participants are mechanical engineering students, biology is not a required part of their curriculum so their knowledge of biology is comparable to that of a practicing engineer who has not worked with biological systems. The experiment took place throughout the course of the semesters. The data collected for this experiment collected the assigned course homework or in-class assignments, and no additional compensation was provided for participation in the experiment. Students provided their consent for their work to be used for research. The syllabus and class structure can be found in Appendix F.

4.1.1   Homework Assignments and Design Problems

The five methods for Bio-Inspired design were taught throughout both semesters as individual modules by the same instructor in the following order: Directed Method, Case Study, AskNature, BioTRIZ, and Bio-Keyword Search. The lecture modules used to teach BioTRIZ and Bio-Keyword Search are shown in Appendix G1 and G2,

respectively. At the end of each module, there were a few class exercises and worked examples to help practice. Then, the students were given an assignment containing a design problem, for which they were to generate concepts using the method of that module. Since AskNature.org was also presented and tested as a tool to perform Bio-Inspired Design, for the purpose of this elective course, the students were asked to exclude AskNature.org as a possible source of information when using the Case Study method. The prompts used to direct participants to use a specific method for each design problem, and the method can be seen in handouts in Appendix A.

The design problems, described in Section 3.1, were chosen to involve tasks that the students would be familiar with, but with a small change that would make the task more challenging. For example, many of the students have likely removed the husk and silk from corn, but may not have considered how to do so for mass production. The problems also needed to have mechanical solutions since the participants were mechanical engineers.

After learning one of the Bio-Inspired design method modules, each student was given a design problem as a prompt for generating concepts. For Semester 1, two problems were given for the Directed method (Alarm and Corn), and for Semester 2, only Alarm was used for Directed. Two problems were implemented in Semester 1 for the Directed Method because there was concern if the problems would be good ones. For the other methods, the design problems were rotated. The various problems and their assigned methods are graphically depicted in Table 3.

Table 3: Graphical representation of experimental setup of methods and problems

	Problem					
Method	Alarm	Corn	Blind Cup	Towel Ironing	Coconut	Peach
Directed	Semester 1 / Semester 2	Semester 1				
Case Study			Semester 1			Semester 2
Ask Nature			Semester 2	Semester 1		
BioTRIZ				Semester 2	Semester 1	
Bio-Keyword					Semester 2	Semester 1

Semester 1 (red) **Semester 2** (teal)

The instructor of the course was directed to follow the script in Appendix A for each homework assignment during class time, as an announcement to the students. Additionally, each student was asked to generate as many concepts as they could for 50 minutes, no matter the level of feasibility, using the prompts in Appendix A. Some minor modifications were made in the problem statements from Semester 1 to Semester 2, such as adding extra instructions in the method sections. Originally, it was planned to only allow participants to generate concepts for 50 minutes. In Semester 1, the instructions to limit the participants' concept generating to 50 minutes was present but unclear for certain problems and was therefore assumed to be overlooked. This was recognized from observing the student's responses: some were missing a 50 minutes line. In Semester 2, the instructions were still unclear but looking at the collected homework, it was noticed that some participants observed the 50 minutes line rule and some did not. For fairness of rating, all concepts generated, even past the 50 minutes line, were included in the metrics' ratings. This may have caused a disparity in the mean number of concepts generated per participant for one problem. The concepts were to be sketched by hand

with annotations. An example concept set generated by a student can be seen in Appendix B. Some students missed a few classes or did not turn-in their assignments, thus the number of designs submitted for each combination varies. The number of assignments collected for each method is supplied in Table 4.

Table 4. Number of participants for each method per semester

	Semester 1	Semester 2
Directed	17 (Alarm), 15 (Corn)	41
Case Study	32	41
AskNature	29	41
BioTRIZ	24	35
Bio-Keyword Search	23	32

The ideas generated by the students, were evaluated using the quantity, quality, novelty, variety and number of concepts metrics, as discussed in Sections 3.2. These metrics were used to quantitatively compare the experimental conditions based on the concepts generated by the participants. In order to ensure reliability of the metrics, two separate evaluators rate the concepts to obtain inter-rater agreement. The two ratings were tested using Pearson's Correlation for quantity, and Cohen's Kappa for quality. That way, one person is not rating differently than another.

Two graduate students were trained using a Metric Training packet [124]. A single rater evaluated all the data from this experiment. The second rater evaluated the results from at least 20 participants in each condition for all the metrics. These second ratings are used to establish inter-rater agreement and ensure that the overall ratings are consistent and repeatable. The main rater already obtain satisfactory inter-rater agreement for the

Corn problem for another study [132], thus required inter-rater agreement for the remaining problems of this thesis. For the quality, quantity, novelty and variety metric, there was agreement with Cohen's Kappa values of K > 0.68 and Pearson correlation of R > 0.74, R > 0.88, R > 0.77 respectively. For All the inter-rater agreement values are shown in Table 5 for all the design problems.

Table 5: Inter-Rater Agreement Statistics

	Quantity	Quality	Novelty	Variety
	Pearson R	Cohen's Kappa K	Pearson R	Pearson R
Alarm	0.96	0.68	0.93	0.97
Towel Ironing	0.78	0.69	0.96	0.92
Blind Cup	0.77	0.68	0.90	0.87
Coconut	0.85	0.73	0.88	0.77
Peach	0.74	0.69	0.89	0.94

Using the equivalency method described in Section 3.3, each participant's quantity and quality scores were scaled individually. It was originally planned to scale the resulting metrics of all the homework problems in this experiment to their corresponding Peanut Sheller equivalences, however, due to changes in planning and experiments, the equivalency factors were not calculated for Peach. In other words, this thesis will present scaled quantity and quality metric scores for all the design problems in this experiment (Alarm, Corn, Blind Cup, Coconut and Towel Ironing) except for Peach. As mentioned earlier, the novelty and variety scores were not scaled due to differences in rating styles between the freshman data analysis and this thesis'.

4.1.2   Semester Project

For both semesters, there was a semester long project to be worked in teams. At the beginning of the semester, the students were presented a problem for which they were to generate various concepts. After each method module, the groups were to use the newly learned module to generate concepts for their team projects. These assignments were assigned simultaneously with the individual homework assignments, however, they were generally due a few days after the individual homework assignment's due date.. Thus, the order in which the students completed the homework and these group project assignments varied. At the end of the semester, each group was to write a final report and develop a slideshow presentation to summarize the problem statement, the various concepts generated with each method, the choice of a final concept that best met the problem requirements, their preferred method to use. Although not explicitly asked, some teams mentioned the method they thought helped to generate the most creative and varied set of concepts. The instruction set for the final report and presentation is shown in Appendix J.

In Semester 1, there were 8 teams, however through data collection and transfer, the reports and presentations for the 8th team was missing, leaving only data from 7 teams. For Semester 1, the students' semester long project was to generate concepts to render their on campus dining more efficient at cleaning dishes.

In Semester 2, there were 11 teams. For their semester long project, each team was to develop their own engineering problem that they wished to solve. These problems

varied among teams, and included problems such as a human powered and easily cleaned device to cut fruits and vegetables to decrease meal prep times, a new system for tailgating at sporting events to reduce setup time, and a method to cool tents while camping in warm environments. The full list, as directly stated by the groups in their reports, can be found in Appendix I.

To obtain valuable quantitative information from these semester long project reports and presentation, the analysis consisted of reading through the written final reports in conjunction with their associated final power point presentations, and recording what the teams had declared to be their favorite methods to use, which method or methods their chosen final concept was drawn from, which methods the teams had declared to aid at generating the most creative and a more varied pool of concepts, and the number of concepts that were generated using each method.

4.1.3 Self-Efficacy and Survey

Upon the start of the course, students were given a consent form and Carberry *et al.*'s Engineering Design Self-Efficacy Instrument, described in Section 3.4 [135]. At the end of the course, the same Engineering Design Self-Efficacy Instrument was given to the students. The self-efficacy instrument asks for the participants' degree of confidence in their abilities, their motivation level, their outcome expectancy, and their degree of anxiety for engineering design and seven of the eight steps of the engineering design process. One of the steps of the survey, "research design need" was removed for this particular experiment since it did not apply to a Bio-Inspired Design curricula. For each of these task-specific self-concepts, 8 items were scored using a 100-point scale.

The Engineering Design Self-Efficacy Instrument forms were collected as hard copies from the students and the scores were manually entered into a spreadsheet twice to eliminate possible errors from manual data entry. The difference between the Pre-Course and Post-Course Self-Efficacy forms were analyzed, as well looking at the comparison of both semesters' Pre-Course and Post-Course forms.

An additional survey was also given to each student at the end of the course, asking "Which method did you find most useful and why?", to which the responses were open ended. Example answers are shown in Figure 6. To be processed and analyzed, each student's answer was read by a graduate student, and the methods mentioned in the answers were recorded and counted. If the student mentioned more than one method, each method was still counted. The reason "why" they chose the methods were taken into account and used as part of the discussion for the effects of each method. Both semesters' data were combined for analysis.

Figure 6: Example Method Usefulness Survey Answers

4.2 Homework Assignments Results

4.2.1 Collected Homework

Due to small sample sizes and irregularity in the responses among participants, the resulting quantity, quality, novelty, variety, and number of concepts metrics failed the normality tests, which prevented the use of parametric data analysis [142]. Therefore, Independent Samples Kruskal-Wallis H tests and Mann-Whitney U tests were used as a non-parametric version of one way ANOVA's and t-tests, respectively [142].

4.2.1.1 Quantity

Figure 7 shows the comparison of methods using the Kruskal-Wallis test, based on the mean quantity of ideas generated per participant. Based on these results ($\chi^2 = 86.6$ df = 4, $p < 0.001$), there is a significant difference across the different methods. The full Pairwise comparison statistics are shown in Table 6
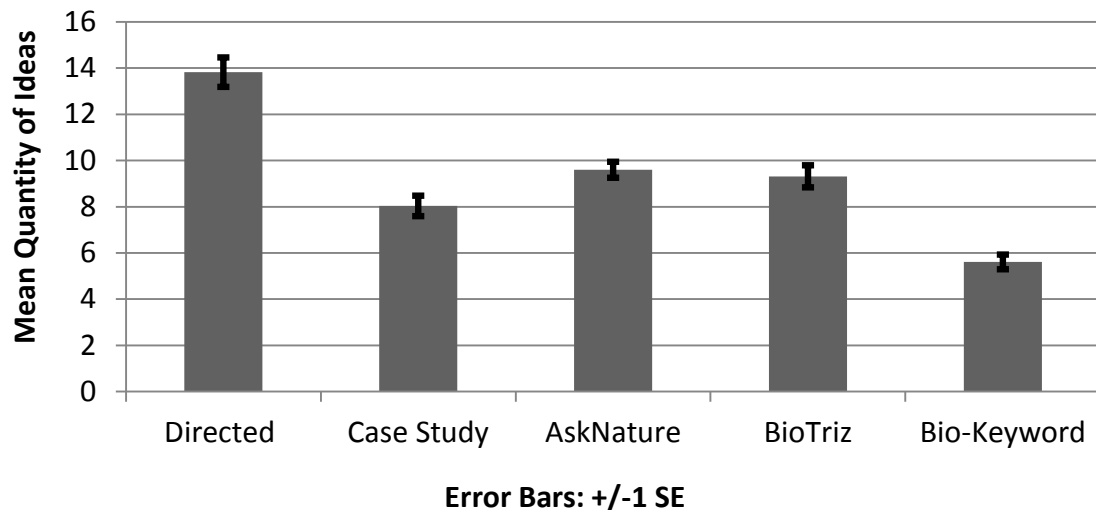
Figure 7: Mean quantity of ideas comparison across methods (Scaled)

Table 6: Pairwise Comparison of Mean Quantity of Ideas of Methods (Scaled)

	Test Statistic	Std. Error	Std. Test Statistic	Sig.	Adj. Sig.
BioKeyword - Case Study	50.5	19.2	2.63	0.009	0.087
BioKeyword - BioTRIZ	76.9	16.9	4.55	< 0.001	< 0.001
BioKeyword - AskNature	83.6	16.4	5.09	< 0.001	< 0.001
BioKeyword - Directed	142.2	16.3	8.72	< 0.001	< 0.001
Case Study - BioTRIZ	-26.4	16.9	-1.56	0.12	1.00
Case Study - AskNAture	-33.1	16.4	-2.02	0.043	0.43
Case Study - Directed	91.7	16.3	5.63	< 0.001	< 0.001
BioTRIZ - AskNature	-6.73	13.6	0.49	0.62	1.00
BioTRIZ - Directed	65.3	13.5	4.85	< 0.001	< 0.001
AskNature - Directed	58.5	12.9	4.55	< 0.001	< 0.001

Of the five methods, the Bio-Keyword Search method provides a statistically significant lower mean quantity of ideas than the other four (Kruskal-Wallis Test, $p < 0.088$), and the Directed method provides a statistically significant higher mean than the other four (Kruskal-Wallis Test, $p < 0.001$). There is no statistically significant difference between Case Study, AskNature and BioTRIZ.

The raw (un-scaled) results are also displayed in Figure 8 with the associated statistics in Table 7, showing that the trends and differences among methods are still the same as the scaled results. Although, the means are overall slightly higher in the scaled data than the un-scaled.
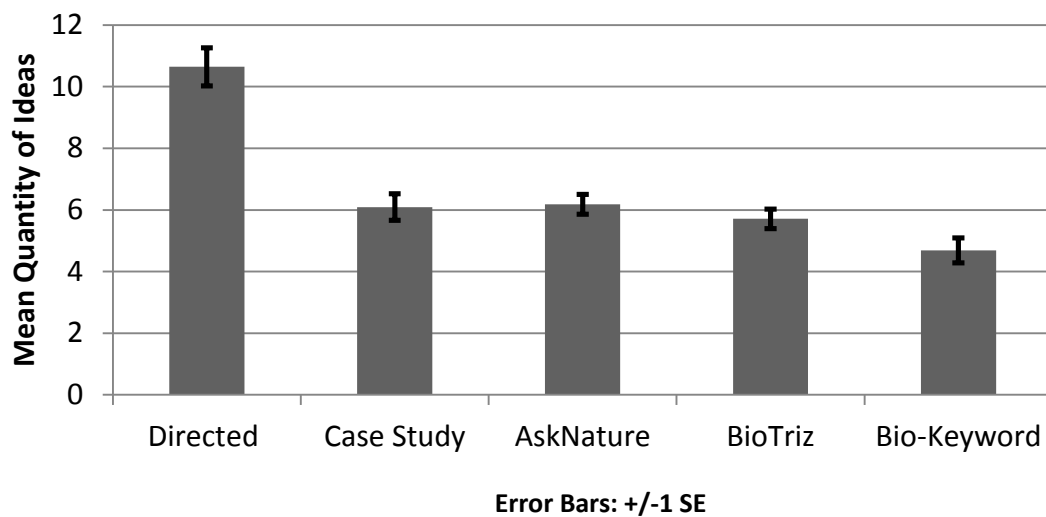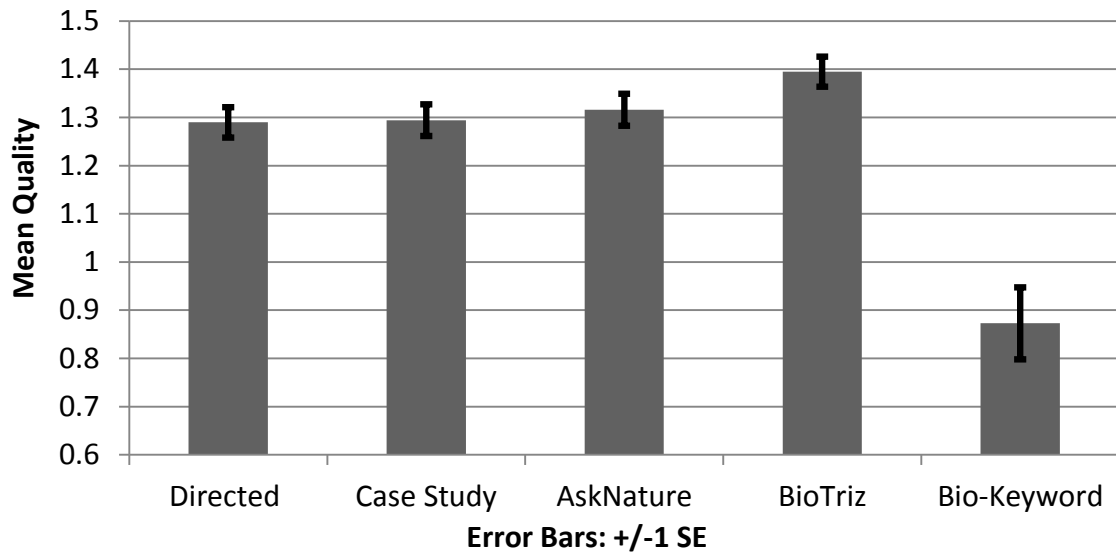
Figure 8: Mean quantity of ideas comparison across methods (Un-Scaled)

Table 7: Pairwise Comparison of Mean Quantity of Ideas of Methods (Un-Scaled)

	Test Statistic	Std. Error	Std. Test Statistic	Sig.	Adj. Sig.
BioKeyword - Case Study	16.3	17.4	0.94	0.35	1.00
BioKeyword - BioTRIZ	71.1	17.4	4.1	< 0.001	< 0.001
BioKeyword - AskNature	106.3	17.4	6.1	< 0.001	< 0.001
BioKeyword - Directed	180.8	17.4	10.4	< 0.001	< 0.001
Case Study - BioTRIZ	-54.8	17.4	-3.2	0.002	0.016
Case Study - AskNature	-89.9	17.4	-5.2	< 0.001	< 0.001
Case Study - Directed	164.5	17.4	9.5	< 0.001	< 0.001
BioTRIZ - AskNature	35.1	17.4	2.0	0.043	0.429
BioTRIZ - Directed	109.7	17.4	6.3	< 0.001	< 0.001
AskNature - Directed	74.6	17.4	4.3	< 0.001	< 0.001

54

4.2.1.2   Quality

Figure 9 shows the comparison of methods based on the mean quality of ideas provided. Based on the Kruskal-Wallis test results ($\chi^2 = 33.8$, df = 4, $p < 0.001$), there is a significant difference across the different methods. The full Pairwise comparison statistics can be seen in Table 8.

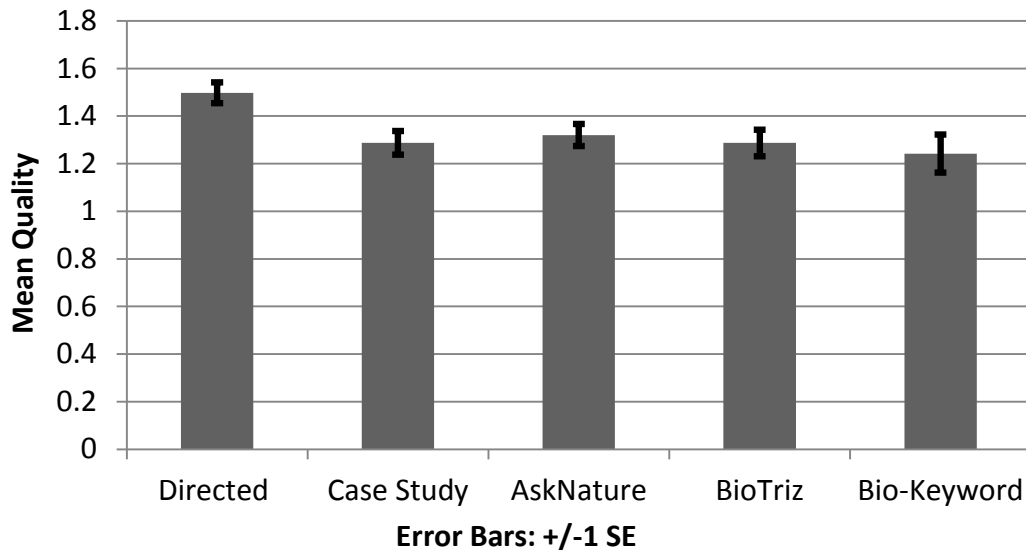**Figure 9: Mean quality of ideas comparison across methods (Scaled)**

Table 8: Pairwise Comparison of Mean Quality of Ideas of Methods (Scaled)

	Test Statistic	Std. Error	Std. Test Statistic	Sig.	Adj. Sig.
BioKeyword-AskNature	73.1	16.4	4.5	< 0.001	<0.001
BioKeyword -Directed	75.2	16.3	4.6	< 0.001	< 0.001
BioKeyword -Case Study	76.4	19.2	3.9	< 0.001	<0.001
BioKeyword - BioTRIZ	95.5	16.9	5.7	< 0.001	<0.001
AskNature - Directed	2.07	12.8	0.16	0.87	1.00
AskNature - Case Study	3.33	16.4	0.20	0.84	1.00
AskNature - BioTRIZ	-22.4	13.6	-1.7	0.099	0.99
Directed - Case Study	-1.26	16.3	0.078	0.94	1.00
Directed - BioTRIZ	-20.3	13.4	-1.5	0.13	1.00
Case Study - BioTRIZ	-19.1	16.9	-1.1	0.26	1.00

Of the five methods, the Bio-Keyword Search method provides a statistically significant lower mean quality of concepts than the other four (Kruskal-Wallis Test, $p < 0.001$). However, there is no statistically significant difference between Directed, Case Study, AskNature and BioTRIZ, so there is no conclusive difference among those four methods for quality of concepts metrics.

For a comparison of the scaled and un-scaled scores, the un-scaled results are displayed in Figure 10 and the associated pairwise comparison statistics are shown in Table 9. It shows that trends are very similar to the scaled results, with the exception that the statistical significance in difference shows Directed to be slightly higher than the other methods, and the significance in differences between Bio-Keyword and Case Study, AskNature and BioTRIZ are lower.


Figure 10: Mean quality of ideas comparison across methods (Un-Scaled)

Table 9: Pairwise Comparison of Mean Quality of Ideas of Methods (Un-Scaled)

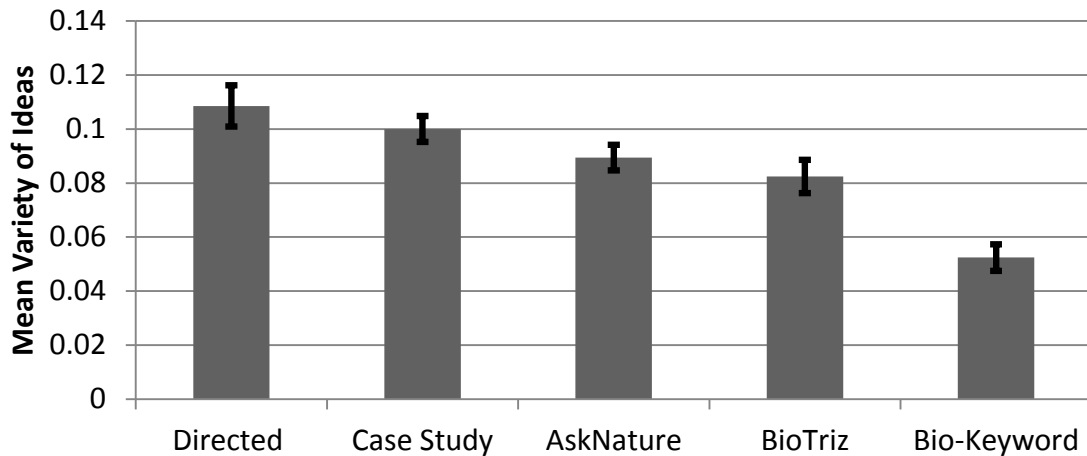|	Test Statistic	Std. Error	Std. Test Statistic	Sig.	Adj. Sig.
BioKeyword - BioTRIZ	3.6	16.1	0.23	0.82	1.00
BioKeyword - Case Study	12.3	18.4	0.67	0.51	1.00
BioKeyword - AskNature	12.6	15.7	0.80	0.42	1.00
BioKeyword - Directed	47.7	15.6	3.1	0.002	0.022
BioTRIZ - Case Study	8.6	16.1	0.53	0.59	1.00
BioTRIZ - AskNature	8.9	12.9	0.69	0.49	1.00
BioTRIZ - Directed	44.0	12.9	3.4	0.001	0.006
Case Study - AskNature	-0.34	15.7	-0.022	0.99	1.00
Case Study - Directed	35.4	15.6	2.3	0.023	0.23
AskNature - Directed	35.1	12.3	2.9	0.004	0.043

4.2.1.3   Novelty

Figure 11 shows the comparison of methods based on the mean novelty scores of ideas generated. The statistical results, using the Kruskal-Wallis test, show no significant difference between any method (χ^2 =4.75, df = 4, p = 0.314). While the comparison of the methods is statistically inconclusive, the high mean novelty score of each method greater than 0.9 demonstrate each method's ability to generate novel ideas.
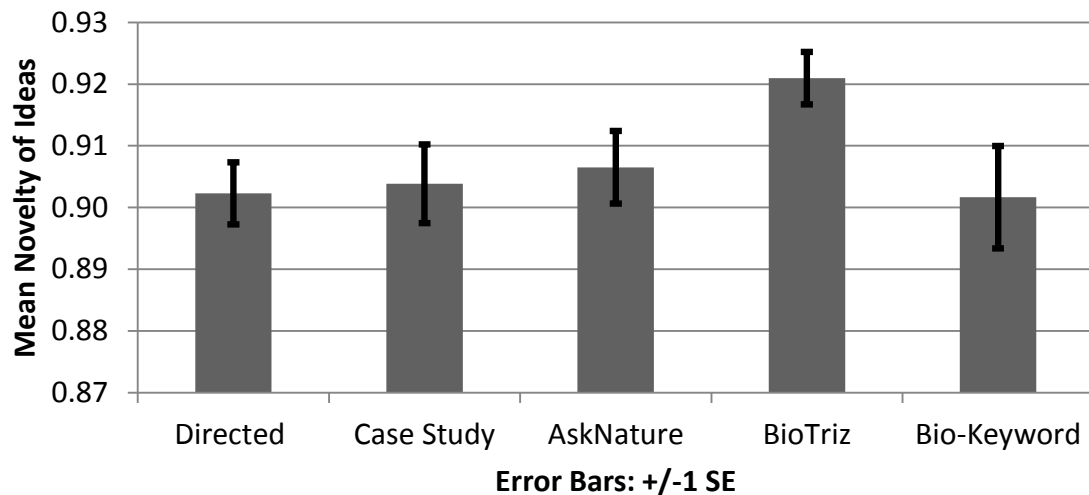
Figure 11: Mean novelty comparison across methods

4.2.1.4   Variety

Figure 12 shows the comparison of methods based on the mean variety scores of ideas generated. The statistical results, using the Kruskal-Wallis test, shows statistically significant difference between the methods (χ^2 =87.2, df = 4, p < 0.001). The full Pairwise comparison can be seen in Table 10.

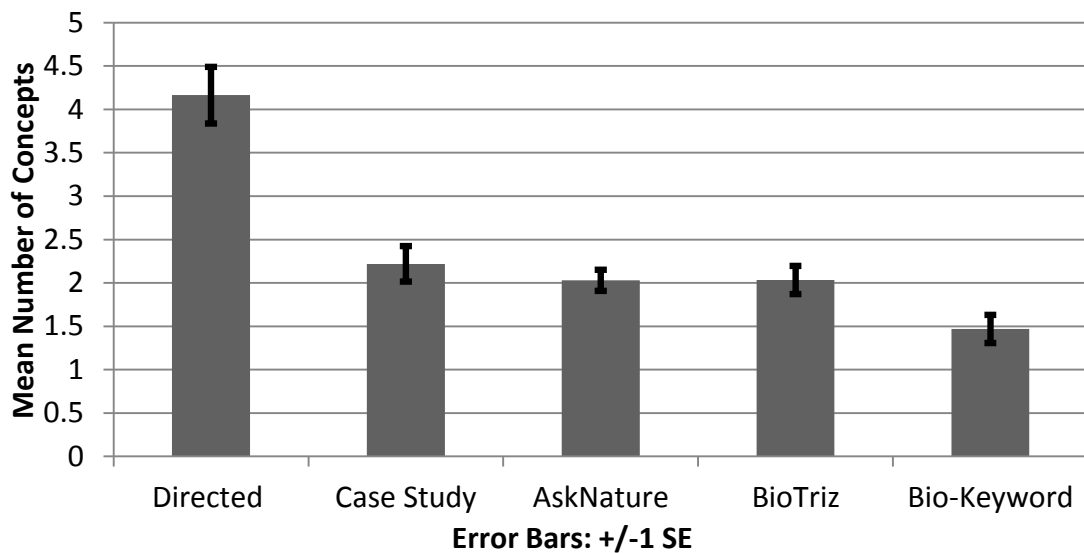**Figure 12: Mean variety comparison across methods**

Table 10: Pairwise Comparison of Variety scores across methods

	Test Statistic	Std. Error	Std. Test Statistic	Sig.	Adj. Sig.
Function- BioTRIZ	60.5	17.6	3.5	< 0.001	< 0.001
Function - AskNature	112.3	17.6	6.4	< 0.001	< 0.001
Function - Directed	131.1	17.6	7.5	< 0.001	< 0.001
Function - Case Study	137.9	17.6	7.9	< 0.001	< 0.001
BioTRIZ - Ask Nature	51.8	17.6	2.9	0.003	0.032
BioTRIZ - Directed	70.6	17.6	4.0	< 0.001	< 0.001
BioTRIZ - Case Study	77.4	17.6	4.4	< 0.001	< 0.001
Ask Nature - Directed	18.8	17.6	1.1	0.28	1.00
Ask Nature - Case Study	25.7	17.6	1.5	0.14	1.00
Directed - Case Study	-6.85	17.6	-0.39	0.69	1.00

From the pairwise comparison results, Directed, Case Study and AskNature show no statistically significant difference among each other (Mann-Whitney test, p = 1.00). However, BioTRIZ is lower than Directed, Case Study and AskNature with statistical significance (Mann-Whitney test, p < 0.032). Bio-Keyword is even lower than the other four methods, also with a statistical significance (Mann-Whitney test, p < 0.006).

4.2.1.5   Number of Concepts

Figure 13 shows the comparison of methods using the Kruskal-Wallis test, based on the mean number of concepts generated. Based on these results (χ^2 =51.9, df = 4, $p < 0.001$), there is a significant difference across the different methods. The full Pairwise comparison statistics can be seen in Table 11.

Figure 13: Mean number of concepts comparison across methods

Table 11: Pairwise Comparison of Number of concepts across methods

|	Test Statistic	Std. Error	Std. Test Statistic	Sig.	Adj. Sig.
BioKeyword - BioTRIZ	34.9	16.3	2.2	0.031	0.31
BioKeyword - AskNature	40.5	15.8	2.6	0.010	0.11
BioKeyword - Case Study	49.8	18.5	2.7	0.007	0.072
BioKeyword - Directed	100.6	15.7	6.4	< 0.001	< 0.001
BioTRIZ - AskNature	4.58	13.1	419.0	0.68	1.00
BioTRIZ - Case Study	14.8	16.3	0.91	0.36	1.00
BioTRIZ - Directed	65.6	12.9	5.1	< 0.001	< 0.001
AskNature - Case Study	9.34	15.8	0.59	0.56	1.00
AskNature - Directed	60.1	12.4	4.9	< 0.001	< 0.001
Case Study - Directed	50.7	15.7	3.23	0.001	0.012

Of the five methods, the Bio-Keyword Search method provides a statistically significant lower mean number of concepts than the other four (Mann-Whitney test, $p < 0.11$), except when compared to BioTRIZ (Mann-Whitney test, $p = 0.31$). The Directed method provides a statistically significant higher mean than the other four (Mann-Whitney test, $p < 0.012$). However, there is no statistically significant difference between Case Study, AskNature and BioTRIZ, so there is no conclusive difference among those three methods in terms of the number of concepts (Mann-Whitney test, $p > 0.95$).

4.3 Semester Project Results

4.3.1 Method Used For Final Concept

For the Bio-Inspired elective course at Texas A&M University, each of the final concepts provided by the teams was developed using one or two Bio-Inspired design methods. For each final concept, the methods used were counted. The resulting number of final concepts with their respected method used is displayed in Figure 14, with the

associated statistical analysis in Table 12 that show statistical significance. Case Study and AskNature most often led to the final concepts. Fewer of the concepts generated by the Directed, BioTRIZ and Bio-Keyword Search methods were selected as final concepts.
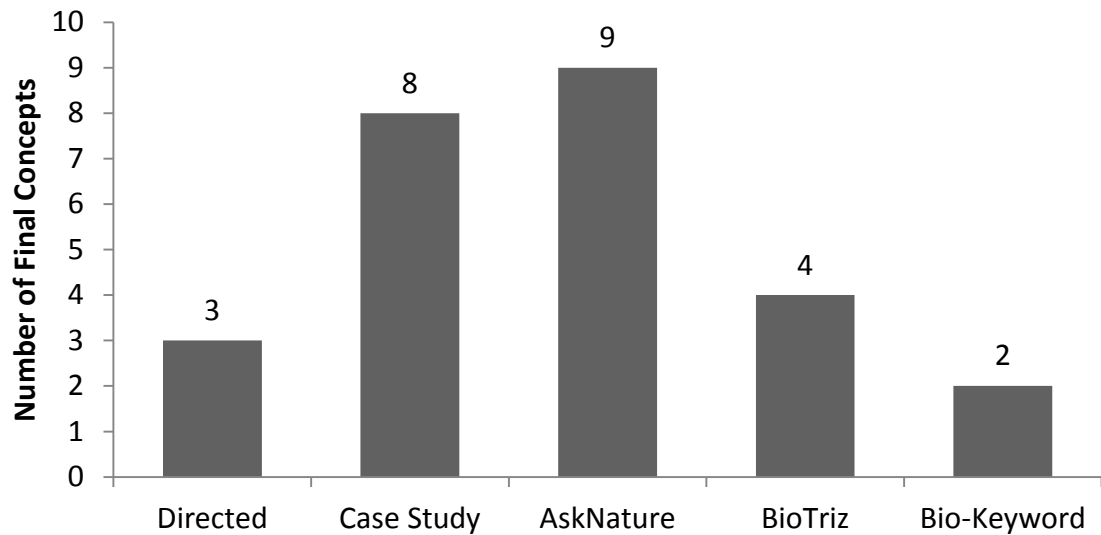

Figure 14: Number of Final Concepts Per Method

Table 12: Number of Final Concepts per Method Statistical Results

Method			
	Observed N	Expected N	Residual
Directed	3	5.2	-2.2
Case Study	8	5.2	2.8
AskNature	9	5.2	3.8
BioTRIZ	4	5.2	-1.2
Bio-Keyword	2	5.2	-3.2
Total	26		

Test Statistics	
	Method
Chi-Square	7.46
df	4
Asymp. Sig.	.11

4.3.2   Methods Preferred By Team

At the end of their final project report, each of the teams listed which method or methods they preferred. Some listed one, some listed two, and some did not respond. The preferred methods were counted for each team, and the total tally of method preference is shown in Figure 15 with the associated statistical analysis in Table 13 that shows statistical significance. The most preferred methods were AskNature and BioTRIZ, the Directed and Case Study methods were preferred less, and none of the groups preferred the Bio-Keyword Search method.
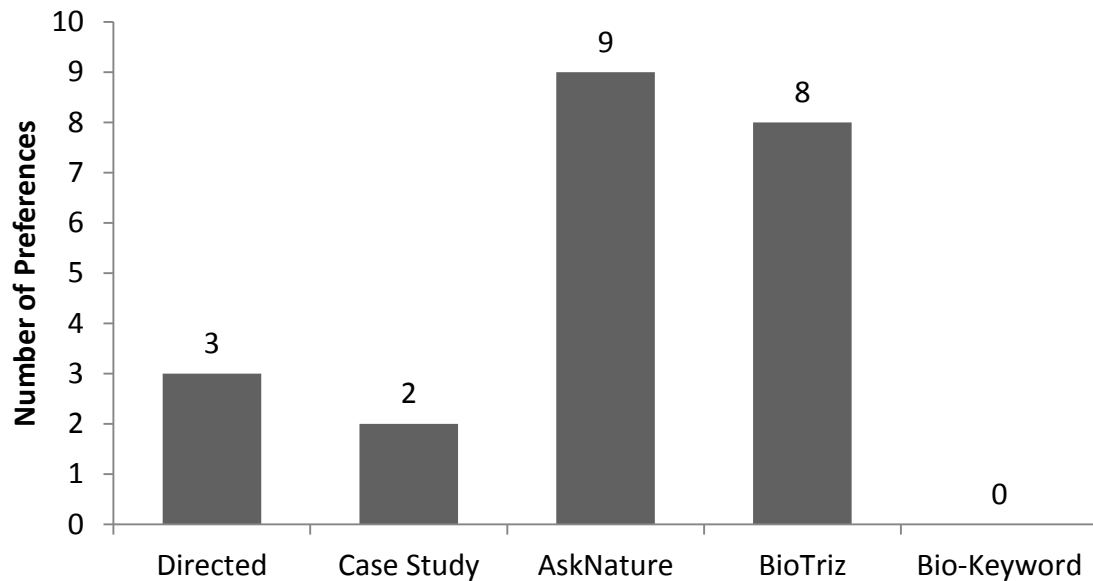
**Figure 15: Tally of Team Preferences across Methods**

Table 13: Tally of Team Preferences across Methods Statistical Results

Method			
	Observed N	Expected N	Residual
Directed	3	5.5	-2.5
Case Study	2	5.5	-3.5
AskNature	9	5.5	3.5
BioTRIZ	8	5.5	2.5
Total	22		

Test Statistics

	Method
Chi-Square	6.7
df	3
Asymp. Sig.	.081

4.3.3   Team-Chosen Method Which Provided Most Variety and Creativity

At the end of their final project reports (although not explicitly asked for in the instructions), some teams team noted which method, in their opinion, allowed them to be most creative and to generate a large variety of concepts. This was suggested by the instructor, but not required. Thus, some teams did not provide a critique of the methods within their reports. Some teams noted one method, while others noted two methods. The total tally of the responses for each method is shown in Figure 16 with the associated statistical analysis in Table 14 that shows a lack of statistical significance. Visually, the highest noted methods were Directed and AskNature, followed by Case Study and BioTRIZ, leaving Bio-Keyword Search with no mentions. However, the lack of statistical significance leads to the inability to draw concrete conclusions.
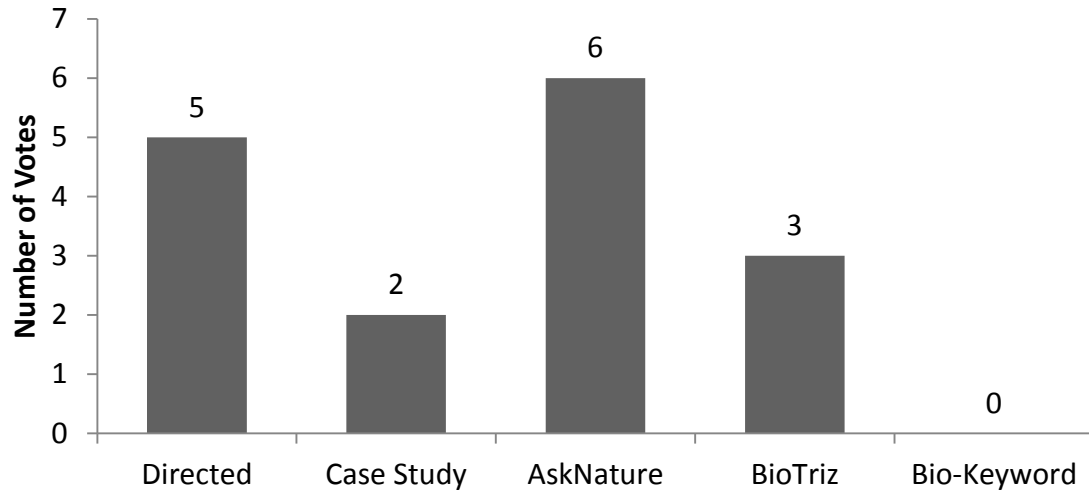
Figure 16: Tally of Team-Noted Method Providing the most Variety and Creativity

**Table 14: Tally of Team-Noted Method Providing the most Variety and Creativity**

Statistical Results

Method

	Observed N	Expected N	Residual
Directed	5	4.0	1.0
Case Study	2	4.0	-2.0
AskNature	6	4.0	2.0
BioTRIZ	3	4.0	-1.0
Total	16		

Test Statistics

	Method
Chi-Square	2.5
df	3
Asymp. Sig.	.48

4.3.4 Number Of Concepts Generated

Each team generated many concepts with each method. The total number of concepts generated by all teams for each method is displayed in Figure 17 with the associated statistical analysis in Table 15 that shows statistical significance. The teams generated nearly the same number of concepts using Case Study, AskNature and BioTRIZ, slightly fewer using Directed, and significantly fewer using Bio-Keyword Search.
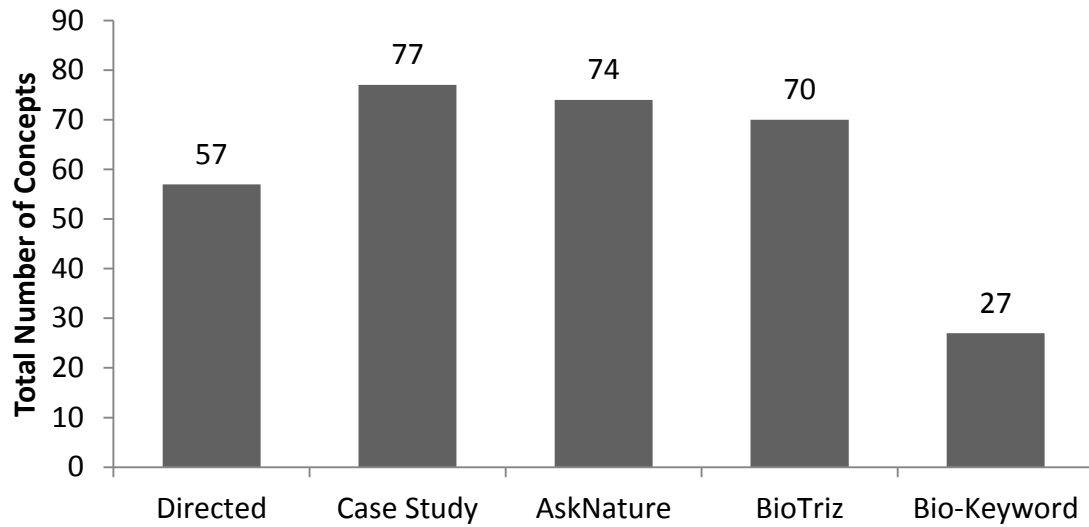
Figure 17: Total Number of Concepts Generated per Method

Table 15: Total Number of Concepts Generated per Method Statistical Results

Method			
	Observed N	Expected N	Residual
Directed	57	61.0	-4.0
Case Study	77	61.0	16.0
AskNature	74	61.0	13.0
BioTRIZ	70	61.0	9.0
Bio-Keyword	27	61.0	-34.0
Total	305		

Test Statistics	
	Method
Chi-Square	27.5
df	4
Asymp. Sig.	<0.001

4.3.5   Method Usefulness Survey

The students' answers to the question "What methods did you find most useful and why?" were analyzed and counted. Students' answers varied between one and three methods. The resulting tally of these counts is shown in Figure 18 with the associated statistical analysis in Table 16 that shows statistical significance. Some of the responses

of the students are shown in Appendix J. In the students' opinion, BioTRIZ was most prominent in being useful. AskNature was the second most useful, followed by Bio-Keyword Search. Very few found Directed and Case Study to be useful.
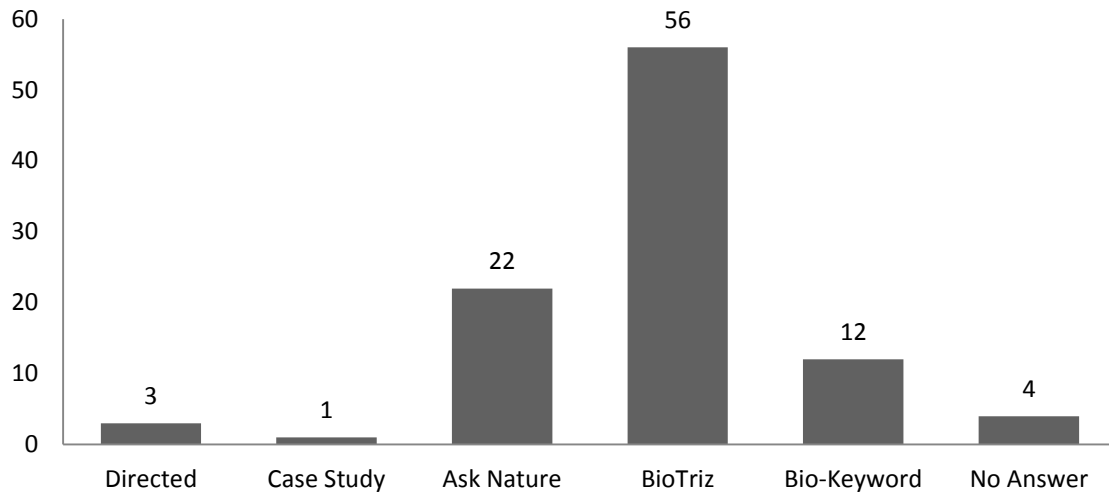
Figure 18: Tally of Most Useful Method

Table 16: Tally of Most Useful Method Statistical Results

Method

	Observed N	Expected N	Residual
Directed	3	16.3	-13.3
Case Study	1	16.3	-15.3
AskNature	22	16.3	5.7
BioTRIZ	56	16.3	39.7
Function Modeling	12	16.3	-4.3
Did not respond	4	16.3	-12.3
Total	98		

Test Statistics

	Method
Chi-Square	134.0
df	5
Asymp. Sig.	<0.001

4.4 Discussion of Methods Results

For the quantity of ideas metric, the Bio-Keyword Search method has a lower mean than Directed, Case Study, AskNature and BioTRIZ. For this metric, there is no discernable difference between AskNature, BioTRIZ and Case Study, while Directed shows a significantly higher mean than the other 4. This could be due to the fact that participants tended to generate fewer concepts for the Bio-Keyword Search method. Additionally, the Bio-Keyword Search method was never selected in the reports as a method that provided creativity and variety; this may be caused by the possibility that the students had a negative perception of the Bio-Keyword Search method as they were unable to generate many concepts with it. Furthermore, the databases used at the time provided large biological passages, requiring more reading and enigmatic analogies. The development of the databases were still in on-going thus were limited in functionality. Since then, there has been major work and improvement done to the tool [143].

Looking at the quality of concepts generated with Directed, Case Study, AskNature and BioTRIZ, all four methods help to provide generally the same level of output quality. There is evidence that these four methods provide numerous high quality concepts since the mean quality scores are all 1.2. However, through the Bio-Keyword Search method, students generated significantly lower levels of quality than the other four. This could be attributed to the fact that using the Bio-Keyword Search method was more challenging than others since the bio-keyword search tool was not fully developed, causing lower quality information and fewer high quality concepts.

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The Directed method was found to be the method which tends to generate a higher number of concepts, while Bio-Keyword Search generates the lowest number of concepts. Because the Directed method was tested using the Alarm Clock design problem, the participants (college students that often use alarms) were more likely to provide more concepts since the design problem was more familiar to them. The latter is better supported when looking at the number of concepts that the teams provided during their semester project. Because their project problems were less familiar to them than an Alarm Clock, they generated fewer concepts using the Directed method, as compared to the other methods. The use of linear equating attempted to mitigate such differences in problem familiarity, however these results suggest the need for further investigation (discussed later). With the use of the other methods and more than 50 minutes to generate concepts, the students were able to generate more concepts to their semester long problem relative to the number of concepts from their individual homework problems. This suggests that time allocated to use a method may have an effect on concept outcomes. The Directed method also allowed more freedom to generate concepts based on their imagination, thus requires less time to generate as many concepts as possible. Contrarily, using AskNature, BioTRIZ and the Bio-Keyword Search methods is very time consuming as they require a more structural and exploratory approach. Furthermore, AskNature is limited to the extent of its library, so finding multiple ideas to solve a problem can be challenging. BioTRIZ also may limit the number of concepts that can be generated since it provides very specific ways of solving problems. For the Bio-Keyword Search method, the students must spend an extensive amount of time decomposing each problem down to its individual functionalities and performing a bio-keyword search.

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Since the participants were limited on time, this may have hindered their ability to provide many concepts and quantity of ideas. Furthermore, from the lack of favoritism of the Bio-Keyword Search method, the students may have been less inclined to put in effort to generate more than a couple of concepts. This trend of fewer concepts using the Bio-Keyword Search method can be seen from both the results of the homework and semester long project analysis.

In terms of novelty, all the methods helped the participants generate highly novel ideas. However, since there was a lack of statistical significance when comparing the methods to each other, the comparison is inconclusive. Although, visually, it is apparent that BioTRIZ seems to help generate more novel solutions than the other methods. Thus, using BioTRIZ allows users to analyze a problem differently and apply this unique view to generate more novel solutions, perhaps causing slightly less fixation than the other methods.

The variety results show that the Directed, Case Study and AskNature methods offer a higher variety of ideas than BioTRIZ and Bio-Keyword Search. This means that Directed, Case Study and AskNature allows the concepts generated to span a greater ideation space. This may be attributed to the fact that those three methods take less time and offer a less focused space of ideas. With the Directed method previously displaying a greater number of concepts in a short amount of time, the participants have the ability generate more solutions, and the greater number of solutions allow a greater spread in the solutions space. Similarly, Case Study and AskNature require less time than BioTRIZ

and Bio-Keyword Search, and displays many examples for participants to choose from, thus allowing a variety of solutions. Furthermore, BioTRIZ aids in generating a higher variety of ideas than Bio-Keyword Search, and that difference can also be accounted by the relationship of this metric to the number of concepts generated and the time factor.

As far as the methods preferred, the answers vary from student to student, and from group to group. This shows that each method clearly has some benefits to the user, but those benefits vary depending on who is using them, what their needs are, and possibly the type of designer that they are. Some may prefer the "easier" method to use, and some may prefer a challenging, yet rewarding method. Future work needs to ask why certain methods were preferred. Looking at the groups' answers as far which method they thought provided the most variety and creativity, the answers were varied, meaning that that each method is believed to provide variety and creativity in the concepts, except for the Bio-Keyword Search method. The technical difficulties encountered when using the Bio-Keyword Search method could have influenced the student's choices, leaving the full effect of the Bio-Keyword Search method to be determined when it is fully developed.

In general, all the methods proved to have certain benefits over others, either from resulting concepts or student feedback. Assuming that the fundamental principles behind the Alarm design problem had no effect on the outcomes despite being scaled using an equivalency factor, the Directed method shows advantages in providing higher quantity of ideas, and a larger number of concepts in a shorter amount of time. However, despite these advantages, it was not perceived as a useful or preferred method to the students, and

it did not generate the most final concepts for the final projects. This could have been due to the fact that students were limited to their own knowledge of nature in the context of Bio-Inspired design. Case Study and AskNature show a relative advantage over the others when it comes to generating final concepts; meaning that those two methods are the most effective at providing the best concepts. AskNature and BioTRIZ are the most preferred methods to use, based on team preference, and also the most useful, based on the method usefulness questionnaire. According to some student comments, BioTRIZ was very straightforward and provided direct ideas to solve the problems. It did not suggest any one particular solution but simply offered inventive principles that could be used to solve the problem. Its ease of use and systematic approach were probable factors in making it the most useful method to most of the students. Furthermore, Bio-Keyword Search design was the least preferred, generated the lowest level of quality, quantity and variety of ideas, was never chosen as the method to provide the most variety or creativity, and had the lowest number of concepts. However, it was considered to be the most useful method more often than the Directed and Case Study methods, and generated highly novel solutions. This shows that despite the challenges encountered due to the malfunctioning of the databases used with it, the underlying principle behind functional modeling and breaking down the problems, it method was selected as most useful by some of students. It other words, some students acknowledge it's potential, thus was not a completely useless method. It helped students understand the problem better by breaking down the problems into basic functions, and allowed them to focus on the important aspects of the design. Even though there are differences between methods when it comes to generating final concept solutions, each method helped at least one team to provide a

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final concept, meaning that each method is effective at helping to generate good, "best concept" worthy concepts.

4.5 Self-Efficacy Results and Discussion

4.5.1 Selecting EDP For Analysis And Discussion

ED (Engineering Design) and EDP (Engineering Design Process), in theory, should approximately have the same values since EDP is the engineering design process, and ED is the overall ability to conduct engineering design. As discussed in Chapter 3, these 8 steps are: Identify the need or problem, research the need or problem, develop possible solution(s), select the best possible solution(s), construct a prototype, test and evaluate the solution(s), communicate the solution(s), and redesign [137] For each of the four self-concept areas, the ED score consists of one rating per individual, whereas EDP score is the average of the 8 individual step ratings within the respective self-concept area. From the combination of both semesters' data, the similarities in the two scores were compared to see how interchangeable they were. According to Carberry *et al.*'s experiments, they obtained a Pearson Correlation between ED and EDP of 0.89 for confidence, 0.88 for motivation, 0.89 for success and 0.79 for anxiety [135]. The same Pearson correlation analysis was performed on the combined semesters' data, and the R-values obtained were slightly different from Carberry *et al.*, however, they were still fairly high with p-values lower than 0.001, showing statistical significance in the correlation. Those R-values are shown in Table 17, Motivation seems to have the lowest Pearson correlation, but it is still acceptable.

**Table 17: Pearson Correlation between ED and EDP (N= 66)**

		Pearson R	P-Value
Self-Efficacy	Pre	0.80	< 0.001
	Post	0.79	< 0.001
Motivation	Pre	0.76	< 0.001
	Post	0.71	< 0.001
Expectancy	Pre	0.88	< 0.001
	Post	0.84	< 0.001
Anxiety	Pre	0.85	< 0.001
	Post	0.92	< 0.001

From these obtained values, it is safe to assume that the ED and EDP values are similar and show the same scores and trends, interchangeably. Thus the two are equivalent and reflect the robustness of the instrument to effectively gather one's self-reflection in both a general and detailed aspect. Accordingly, the EDP scores were used for analysis and comparisons. EDP scores show a stronger score of Self-Concepts by nature because it accounts for each of the individual engineering design processes. Thus, it shows a more comprehensive score and evaluation of each subject.

4.5.2   Effect of Course On Self-Concept Scores

The difference between the two samples for Self-Efficacy (Confidence) had no significant outliers and was approximately normally distributed, $p =0 .567,$ thus a parametric Paired t-test was used to compare the differences in self-efficacy before and after the Bio-Inspired elective course since the matched-pair samples were measured on a continuous scale [144]. However, the difference between paired samples for motivation, expectancy, and anxiety failed to meet the normality criterion, $p < 0.005$. These three categories' population distributions of differences were graphed as boxplots and visually examined and were found to display symmetry Meeting that assumption [145], a Related-

Samples Wilcoxon Signed Rank Test was used to determine the significance between the Pre-Course and Post-Course results for motivation, expectancy and anxiety [142]. This is equivalent to a paired t-test for non-parametric data. The resulting mean self-concept scores are displayed in Figure 19, with the associated differences in Pre to Post scores shown in Figure 20.
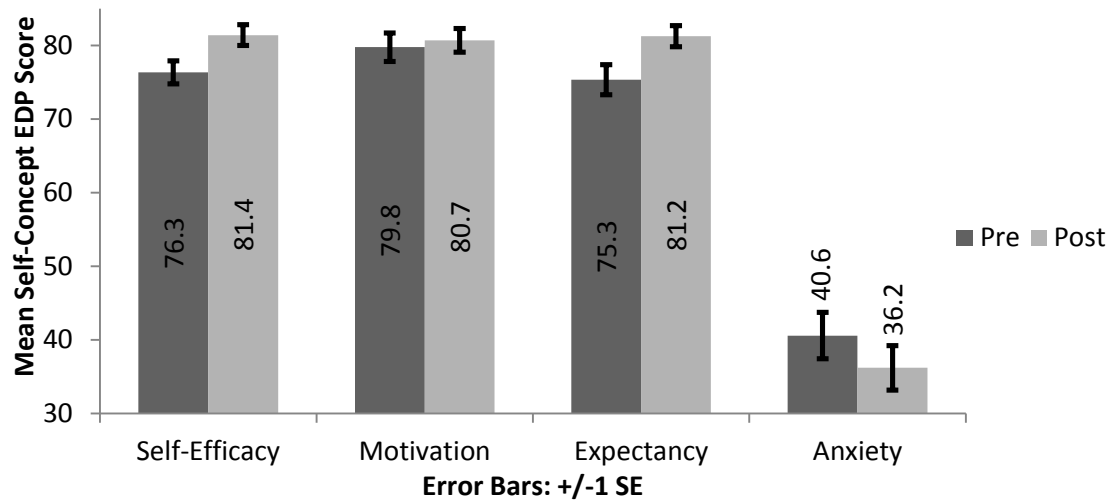
Figure 19: Pre and Post EDP Self-Concept Scores for Combined Semester 1 and 2 Data Sets
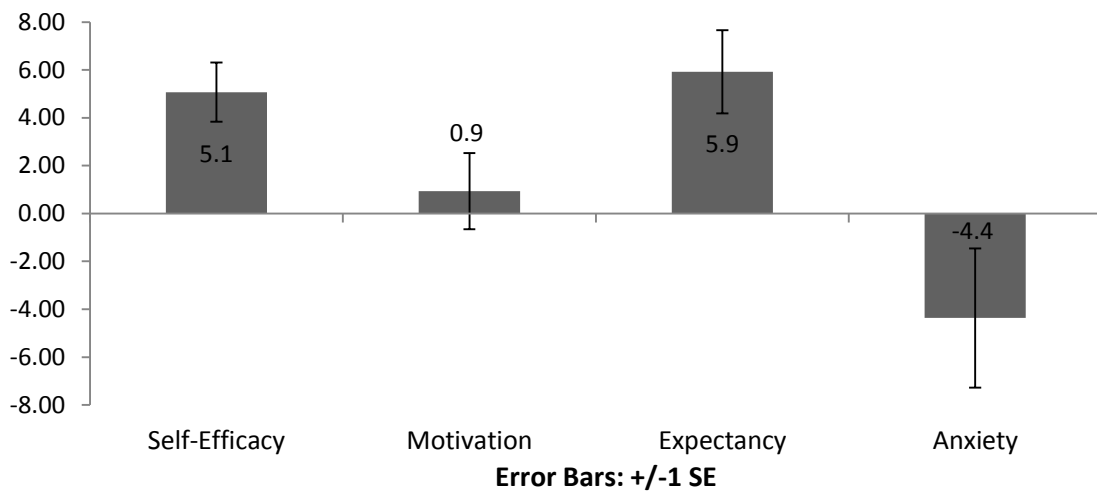
Figure 20: Difference between Pre and Post EDP Self-Concept Scores for Combined

Semester 1 and 2 Data sets

4.5.2.1 Self-Efficacy

When comparing the Pre-Course and Post-Course self-concept scores, the students show a clear increase in their confidence to perform engineering design tasks by a mean score of 5.07. There is a statistically significant difference between Pre and Post course score means (Paired T-test, t = 4.11, df = 65, $p < 0.001$). Through the course of the semester, the students were exposed to engineering design knowledge which was able to increase their self-reported ability to conduct engineering design tasks.

4.5.2.2 Motivation

The students do not show any significant change in motivation when comparing the Pre and Post Course surveys (Related-Samples Wilcoxon Test, Z = -0.76, N = 66, $p = 0.46$). An explanation for such a stagnant score is that this was an elective course the students choose to take and it would make sense that they are highly motivated to be designing.

4.5.2.3 Outcome Expectancy

When comparing the Pre-Course and Post-Course outcome expectancy scores, the students show a clear increase in their confidence to perform engineering design tasks by a mean score of 5.92 after completing the course. There is a statistically significant difference between Pre and Post score means (Related-Samples Wilcoxon Test, Z = -3.78, N = 66, $p < 0.001$). Similar to self-efficacy, the student's expectation of success when conducting engineering design tasks was successfully increased.

4.5.2.4   Anxiety

The mean scores for anxiety show larger variance in responses. With a marginally statistically significant difference between Pre and Post course mean scores (Related-Samples Wilcoxon test, $Z = -1.66$, $N = 66$, $p = 0.098$), the students' anxiety towards performing engineering design tasks has been decreased throughout the course of the semester. It is possible that some students' level of anxiety were reduced, while others realized that conducting engineering design tasks are harder than they thought, which resulted in an increase of anxiety.

4.5.2.5   Individual Semester Trends

While the last four sections presents the results of the combined Semester 1 and Semester 2 data, the same but more detailed graphical data by semester can be seen in Figure 21 and Figure 22 and with the associated statistical results in Table 18 and Table 19 for Semester 1 and Semester 2, respectively. Both ED and EDP scores are shown to display the similarity between the two, and to support the decision of only displaying EDP over ED. As displayed, each individual Semester results in the same trends as observed in the last four sections.
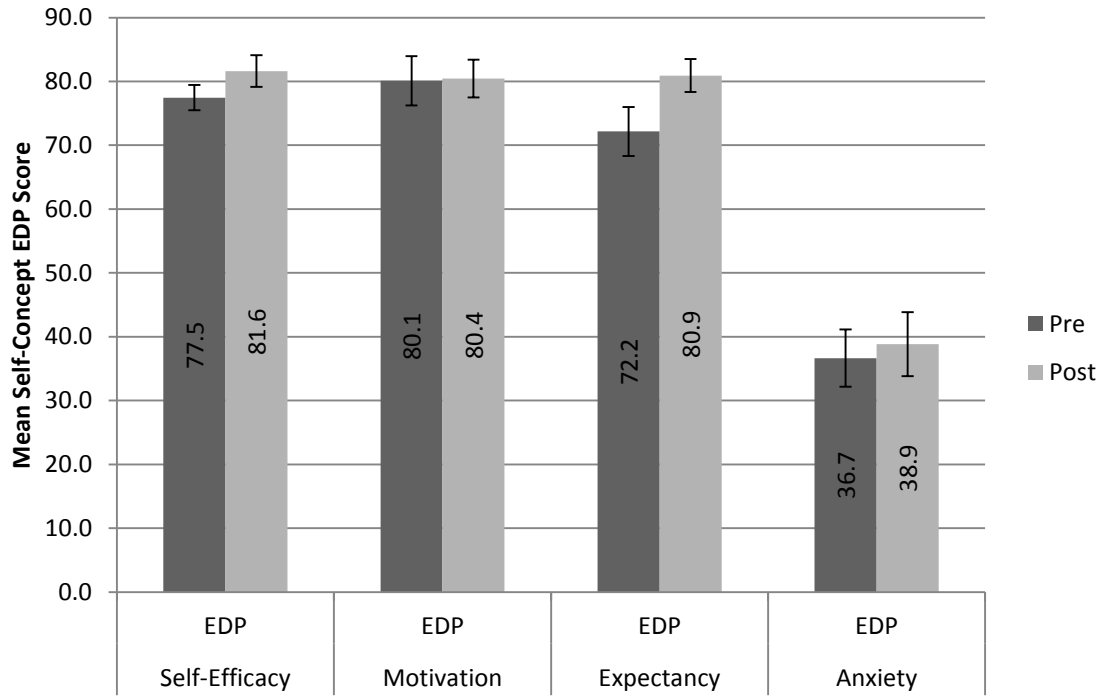
Figure 21: Pre and Post Self-Concept Scores for Semester 1

Table 18: Pre and Post Self-Concept Statistics for Semester 1

		Pre		Post		Difference		
		Mean	SE	Mean	SE	Mean	SE	Paired T-test P-value
Self-Efficacy	ED	74.4	±2.99	85.3	±2.59	10.8	±1.93	< 0.001
	EDP	77.5	±1.97	81.6	±2.49	4.16	±1.75	0.025
Motivation	ED	77.8	±4.75	82.8	±3.03	5.04	±3.81	0.19
	EDP	80.1	±3.88	80.4	±2.96	0.32	±2.61	0.90
Expectancy	ED	70.4	±4.22	82.2	±2.50	11.8	±4.05	0.007
	EDP	72.2	±3.84	80.9	±2.58	8.80	±3.52	0.019
Anxiety	ED	39.3	±5.57	38.3	±5.58	-0.93	±5.38	0.87
	EDP	36.7	±4.47	38.9	±5.01	2.31	±3.77	0.55
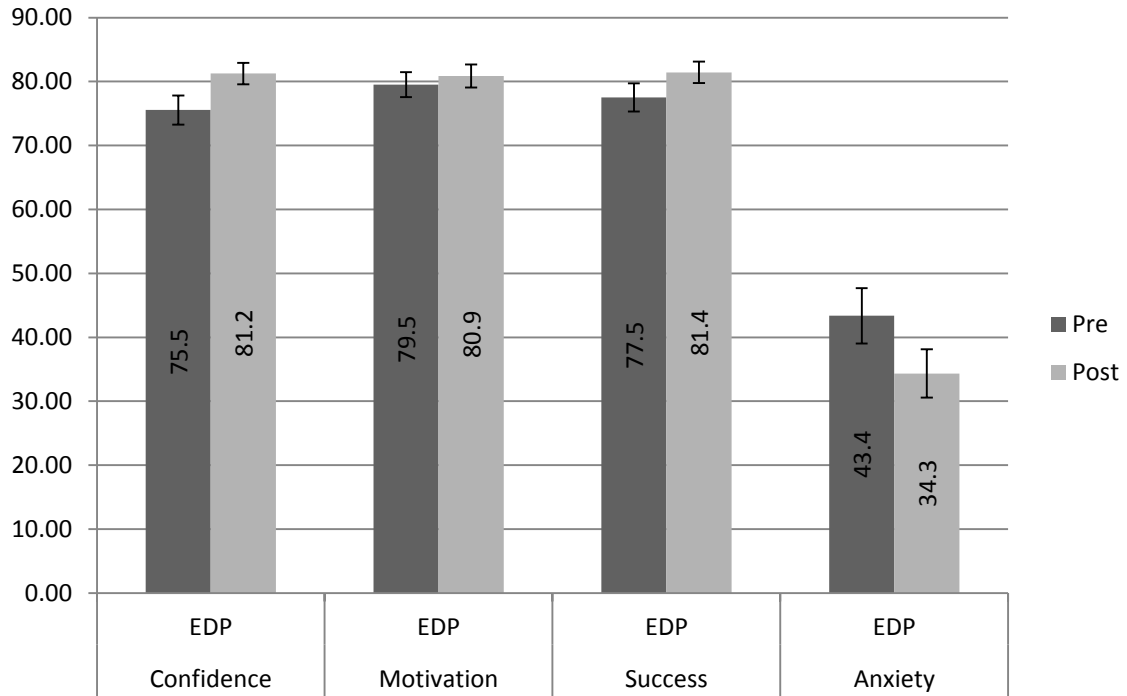
Figure 22: Pre and Post Self-Concept Scores for Semester 2

Table 19: Pre and Post Self-Concept Statistics for Semester 2

		Pre		Post		Difference		
		Mean	SE	Mean	SE	Mean	SE	Paired T-test P-value
Self-Efficacy	ED	73.6	±2.61	82.8	±1.87	9.23	±2.39	< 0.001
	EDP	75.5	±2.28	81.2	±1.67	5.70	±1.71	0.002
Motivation	ED	81.5	±2.53	80.5	±2.26	-1.03	±3.20	0.75
	EDP	79.5	±1.95	80.9	±1.81	1.38	±2.02	0.49
Expectancy	ED	79.2	±2.45	80.8	±2.06	1.54	±1.96	0.44
	EDP	77.5	±2.20	81.4	±1.70	3.93	±1.62	0.021
Anxiety	ED	46.3	±4.75	39.2	±4.70	-7.11	±5.09	0.17
	EDP	43.4	±4.32	34.3	±3.77	-9.01	±4.05	0.032

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4.5.3 Comparing Two Years for Pre and Post Course Results

Comparing the Pre-Course results of both years, in Figure 23, it can be seen that the students started at various levels. But when looking at the Post-Course results in Figure 24, a "leveling-off" effect for self-efficacy, motivation and expectancy at an approximate score of 80, is detected. It seems that most students reach that level of self-concept, and cannot reach higher for both years.

Anxiety on the other hand, does not conform to that trend. Since for anxiety, a score closer to 0 is more desirable, the scaling scheme is different from the other 3 categories where a score closer to 100 is more desirable. Thus the "leveling-off" around a score of 80 trend cannot be compared. Thus, comparing the levels for both years for Pre and Post Course anxiety leads to inconclusive results.
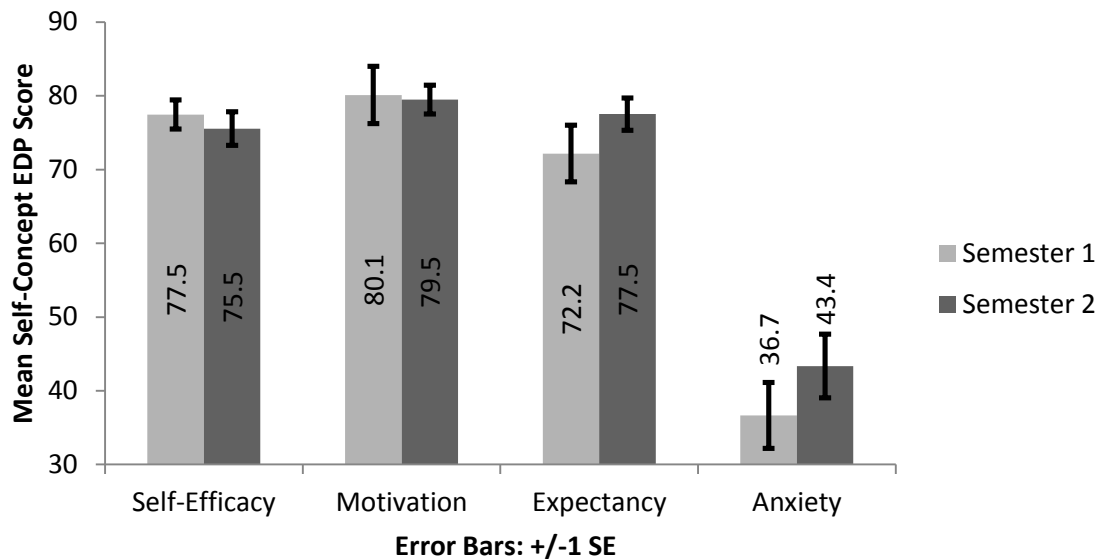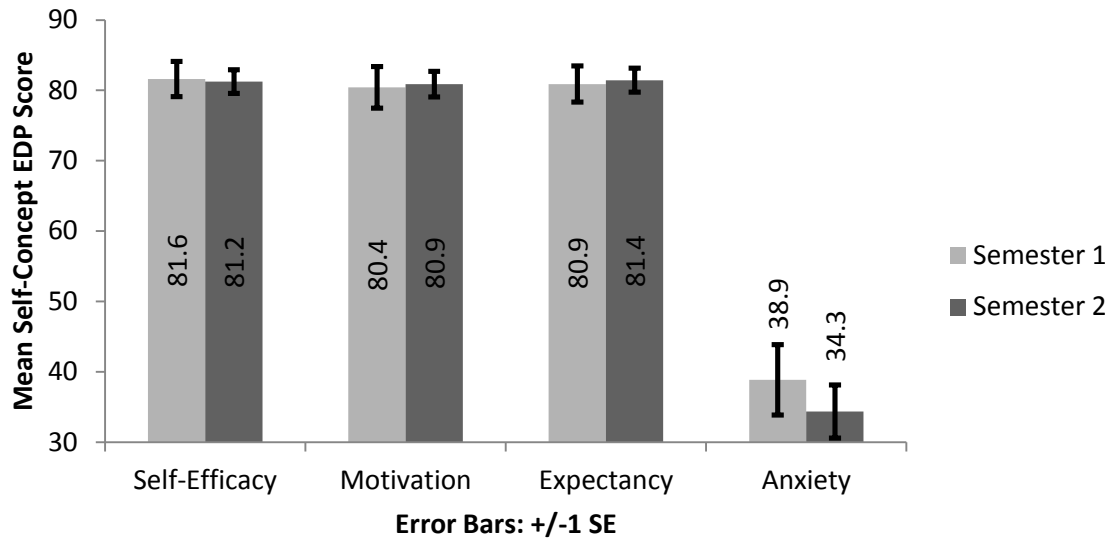

Figure 23: Comparison of Pre-Course Self Concept between Semester 1 and 2

Figure 24: Comparison of Post-Course Self Concept between semester 1 and 2

4.5.4 Additional Information

It was noticed that some students checked one column all the way down (assumingly) without contemplating what each of the tasks were. There is no guarantee or it cannot be proven that these students were being careless. Thus, as a quick check, those students were identified and removed from the data. After removing them, the difference in the resulting data was unnoticeable than it was with those students included. Since it was not guaranteed what the students' level of care was, those students' responses were included in the data presented.

4.6 Limitations

In order to effectively compare the various methods to each other, the different problem sets used to test the participants need to provide the same level of output. All the problems are different, so the root of the problem may cause it to be easier to solve using certain methods. The resulting quantity and quality metrics may vary because the problems may inherently provide higher quantifiable components and high levels of quality. This could be affected by the complexity of the problem and number of components required to solve the problem. Some problems are easier to provide concepts for that satisfy customer needs and perform required functions. A continuous rotation of problems may also provide better results as it could eliminate problem-method interactions. It could facilitate the use of full 5 by 5 ANOVA to better isolate the variables.

The timeline for the design problem was supposed to be based on a 50 minutes interval. However, as discussed, the instructions were not clear, resulting in some students observing the 50 minutes rule, and some not. Due to this experiment mishap, the two options were to consider all concepts generate by all subjects, or assume that every student observed the 50 minute rule and only consider the concepts generated before the 50 minute line for those who were obedient. Of course, both approaches would create some discrepancies in the results obtained from the data analysis. This study considered all concepts generated by all subjects, assuming that those who did not draw a line did not observe the rules. For future work, this rule should be reconsidered since the overall results show how some methods are more time-consuming than others. Perhaps allowing

the students to generate as many concepts as possible, until exhaustion, would be a better approach. Using undergraduate students as test subjects to evaluate methods can be very challenging as they may not tackle the problems with a level of seriousness that is desired by researchers. Thus, there is a need to determine a method of better incentivizing students to uphold a degree of sincerity as they engage in their homework activities. This would ensure validity in the ideas they generate and not aimless concepts for the sake of getting a grade.

There was no distinct method to validate the effectiveness of using the problem equivalency method. However, it does raise a few questions that the following chapter of this thesis will attempt to answer: the participants may have a higher familiarity with a problem from experience or have knowledge of existing concepts, which allows them to generate more concepts with higher effectiveness. Additionally, some problems may have a higher number of available analogies in nature. These are characteristics that the problem equivalency equation may not account for.

Additionally, some of the survey questions may have been ambiguous, such as "Which methods did you find most useful?". For future work, these questions should be rephrased and tested extensively to ensure understanding, and to obtain more precise feedback.

CHAPTER 5: IN SEARCH OF MORE EFFECTIVE DESIGN RESEARCH PROBLEMS

5.1 Background

From observing certain trends from the study conducted in Chapter 4, such as students' increased number of concepts using the Directed method, it raised a concern. Theoretically, it would be expected that students would generate a larger number of concepts using a structured approach such as BioTRIZ and AskNature, which provides a large number of resources and inspirations. However, as seen in the Chapter 4, it was not the case, despite the attempt to use Linear Equating and equivalency factors. Thus, the linear relationship between problems must be explored to effectively use various problems for direct comparison of various methods. Not only does this impact this study, but others as well. Similar design problems are desperately needed for design research. This leads to the quest of exploring further design problems characteristics.

In past studies, the selection and development of design problems for the purpose of testing idea generation skills, has been rationally justified [39, 43, 44, 46, 146]. Creating a design problem that can properly assess one's creativity has not been formally structured. Thus far, when establishing a design problem, the goal is to develop a problem that the participants are familiar with, that they can produce a number of solutions based on their knowledge but do not have an obvious solution. Since most of the participants in this thesis are mechanical engineers, the problems are attempted to be developed as predominantly mechanical in nature (rather than electrical). Many of the design problems in this thesis were for developing countries so that the use of electricity

could be restricted within the design. Each problem statement given to the students in this thesis' studies always begins with a problem description in order to explain the need and motivate the students. Furthermore, the customer requirements were often given in quantitative terms (e.g. target throughput) in order to clarify the problem to the students, to make the problem more realistic, and to make it easier to assess quality. After developing problem statements, the problems were pre-tested by having a group of students solve them to ensure that the participants can easily understand the problem and that there are a variety of concepts.

Design problems are often characterized as "ill-structured" problems due to their open-endedness, ambiguity and lack of determined solution path [147, 148]. The structure of a design problem fundamentally influences the outcome of the design work. Some explanations of a design problem view the problem as the set of constraints on the solutions space; solution development constitutes a search of that space [147, 149]. Later theories suggest that design, unlike other problem-solving activities, relies on redefining the design problem in order to extend the search space [150, 151]. Alternative schools of thought stemming from Schön [152] suggest that design problems are more subjective, and emerge from the interaction with conjectured concepts. The effect of problem-solution co-evolution, is likewise well documented [153, 154].

More recent investigations have begun to define the underlying ontology of design problems [41, 44, 155-164]. Such ontologies may provide useful causal links between the framing of the design problem and the solution. Likewise, Summers *et al.*

have developed measures to characterize a problem in terms of its complexity [157, 159, 160, 164], focusing on size, connectedness and solvability of the problem. These efforts in formalizing the underlying structure of design problems will help design researchers better control for, document and understand the role of the design problems structure in design. The ability to draw equivalency, and gauge problem difficultly across a variety of factors may also be helpful in tool-building, educational instruction and resource planning for industry [157].

In prior work on biologically inspired design, idea generation, and design fixation, researchers defined sets of design problems that were found to be useful throughout their studies [43, 44, 46, 130, 132, 146, 165-167]. Each design problem was written intending for the production of a reasonable number and variety of answers within a single experiment design session. By necessity, the size (in terms of number of functional units, rather than physical size) and the connectedness (in terms of interactions among functional units or components) of each design problem were limited. Likewise, it was attempted to ensure the domain was sufficiently familiar that a student or test subject could immediately understand the requirements, but within a context for which an existing solution was not immediately obvious. For example, to quickly shell a large number of peanuts, without breaking the peanut, using only inexpensive parts and no electricity. This ensured that the participant's understanding of the design problem, mechanics and functions was not a limiting factor and did not require a significant portion of the time, while simultaneously reducing fixation from existing, known solutions. All of the design subjects understand the structure of a peanut sheller, many of

its material properties, and how to remove a peanut from the shell by hand. However, very few (if any) have experience removing shells on a large scale.

Based on these processes, qualitative observations, and literature, twelve characteristics that are important to building "equivalent" problems are hypothesized below. The experiments will first investigate to what extent the problems are different across a set of standard creativity research design metrics. It will then investigate two of the hypothesized characteristics: to what extent *biological and human-made solution familiarity* influence these metrics.

Design Problem Characteristics

To develop an understanding of the factors that influence design research outcomes, based on literature and prior work, a set of hypothesized influential design problem characteristics is listed as follows:

1. Size of the problem in terms of:

    a. functional units

    b. Components [157, 159, 160, 164]

2. Connectedness of the problem in terms of coupling between functional requirements or constraints [157, 159, 160, 164]

3. Participant's familiarity with the design problem

4. Participant's familiarity with the design solutions

5. Participant's familiarity with the underlying principles/domain (inherent to the problem) required to generate solutions [41, 162, 163]

6. Size (number of variables) of the potential solution space [157, 159, 160, 164]

7. The degree to which the potential solution space is constrained

8. Participant's preconceived assumption of constraints due to known solutions, culture or other factors

9. Degree of technical challenge of design problem

10. Potential for fixation [44]

11. Domain of the design problem [161-163]

12. Degree to which external-domain analogous solutions are easily retrieved

    Level of complexity [158, 162, 163]

5.2 Problem Effects

5.2.1 Experimental Setup

This study utilizes the same data that collected in the Chapter 4 experiment for the Directed method in Semester 1. This was done in order to have a detailed comparison between the results the Alarm and Corn Problems.

To provide reasoning behind exploring the results found in Chapter 4, the experimental setup will be re-described to provide a better context to this study: There were 32 student designers in the course. 17 were randomly assigned to the Alarm problem, and 15 to the Corn problem (a small assignment process error resulted in the difference in number of assignments). Each student received a packet containing the problem statement, the customer needs, the method description, and were asked to generate as many concepts as they could for 50 minutes, no matter the level of feasibility. The concepts were to be sketched by hand with annotations. The assignment was completed as a graded homework assignment. Given the latter, the 50 minute regulation was not enforced nor accurately controlled, and the use of external material was also uncontrolled.

5.2.2 Data collected

All 32 students submitted assignments. On average, most students generated 2 or 3 concepts. Some generated as few as one complete design concept and some generated as many as 8 concepts. Each resulting design was coded using quantity, quality, novelty and variety metrics [126, 168] [46, 166]. Using the modified coding Training Packet [124], a trained graduate researcher who already obtained high inter-rater agreement for

Alarm and Corn for a different experiments [132], coded all concepts generated by the 32 students. These two problem results were originally coded only to acquire the data to compare the Bio-Inspired Design methods, but there were no plans to compare them to each other reducing the potential for bias.

5.2.3 Results

The data was coded for quantity, quality, number of concepts, novelty and variety. The resulting metric sets did not meet the normality or equal variance criteria required for parametric T-tests and ANOVA (Shapiro-Wilk Normality Test, $p < 0.095$ and Levene's Test for Equal Variance, $p < 0.065$). Since the data was not normally distributed or had equal variance, non-parametric statistical analysis Independent Samples Mann-Whitney U tests were used in SPSS to compare the means for each metric. The resulting graphs showing the comparison of means between Alarm and Corn for quantity, quality, novelty and variety are shown in Figure 25 and Figure 26. For the novelty graph, the y-axis has been cutoff below 0.80 and has been enlarged in order to better display the differences.
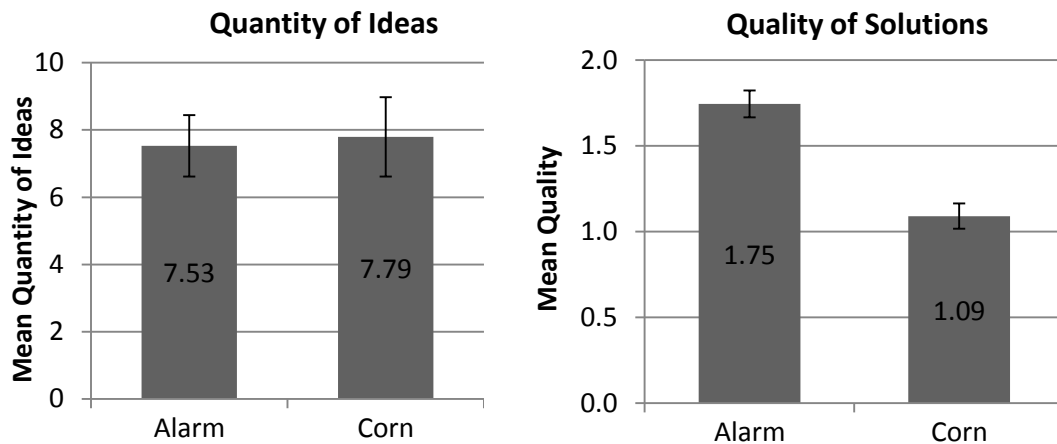
Figure 25: Quantity (A) and Quality (B) Comparison (Error Bars: +/-1 SE)
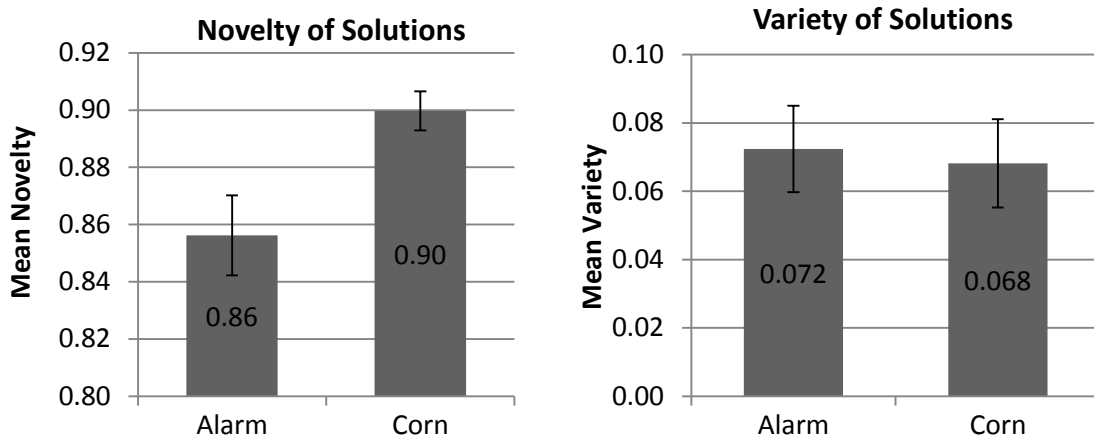
Figure 26: Novelty (A) And Variety (B) Comparison (Error Bars: +/-1 SE)

Comparing the mean quantity of ideas for Alarm and Corn, shown in Figure 25 (a), both are around a mean of 7 ideas per participant. There is no statistical significance between the two (Mann-Whitney test, U(1) = 118, Z =-0.036, p = 0.74). Figure 25 (b) shows the comparison of the quality of concepts, and it can be observed that Alarm has a higher mean quality score than corn. This difference is statistically significant (Mann-Whitney test, U(1) = 23, Z =-4.16, p < 0.001).

The novelty comparison in Figure 26 (a), shows a higher mean novelty for Corn. This difference in means is statistically significant (Mann-Whitney test, U(1) = 55, Z = -2.74, p = 0.005). The participants' mean novelty tends to be greater with the Corn design problem rather than with Alarm.

The mean variety scores for the two problems are shown in Figure 26 (B). With a lack of statistical significance (Mann-Whitney test, $U(1) = 107$, $Z = -0.783$, $p = 0.46$) , it shows that there is no difference between the two problems. So for both Alarm and Corn, participants generate the same variety of concepts.

Figure 27 shows the mean number of concepts generated by each participant for both problems. With a statistically significant difference between the two problems (Mann-Whitney test, $U(1) = 79$, $Z = -1.99$, $p = 0.069$), participants, on average, generate one more concept for Alarm than they do for Corn.
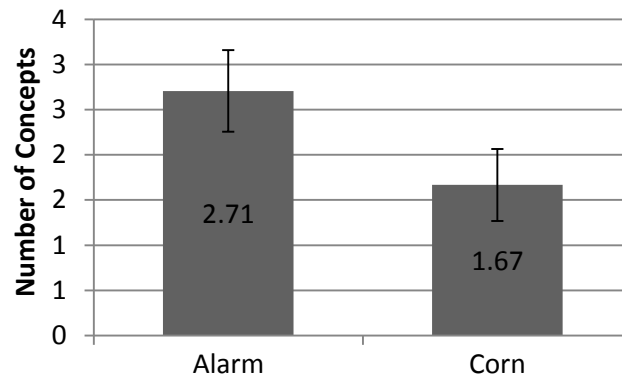
Figure 27: Comparison of Mean Number of concepts Per Participants (Error Bars: +/-1 SE)

This following Table 20 summarizes the mean, standard deviations and statistics previously described. The metrics for which the problems had significant differences are highlighted.

Table 20: Alarm and Corn design problem evaluation metrics summary

	Alarm		Corn		Mann-Whitney U
	Mean	SE	Mean	SE	p-value
Quantity	7.53	0.91	7.79	1.18	0.74
Quality	1.75	0.08	1.09	0.07	<0.001
Novelty	0.86	0.014	0.90	0.007	0.005
Variety	0.072	0.013	0.068	0.013	0.46
Number of concepts	2.71	0.45	1.67	0.40	0.069

5.2.4   Discussion

There were similarities and differences in the evaluation metric scores in this first experiment between Alarm and Corn. It was found that using the same design method, Alarm tended to produce higher levels of quality and numbers of concepts, whereas Corn tended to produce high levels of novelty. However, for both problems, the levels of quantity and variety were comparable. The differences between the two problems could be attributed to the domain of the problem, the participants' familiarity with the problem or existing solutions, the level of complexity of the problem or the technical challenge. On the other hand, the two problems produced similar levels in quantity and variety. This initial finding suggests that while it was attempted at the outset to use "equivalent" problems, these differences should be accounted for through the use of the Linear Equating approach, essentially making them equivalent. However, there was further need to explore the relationship between design problems. Subsequently, the insights gained from the comparison of Alarm and Corn inspired the following Solution Familiarity study. There was a need to conduct a within-subject experiment in order to assess various correlations.

5.3 Solution Familiarity

5.3.1   Experimental Setup

This within-subject follow up experiment to the Problem Effects study was conducted in a different semester but within the same biologically inspired design elective course. This experiment occurred during Fall 2014, with 21 student participants. Similar to the Problem Effects study, the students were mostly Mechanical Engineering majors. This experiment was conducted in class over a period of one week, on 3 separate days: Wednesday, Friday and Monday. The Blind Cup and Peanut Sheller design problems were used, shown in Appendix L1 and L2, respectively.

The first day (Wednesday), the subjects were given the Blind Cup problem, and on the second day (Friday), Peanut Shelling problem. Both days the students were allowed 5 minutes to read the problem, and 35 minutes to generate as many concepts as possible. The time limit was due to the length of class time available. They were directed to generate concepts without the use of any particular method of design. Complete instructions can be seen in Appendix L1 and L2.

The third day, the students were given a survey with four sections, shown in Appendix L3. It asked the students to list the existing solutions and biological analogies to both the peanut shelling and blind cup problems that they were familiar with. They were given 7 minutes to complete each of the 4 sections

Unlike the Problem Effects study, the time limit guideline was enforced since it was a controlled classroom and the possible use of external material was eliminated. In this particular course, the Directed, Case Study and Bio-Keyword Search methods of Bio-Inspired design were taught prior to the time this experiment was performed. However, those methods were irrelevant and unrelated to this experiment's unguided method. In this study, the students were not instructed to use any methods of Bio-Inspired Design to develop concepts.

5.3.2 Data collected

The students were given this assignment in class. 21 students completed the Blind Cup assignment, 20 completed the Peanut Sheller assignment, and 16 completed the survey. Using the same quantity, quality, novelty, and variety evaluation metrics, a graduate researcher (not an author) who already obtained high inter-rater agreement for Peanut Sheller and Blind Cup from different experiments with very similar data [132], coded all concepts generated by the 20 students who completed both problem assignments. A separate graduate researcher reviewed the survey answers, and counted the number of existing solutions and nature analogies each student provided for each design problem.

5.3.3 Results

The difference between the matched data of quantity, quality, novelty, variety and number of concepts met the normality distribution and equal variance criteria [142], therefore a Paired T-test was used to compared the two design problems. The survey response data did not show normal distribution, so a non-parametric Related Sample Wilcoxon Signed Rank Test was used instead to determine the significance in difference

between the two problem sets [142]. Pearson correlation coefficients between problems were calculated by matching paired data from each student.

The resulting mean of each of the five evaluation metrics are shown in Figure Figure 28, along with the associated statistical analysis performed summarized in Table 21. At the aggregate level, the mean value from each sample set and their associated standard error, the resulting p-values from paired T-tests between the two problems is shown. The Pearson's correlation R values correlate each metric at the individual level between problems. A significant difference is observed between the means for quantity (p=0.0012), quality (p=0.063 and variety (p=0.0006). Peanut shows a higher mean of quantity of ideas, whereas Blind Cup shows higher quality and variety. Differences between the mean novelty and number of concepts are not statistically significant.

It is observed, using Pearson's correlation, a moderate to high correlation between problems for each student for quantity (R = 0.53), variety (R = 0.39), and number of concepts (R = 0.68). Generally for human oriented studies, R-values greater than .5 are considered to show a moderate degree of correlation between two variables, [169, 170]. This implies a consistent linear relationship for these metrics between the two problems, across the sample of students.
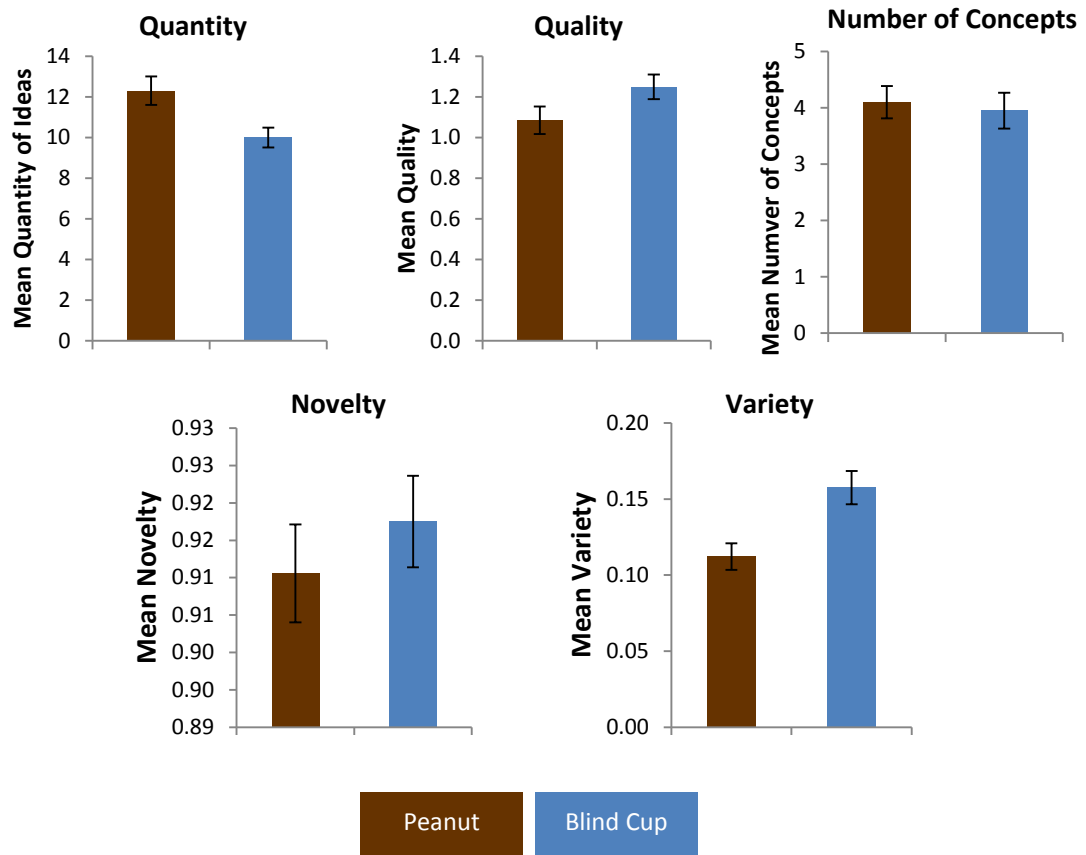
Figure 28: Evaluation Metric Comparison of Peanut and Blind Cup

Table 21: Peanut and Blind Cup Problem Evaluation Metrics Summary

N = 20	Peanut		Blind Cup		Paired T-test	Correlation
	Mean	SE	Mean	SE	p-value	Pearson' R
Quantity	12.3	0.70	10.0	0.49	0.0012	0.53
Quality	1.09	0.068	1.25	0.061	0.063	0.18
Novelty	0.91	0.007	0.92	0.006	0.46	-0.049
Variety	0.11	0.0088	0.16	0.010	0.0006	0.39
Number of concepts	4.10	0.29	3.95	0.320	0.55	0.68

The survey data analysis is summarized in Table 22. From the statistical results, the students as a group generated a nearly equal number of existing solutions for both the Peanut and Blind Cup (Wilcoxon Rank Test, p > 0.94). This infers that students, on

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average, know a similar number of existing solutions for both Peanut and Blind Cup. However, the students were able to draw significantly more analogies in nature for Peanut than for Blind Cup. This difference is statistically significant (Wilcoxon Rank Test, $p < 0.01$). For both existing solutions and analogies in nature, both problems had moderate positive correlation to each other, inferring that each student's answers were relatively consistent from problem to problem.

Table 22: Familiarity survey results summary

N = 16	Peanut		Blind Cup		Related Sample Wilcoxon Signed Rank Test	Correlation
	Mean	SE	Mean	SE	p-value	Pearson's R
Existing Solutions	2.25	0.41	2.31	0.46	0.94	0.56
Analogies in Nature	3.69	0.46	2.25	0.29	0.006	0.46

5.3.4 Discussion

As the resulting comparison shows a similarity in quantity and a difference in the mean variety and number of concept, the correlation values suggest that the quantity, variety and number of concepts are linearly related. In other words, the students consistently generated the same quantity of ideas for both Peanut and for Blind Cup, they consistently generated a higher variety of concepts for Blind Cup than they do for Peanut, and they consistently generated the same number of concepts for both Peanut and Blind Cup. This supports the existence of a linear relationship between the two problems for the quantity, variety and number of concepts metrics under the conditions used in that

study. This means it is valid to use Linear Equating to produce equivalence scores for the two problems for quantity, variety and number of concepts.

Conversely, though statistically significant, the difference in quality between the two problems does not show consistency across all students: some students do better for blind cup, some for peanut.

From the Problem Effects study comparing Alarm and Corn, it was hypothesized that a designer's familiarity with a design problem may affect their outcome. From the familiarity survey results, it was observed that for both problems, the students were consistently aware of an equal number of familiar existing solutions. While this does not support the argument regarding differences in problems, it demonstrates that a) it is possible to design problems with relatively equal familiarity, and b) that despite having similar familiarity and using the same method, student designers still output different results. In other words, there are other characteristics that need to be accounted for in addition to solution familiarity.

When investigating the effect of domain, it is speculated that a problem-method interaction may favor one problem over the other. For example, a problem in one domain may favor a method such as biologically inspired design due to more available solutions in biology. It was found that for the Peanut problem – which involves mechanical and biological components – student designers were able to generate a significantly higher number of analogies to nature versus the blind cup problem. Therefore, if one is testing

the effectiveness of a particular biologically inspired design method, a designer may have access to more analogies for Peanut than Blind Cup. As suggested by the results, using no specific method, participants were able to generate a higher mean of variety for the Blind Cup problem. However, with the ability to draw more analogies in nature for Peanut, the coupling of Bio-Inspired Design methods with these problems could have a potential reverse effect on the variety metric. While these results serve as a first step to expose these critical considerations, further investigations need to explore more problem characteristics to isolate these interactions.

5.4 Limitations

While such experiments with human subjects have many limitations, two limitations are worth special mention. The first is that the comparison between Alarm and Corn in the Problems Effects experiment was a between-subject experiment. This could have affected the overall scores for either problem. It could have occurred that the sample that generated concepts for Alarm could have been more experienced, have higher knowledge and put more effort than the sample for Corn, or vice versa. To eliminate this possible limitation, the follow up study comparing Blind Cup and Peanut was conducted as within-subject.

Second, it is noted that in each case, only two design problems are compared. This is particularly limiting with respect to the discussion on the more general characteristics of design. It is not this thesis' intention to suggest these are the definitive influential design problem characteristics, nor can conclusions be drawn from the scope of this experiment. The intent of this experiment and discussion on the characteristics of

design problems is to provide a little evidence as a starting point for further conversation and research.

Third, despite obtaining statistical significance, the limited sample size is recognized, and it is planned to replicate a similar experiment in the future with larger and more varied sample groups.

CHAPTER 6: CONCLUSION

6.1 Methods

The five methods of Bio-Inspired Design were quantitatively and qualitatively evaluated. For each of the methods, participants were able to generate concepts to design problems and to generate additional concepts for their semester-long projects. While there was concern per the effectiveness of the Linear Equating formula, the Problem Linearity study affirmed its effectiveness at scaling the quantity and variety metrics. Thus, the resulting quantity metrics from the experiment are ratified. Uncovering scalability flaws of the quality metrics, direct comparative differences between methods are inconclusive. However the results still show effectiveness of each method to aid the generation of high quality concepts.

The Bio-Keyword Search method was the least preferred and generated the fewest number of concepts with the lowest quality, quantity, and variety of ideas. The Bio-Keyword Search Method as presented in this thesis relied upon a very newly developed bio-analogy retrieval tool that was still at an infantile state. This was also the students' first exposure to flow-based functional models, and Bio-Keyword Search tends to be one of the most difficult methods for students to master. Follow up work to improve the resources and searches were conducted by Lee [143].

The Directed method was found to generate high quality concepts, and the largest number of concepts and quantity of ideas, despite being the least useful method from the student's opinions. While the Directed method was less structured than the others, its

superior performance may possibly be attributed to the specific Alarm design problem; It is relatively more familiar to students and easier to solve. Furthermore, the time investment associated with using the Directed approach possibly explains the participants' ability to generate a more ideas. Since this approach is less structured and requires less effort of searching, it allows for quicker brainstorming.

The Case Study, AskNature and BioTRIZ methods helped generate similar levels of quality and quantity of ideas, and a similar number of concepts. However, these three methods differ in terms of number of final concepts generated, the team preferences, the one perceived to give the most creativity and variety, and usefulness. Most of the final concepts were generated using Case Study or AskNature, without a large difference between the two, leaving BioTRIZ, Directed, and Bio-Keyword Search with fewer. The teams mostly preferred using AskNature and BioTRIZ equally, as opposed to Directed and Case Study. For usefulness, BioTRIZ was selected the most often by a large margin over the other methods, followed by AskNature. Despite the Bio-Keyword Search method's flaws, it did not receive the least number of votes: Directed and Case Study were considered less useful than the Bio-Keyword Search method.

While BioTRIZ was preferred and thought to be the most useful method by the students, it actually resulted in concepts of similar quality and quantity to that of the Case Study and AskNature methods. This is consistent with other research where designers' preferences do not match the quantitative outcome data. Much more extensive analysis is

needed to tease out the subtleties of the benefits of each method, types of problems the methods are more effective for, and limitations.

While there were large differences when comparing methods to each other in certain categories, all these Bio-Inspired design methods were effective and helped generate Bio-Inspired concepts. Each method was shown to provide numerous concepts with high quality and novelty, each help generate final concepts, and each was found to be useful by some students. Lessons learned in this thesis and the identification of limitations allows for better future experiments and mitigating the effect of confounding variables.

6.2 Self-Efficacy

Over the course of the semesters for the two experiments, the student's self-concept scores generally showed improvements: self-efficacy increased, motivation started and remained high, outcome expectancy increased, and anxiety generally decreased. There was also a general trend showing that student's self-efficacy, motivation and outcome expectancy scores level off at a score of approximately 80, even though those levels initially started off at different levels prior to the course. This may imply that students maximize their self-efficacies to a score of 80 and never feel as though they gain enough experience or information to surpass that level; achieving self-perfection in every criteria may seem unattainable.

While there are statistically significant improvements in students' engineering design self-concept scores from these course long experiments, there is still room for improvement. Although these scores do not directly reflect the student's self-reported ability to conduct Bio-Inspired Design, the insights and experienced gained from learning and using Bio-Inspired Design methods raised their self-efficacy performing traditional engineering design process tasks. As demonstrated by Pajares and Hutchinson, this raise in self-efficacy will increase the future effort expended by the designer in similar domain tasks and increase their motivation to succeed [134, 136]. Exploring and teaching additional Bio-Inspired methods may further increase the magnitude of these improvements.

Additionally, Carberry *et al.*'s self-efficacy instrument was found to be reliable and consistent with their original results and trends [135]. This consisted of the correlation between ED (Engineering Design) and EDP (Engineering Design Process), and the relationship between self-efficacy with motivation, expectancy and anxiety. Thus, this instrument is an effective method to measure people's self-efficacy towards engineering design tasks.

6.3 Problem Equivalency

In this thesis, it was hypothesized that different design problems, despite being designed for similarity, will produce varied results across a set of creativity metrics. A (non-comprehensive) set of design problem characteristics that affect the design outcomes was also hypothesized.

Evidence was provided to support the hypothesis that different design problems, though subjectively intended to be "equivalent," produce varied results across a set of design creativity metrics. In both between-subject and within-subject experiments, each design problem produced significantly varied results; across both experiments, it is shown that quantity, quality, novelty and variety metrics were subject to statistically significant differences, and that the quality metric in particular showed a high degree of variance. It was also demonstrated in the within-subjects study that some metrics, although different on the aggregate, showed moderate to high correlations between individual students; quantity of ideas, variety, and number of concepts in particular seem to correlate well across the problems examined. On the other hand, quality and novelty did not. This suggests that, at least for some metrics, it is possible to attain equivalency between design problems, such that individual performance on one design problem may be predictive of individual performance on another. Though the results show that the students may have equal familiarity with existing solutions for both problems, there is a difference in analogies in nature, showing that when coupled with a Bio-Inspired design method environment, one is able to draw more analogies for one problem, and will therefore generate different outcomes for each problem.

In an attempt to begin to understand the factors at play, a set of characteristics that was felt to possibly influence these outcomes, was defined. The degree, to which the subjectively "equivalent" problems varied, was studied according to two of the design problem characteristics defined: familiarity with existing solutions to the problem and domain of the design problem. It was found that for the peanut and blind cup problem,

design problems were in fact generated, for which students were roughly equivalent in their ability to consider existing solutions. On the other hand, these problems involved different domains, and as a result provided different levels of access to domain-distant analogies. This suggests that the domain of problem can influence the method used in the problem; in this case the peanut problem provided additional access to biological analogies that may influence the process and results from the biologically inspired design method.

A hypothesized list of characteristics that may influence design outcome was provided. Identifying the degree and method with which these characteristics influence design outcomes will enable researchers to better craft more comparable problems. The ability to draw equivalency, and gauge problem difficultly across a variety of factors may also be helpful in tool-building, educational instruction and resource planning for industry [157]. Furthermore, by understanding problem characteristics on the journey to finding equivalent problems, one can also use the criteria not only for design research testing, but to also classify engineering problems encountered in real engineering work and aid in selecting best approaches or methods that target these specific characteristics.

6.4 Future Work

6.4.1 BID Methods

Problem equivalency ratio data needs to be collected to relate Peach Pitter to Peanut Sheller using the Linear Equating method, and calculate the newly scaled scores for Peach Pitter. Although, as suggested by the problem equivalency study, further investigation will need to occur to render the Peach problem equivalent and appropriately apply the linear equating method. Not only for Peach, but for the other problems. In order to draw conclusive comparison results among problems, the problems must be linearly equivalent and allow the accurate use of Linear Equating.

The Bio-Keyword Search method showed some difficulties not only regarding the database, but in the grasping of the concepts behind Functional Modeling. It is a challenging process that requires extensive practice. Thus, for future courses, there should be improvements in the Functional Modeling lectures to aid students in thoroughly understanding its concepts, and allow more time for training and practice. Perhaps prolonging the course into two semesters to allow more incubation and practice time with each method.

Furthermore, it was observed that time is a factor when applying each method. The Directed method showed advantages when the participants were limited to only 50 minutes of idea generation. Thus, future experiments should increase the allocated time to generate solutions and re-evaluate the performance of each method for each of the evaluation metrics.

In this study, each method was taught in the same order through the semester: Directed first, follow by Case Study, AskNature, BioTRIZ and Bio-Keyword Search. The run-order should be explored and determine the effects of teaching one method prior to another.

6.4.2 Problem Equivalency

The sample size of the Problem Equivalency study was small, thus should be repeated with a much larger group of participants. Additionally, the results obtained in this study were for a one pair of design problems. Future experiment should aim to identify the same correlations between different pairs of problem to ensure linear equivalency.

Experiments should be continued to explore the influence of the hypothesized characteristics of design problem on design outcomes. Future experiments should aim to isolate and define specific characteristics that will render two design problems linearly equivalent, or for alternative purposes, completely unequal. While this thesis shows a linear relationship between the two problems examined for quantity and variety, similar experiments should be conducted to determine if that linear relationship is true for other sets of design problems. Furthermore, identifying and improving design characteristics to allow linearity between problems for quality and novelty should be pursued. Furthermore, as those characteristics are determined, more design problems should be created and extensively tested to ensure consistent linearity. It is hoped that this work will allow researchers to provide comparisons among groups or individuals across a range of similar, though not identical, design problems.

APPENDIX A – DESIGN PROBLEMS

A1:*Alarm – Directed (2012)*

MEEN 489: Fall 2012

Individual Design Problem – Personal Alarm Clock

Problem Description:
Alarm clocks are essential for college students; however they will often wake up a roommate and those around them. Design an alarm clock for individual use that will not disturb others. The clock should be portable for use in a variety of situations such as on the bus, in the library, or in a classroom.

Customer Needs:
- Must wake up individual with no disturbance to others.
- Must be portable and lightweight.
- Electrical outlets are not available as a constant power source.
- Low cost.

Please sketch and note (with words) one design solution per page (add pages as needed). If you can, use nature as inspiration for you ideas. If you don't have any inspiration form nature, do come up with as many ideas as you can from whatever sources of inspiration you have. Do this homework "closed" book. In other words, don't go googling or skimming through Bio 101 books for ideas.

A2: *Corn – Directed (2012)*

MEEN 489: Fall 2012

Individual Design Problem - Device to Aid in Shucking Corn

Problem Description:
Corn is currently the most widely grown crop in the Americas with the United States producing 40% of the world's harvest. However, only the loose corn kernels are used when bought canned or frozen in grocery stores. An ear of corn has a protective outer covering of leaves, known as the husk, and strands of corn silk threads run between the husk and the kernels. The removal of husk and silk to clean the corn is known as shucking corn. Design a device that quickly and cheaply shucks corn for mass production.

http://www.art-photograph-gallery.com/pictures-of-corn.html

Customer Needs:
- Must remove husk and silk from corn cob with minimal damage to kernels.
- A large quantity of corn must be shucked quickly.
- Low cost.

Please sketch and note (with words) one design solution per page (add pages as needed). If you can, use nature as inspiration for you ideas. If you don't have any inspiration form nature, do come up with as many ideas as you can from whatever sources of inspiration you have. Do this homework "closed" book. In other words, don't go googling or skimming through Bio 101 books for ideas.

A3: *Blind Cup – Case Study (2012)*

Individual Design Problem – Measuring Cup for the Blind

Problem Description:
Design a volume-measuring apparatus for use while cooking by a person who is blind. It needs to be easy to operate and able to be used for both powders and liquids without splattering during operation. The apparatus needs to measure graduated quantities from 1/4 to 2 cups.

Customer Needs:
- Prevent waste of food products.
- Easy to clean.
- Low cost.

Please sketch and note (with words) one design solution per page (add pages as needed). Use nature as inspiration for your ideas. If you have an idea pop into your head that doesn't seem to use some natural inspiration, do include it. If you have an idea that is inspired
For each idea:

(just do this with notation on the page, or attached to it, do write neatly so I can read it)

- Identify if the idea is bioinspired or not.
- Identify what ideas occurred in an initial 50 minute time period.
- You are welcome to go a googling or otherwise actively search for analogy. Do not use the biomimcry group site (http://www.asknature.org/). Otherwise, I think everything is fair game.
- For each bioinspired idea, describe the analogy clearly. For example, if the analogy is form, describe the key elements of the form. If the analogy is a function, describe the function. If the analogy is both the function and the mechanism that provides the function, discuss that as well. If the analogy is a principle describe it. If the analogy is a strategy describe it.
- For each bioinspired idea for which you actively sought inspiration or analogy, describe your search strategy. If you googled, describe your keywords. If you opened up a biology book state the book you looked it and where looked. If you talked to a biologist, state whom you talked to, what their expertise was, and briefly how the conversation went.
- Categorize your bioinspired design according to the biomimetic technology tree Application and Scale. If you have an Application and/or Scale that doesn't fit any of the existing categories, list what they new category and scale are.

A4: *Towel Ironing – AskNature (2012)*

HW 13 Individual Design Problem - Device to Automatically Remove Wrinkles and Fold Towels

Due Friday Oct. 12 at 1:00 PM

Problem Description:
Design an automatic wrinkle removing device for use for towels in high-end hotels. The purpose of the device is to remove wrinkles from freshly laundered towels and to fold the towels. At this stage of the project, there is no restriction on the types and quantity of resources consumed or emitted.

Customer Needs:
- Remove wrinkles and fold towels quickly.
- Consistently remove all of the wrinkles and fold towels to the same size.

Please sketch and note (with words) one design solution per page (add pages as needed). Use the asknature.org website to find analogies and inspire ideas. If you have an idea pop into your head that doesn't seem to use some natural inspiration, do include it.

For each idea:
(just do this with notation on the page, or attached to it, do write neatly so I can read it)
- Identify if the idea is bioinspired or not.
- Describe your "search" process used in AskNature. If you used a few search or browse strategies, go ahead and describe them briefly
- Identify the analogous system, entity, principle, etc. that you found on ask nature.
- Categorize your inspirational system and solution according to the bioinspired technology tree
- Identify and describe the key analogies used in your solution
- Identify what ideas occurred in an initial 50 minute time period.
- For this exercise, don't use any material beyond what is in the AskNature.org site. In other words, don't go googling or click on links that take you to reference material outside of AskNature.org.

HW 21 Individual Design Problem - Device to Aid in Coconut Harvesting

Due Thursday Nov. 8 at 1:00 PM – please scan and submit electronically

Design Problem - Device to Aid in Coconut Harvesting

Problem Description:
In certain places like the Philippines, Indonesia, and India, coconut harvesting is a major practice. The current process requires a skilled person to climb the tree and cut down the coconuts. The average height of a coconut tree is 35-40 feet and though there are grooves along the tree that make it easier to climb, the tree surface becomes very slippery during the rainy seasons. The process may take as long as 12 hours for large farms that average 150 trees. The goal of this problem is to design a low-cost product to improve the coconut harvesting process so that it is safer and can be done more quickly. The target throughput is at least 500 pounds per hour.

Customer Needs:
- Must climb tree and remove coconut with little damage to fruit.
- Electrical outlets are not available as a power source.
- Low cost.

Use the BIOTRIZ bioinsipired design method to generate solution concepts.
For each idea:
- Describe your "conflict" in the design problem
- Determine the generalized performance parameters in conflict for use in the BioTRIZ conflict
- Using the matrix, identify the BioTRIZ principles that should overcome the conflict
- Using the principles, do your best to develop a design solution for the problem.
- Sketch out your solution
- Also, be sure to include any discussion or critique of the applicability of the method or suggested principles in the slides.
- Critique your solution
- Identify what ideas occurred in an initial 50 minute time period.
- For this exercise, don't use any material beyond the BioTRIZ matrix and principles.

Do this with notation on the page, or attached to it, do write neatly so I can read it.

HW 25 Individual Design Problems – Device to Aid in Pitting Peaches
Functional Modeling Approach

Due Tuesday Dec. 4 at 1:00 PM – please scan and submit electronically

Problem Description:
Peaches have a pit in the center of the fruit that should not be eaten. Ripe peaches are delicate, soft, and bruise easily. For certain types of peaches, the flesh of the peach clings tightly to the pit. Design an automated device that can cleanly remove the pits of all ripe peaches while keeping the fruit intact and without wasting much of the fruit. The peaches cannot be genetically modified. The target throughput is approximately 50 pounds per hour.

Customer Needs:
- Must remove entire peach pit with minimal damage to the peach.
- A large quantity of peaches must be quickly pitted.
- Low cost.

Please sketch and note (with words) one design solution per page.

For this problem, use the function based and bio keyword design method to generate a solution concept. In summary
- Create a black box functional model of the design problem
- Create a detailed functional model for the problem
- Using either the black box function or and "important" function from your model, search the biological data base.
- Review the results.
- From this, do your best to develop a design solution for the problem.
- Include in your HW submission, the passage that "sparked" an idea.
- Sketch out your solution, scan it (photo it, etc.) and put it into the slides
- Also, be sure to include any discussion or critique of the applicability of the method in the slides.
- Identify and properly reference any additional material you looked up to help you understand the system, entity, etc.
- Generate your solution. Include sketches, descriptions, etc.
- Categorize your inspirational system and solution according to the bioinspired technology tree
- Identify and describe the key analogies used in your solution
- Identify what ideas occurred in an initial 50 minute time period

MEEN 489: Fall 2013

HW 5 Individual Design Problem – Personal Alarm Clock

Due [in class exercise] Thursday September 5

Problem Description:
Alarm clocks are essential for college students; however they will often wake up a roommate and those around them. Design an alarm clock for individual use that will not disturb others. The clock should be portable for use in a variety of situations such as on the bus, in the library, or in a classroom.

Customer Needs:
- Must wake up individual with no disturbance to others.
- Must be portable and lightweight.
- Electrical outlets are not available as a constant power source.
- Low cost.

Please sketch and note (with words) one design solution per page (add pages as needed). Please try to use nature as inspiration for you ideas. If you don't have any inspiration from nature, do come up with as many ideas as you can from whatever sources of inspiration you have. Do this homework "closed" book. In other words, don't go googling or skimming through Bio 101 books for ideas. Just brainstorm it up. Indicate on your notes the 50 minute mark so I can tell what work was done after the first 50 minutes. If you have been asked to generate solutions to this problem before, indicate so and when/where/what class.

A8: *Blind Cup – AskNature (2013)*

HW 20
Individual Design Problem – Measuring Cup for the Blind

Problem Description:
Design a volume-measuring apparatus for use while cooking by a person who is blind. It needs to be easy to operate and able to be used for both powders and liquids without splattering during operation. The apparatus needs to measure graduated quantities from 1/4 to 2 cups.

Customer Needs:
- Prevent waste of food products.
- Easy to clean.
- Low cost.

Please sketch and note (with words) one design solution per page (add pages as needed). Use the asknature.org website to find analogies and inspire ideas. If you have an idea pop into your head that doesn't seem to use some natural inspiration, do include it.

For each idea:
(just do this with notation on the page, or attached to it, do write neatly so I can read it)
- Identify if the idea is bioinspired or not.
- Describe your "search" process used in AskNature. If you used a few search or browse strategies, go ahead and describe them briefly
- Identify the analogous system, entity, principle, etc. that you found on ask nature.
- Categorize your inspirational system and solution according to the bioinspired technology tree
- Identify and describe the key analogies used in your solution
- Identify what ideas occurred in an initial 50 minute time period.
- For this exercise, don't use any material beyond what is in the AskNature.org site. In other words, don't go googling or click on links that take you to reference material outside of AskNature.org.

A9: *Towel Ironing – BioTRIZ (2013)*

MEEN 489 Bioinspired Engineering Design

HW 25 (Individual): Concept Generation Exercise

Due Nov. 7 12:30 PM.

Submission format: Electronic

Individual Design Problem – Device to Remove Wrinkls

Problem Description:
Design an automatic wrinkle removing device for use for towels in high-end hotels. The purpose of the device is to remove wrinkles from freshly laundered towels and to fold the towels. At this stage of the project, there is no restriction on the types and quantity of resources consumed or emitted.

Customer Needs:
- Remove wrinkles and fold towels quickly.
- Consistently remove all of the wrinkles and fold towels to the same size.

Please sketch and note (with words) one design solution per page (add pages as needed). Use the asknature.org website to find analogies and inspire ideas. If you have an idea pop into your head that doesn't seem to use some natural inspiration, do include it.

Use the BIOTRIZ bioinsipired design method to generate solution concepts.

For each idea:
- Describe your "conflict" in the design problem
- Determine the generalized performance parameters in conflict for use in the BioTRIZ conflict
- Using the matrix, identify the BioTRIZ principles that should overcome the conflict
- Using the principles, do your best to develop a design solution for the problem.
- Sketch out your solution
- Also, be sure to include any discussion or critique of the applicability of the method or suggested principles in the slides.
- Critique your solution
- Identify what ideas occurred in an initial 50 minute time period.
- For this exercise, don't use any material beyond the BioTRIZ matrix and principles.

Do this with notation on the page, or attached to it, do write neatly so I can read it.

Individual Design Problem – Device to Aid in Coconut Harvesting

Problem Description:

In certain places like the Philippines, Indonesia, and India, coconut harvesting is a major practice. The current process requires a skilled person to climb the tree and cut down the coconuts. The average height of a coconut tree is 35-40 feet and though there are grooves along the tree that make it easier to climb, the tree surface becomes very slippery during the rainy seasons. The process may take as long as 12 hours for large farms that average 150 trees. The goal of this problem is to design a low-cost product to improve the coconut harvesting process so that it is safer and can be done more quickly. The target throughput is at least 500 pounds per hour.

Customer Needs:
•   Must climb tree and remove coconut with little damage to fruit.
•   Electrical outlets are not available as a power source.
•   Low cost.

Please sketch and note (with words) one design solution per page.

For this problem, use the function based and bio keyword design method to generate a solution concept. In summary
- Create a black box functional model of the design problem
- Create a detailed functional model for the problem
- Using either the black box function or and "important" function from your model, search the biological data base.
- Review the results.
- From this, do your best to develop a design solution for the problem.
- Include in your HW submission, the passage that "sparked" an idea.
- Sketch out your solution, scan it (photo it, etc.) and put it into the slides
- Also, be sure to include any discussion or critique of the applicability of the method in the slides.
- Identify and properly reference any additional material you looked up to help you understand the system, entity, etc.
- Generate your solution. Include sketches, descriptions, etc.
- Categorize your inspirational system and solution according to the bioinspired technology tree
- Identify and describe the key analogies used in your solution
- Identify what ideas occurred in an initial 50 minute time period

A11: *Peach – Case Study (2013)*

MEEN 489 Bioinspired Engineering Design
HW 12 (Individual): Concept Generation Exercise
Due Tuesday October 8, 12:30 PM.
Submission format: Electronic

Individual Design Problem – Device to Aid in Pitting Peaches

Problem Description:
Peaches have a pit in the center of the fruit that should not be eaten. Ripe peaches are delicate, soft, and bruise easily. For certain types of peaches, the flesh of the peach clings tightly to the pit. Design an automated device that can cleanly remove the pits of all ripe peaches while keeping the fruit intact and without wasting much of the fruit. The peaches cannot be genetically modified. The target throughput is approximately 50 pounds per hour.

Customer Needs:
- Must remove entire peach pit with minimal damage to the peach.
- A large quantity of peaches must be quickly pitted.
- Low cost.

Please sketch and note (with words) one design solution per page (add pages as needed). Use nature as inspiration for your ideas. If you have an idea pop into your head that doesn't seem to use some natural inspiration, do include it. If you have an idea that is inspired from nature and you know the analogy state it.

For each idea:
(just do this with notation on the page, or attached to it, do write neatly so I can read it)
- Identify if the idea is bioinspired or not.
- Identify what ideas occurred in an initial 50 minute time period.
- You are welcome to go a googling or otherwise actively search for analogy. Do not use the biomimcry group site (http://www.asknature.org/). Otherwise, I think everything is fair game.
- For each bioinspired idea, describe the analogy clearly. For example, if the analogy is form, describe the key elements of the form. If the analogy is a function, describe the function. If the analogy is both the function and the mechanism that provides the function, discuss that as well. If the analogy is a physical principle, describe it. If the analogy is a strategy, describe it.
- For each bioinspired idea for which you actively sought inspiration or analogy, describe your search strategy. If you googled, describe your keywords. If you opened up a biology book state the book you looked in and where looked. If you talked to a biologist, state whom you talked to, what their expertise was, and briefly how the conversation went.
- Categorize your bioinspired design according to the biomimetic technology tree Application and Scale. If you have an Application and/or Scale that doesn't fit any of the existing categories, list the new category and scale.

APPENDIX B – PEANUT SHELLING BIN'S LIST DESCRIPTION

Bin Name	Description
Adhesive	using a sticky material to attach to the shell and then pull off to remove the shell
Black box	have a device where they input the peanuts and they are magically outputted without shells
Blade	using a knife, razor, blade, sharp edge, etc. to cut the shell
Boil to remove shell	boiling the entire peanut to degrade the shell and using the convection currents to remove them (if boiling is only used to soften the shell and not to remove it, then it would fall under "softening shell")
Brittle shell	making the shell brittle in some way so that they'll break easily (ex: flash freezing)
Buoyancy (in liquid)	dumping peanuts and their removed shells into liquid in order to separate out the nuts (the shells will float and the peanuts will sink)
Burn shells	using fire to burn the nut in the shell to destroy the shell (often resulting in a "roasted" nut)
Centrifuge	putting the whole peanut into a centrifuge to break the shell
Chemical	using some form of chemical that will degrade/disintegrate/destroy the shell
Conical rollers	similar to the Full Belly example (see picture)
Cylindrical or spherical rollers	a roller or multiple rollers that are a cylinder in shape or just a ball that rolls around to crush the shells
Eating/decomposition	using an algae/insect/genetically engineered animal that eats only the shells or eats the entire peanut and somehow regurgitates or poops out the nut
Filter/mesh	using a filter or mesh or sifter or even just a plate with holes in it to separate out the nuts and the broken shell pieces
Flexible tube	rolling a peanut inside a flexible tube to crush or peel away the shell. Similar to a garlic roller
Force on ends	applying a force on both ends of the entire peanut to break the shell in half
Friction/abrasive	using a textured or abrasive surface to rub off the shell
High frequency radio waves	to destroy the shell, often mentions the resonant frequency
High velocity impact	dropping the peanuts from a great height, shooting peanuts against a wall, etc. basically anything where the peanut moves quickly to impact a surface that will cause the shell to break
Hinged plates	two plates that are hinged to compress the shell, similar to a nutcracker
Hold shell in place, nut falls o	a way to separate out the nuts from the shell, the shell is held in some way and the nuts are either shaken out or fall out due to gravity
Human	using a person to either shell the peanuts or to sift out the peanuts from the shells (however if they're just using human weight to crack the shells, that would fit under press/weight)
Laser	using a laser to burn off part or all of the shell
Magnet	anything magnet related, often relates to making the shell magnetic and using that to break the shell
Mass difference	using the difference in mass to separate out the broken shells and the nuts, often use some form of air jet/wind to blow away the lighter shells while leaving the nuts in place, also known as winnowing
Metal screen/grate/force thro	using a screen, grate, or simply holes that are the size of the peanut so that the shells will break when the whole peanut is forced through
Mixer (eggbeater)	using spinning paddles or chains to break the peanuts
Needles/hooks/spikes	putting hooks/spikes into the peanut and then pulling them apart to break the nut
No shell peanuts	genetically engineer the peanuts to not have shells or to lose their shells easily
Press/weight	using a press or weight (including humans or animals) to crush the shells, different from hinged plates/nutcracker
Pressurized fluid	using an air jet or waterjet directed at the peanut to break it or placing the peanut in a chamber of static fluid at a high pressure to crush the shell
Punch	forcing a punch through the entire peanut that is positioned to remove just the peanut
Reframing the problem	changing the problem so they are not creating a device/method to shell peanuts, for example: selling the peanuts in shells because some consumers like to crack the shells themselves
Robot hands	using a robot (or just its hands) to shell the peanuts similar to how a human does it
Scrape/brush	using a brush to scrape at the whole peanuts to break the shell
Shear	often uses two plates on either side of the peanut that move in opposing directions (laterally or rotating)
Softening shell	any method to soften the shell (like soaking it) in order to make it easier to shell the peanuts
Spring around shell	putting the peanut inside a spring and then stretching the spring to crush the peanut
Squeeze from one end	peanuts are forced into a smaller area so that they are compressed from one end to break the shell
Thermal expansion	using heat to cause peanut shells to break due to different thermal expansion coefficients between peanuts and shells
Toothed rollers/gears	letting the peanuts fall onto gears or toothed rollers that will crush the peanut shells between their teeth
Torsion	twisting the shell of the peanut to break it
Train animal	have an animal shell the peanuts (different from having the animal eat the peanut shells)
Tumblers	putting the peanuts in a tumbler with other items that will crush the shells when spun
Vacuum	removing the air and using the pressure difference to crack the peanut
Vibration/shake	shaking the peanuts, often used to help sift the cracked nuts to filter out the peanuts

APPENDIX C – BIN'S LIST FOR ALARM, CORN, BLIND CUP, COCONUT, TOWEL IRONING AND PEACH

Alarm	Corn	Blind Cup	Coconut	Towel Ironing	Peach
Human	Abrasives	Acoustic/Echolocation	Adhesive (gloves, pants, shoes)	Folding Panels	Air/Water Pressure Jet
Spotlight	Adhesive	Additive cup	Abrasive on a rope	Steam (stand alone)	Blackhole/Antimatter
Alter Dreams	Animal shucking	Adjust base/side	Basket/backpack	Human	Blade
Wearable Vibrator	Automatic size adjustment	Adjustable bag	Bending tree	Steam Room	Chemical/Syringe
Wearable Sprayer	Automatic solution/black box	Adjustable cone	Burn/dissolve stem	Heated Press	Expandable Needle/Insertion
Flashing Contacts	Blade	Air pump amount (volume measure)	Bury tree in dirt	Heated Rollers	Genetic Modification
Directed Sound	Brushes	Attachment to Pouring Container	Cable lift/suspension	Rollers	Grind/Blend
Headphones	Chemicals	Black box/robot	Change the problem	Robotic Arm/claw	Heat
Wearable Lights (glasses, bracelet, etc.)	Drill	Braille	Chemical Agent	Hot Air Room	Hollow Sharp Tube
Scents	Eating	Screw Controlled Bottom Platform	Climbing equipment on tree	Heated Tumbler	Hooks/Spikes/Claw
Winds	Electricity	Claw/Double Scoop	Conveyer belt	Gravity Assisted Folding	Human
Projectile	Embrittle husk	Continuous sensors	Cut down the tree	Water Spray	Imaging
Stabbing/Studs	Entanglement	Floating indicators/device	Gun - attach to coconut	Magic	Inner Drill/Grind
REM Cycle	Filter	Flow Measurement	Gun - impact	Tumbler	Laser
Insects	Fire	Funnel	Handheld blade	Blackbox Folding Machine	Motor/Twist
Electrocution	Funnel	Gates	Helmet	Redefine Problem	Pliers/Clamp
Sensitizing Drug	Humans	Graduated sensors	Hot air balloon	Wind	Pressure
Sleeping Pills	Huskless/Modified husk	Impact toggle/switch	Inflatable structure	Rising Divider	Punch/Piston
Temperature	Impact	Inflatable	Jet pack	Clamps/clips	Robot Hands
Hair Pulling	Inflatable	Lid/Cover	Ladder	Rotation Folding	Scoop
Sunlight	Lasers	Magic Seeing Glasses	Laser	Magnets	Screw/Cork Screw
Flavor Capsule	Magnets	Plugged holes	Lift	Hooks	Shaker
Tickling	Manual clamp	Preset cup/size	Modify trees or coconuts	Sensors	Smash/Squeeze
Falling Sensation	Moving fluid (air & water)	Scales/Weight	Movable enclosure	Strainer	Sound Wave
Impact	Perforate	Corkscrew intake	Net or canopy	Vacuum	Suction/Vacuum
Biological Clock	Popcorn	Self-dispensing machines	Grappling Projectile	Static Electricity	Teeth Jaw/Pincers
Restrict Breathing	Remove core	Sound/Speaker	Platform/walkway system	Tension	Train/Engineer Organism/Animal
Wakeup Drug	Restructure problem	Spillover/overflow Container	Preset Stem Cutting Device	Shaking	Tweezers
Change Posture	Robotic hands	Stepped/Ridges (touch)	Pressurized fluid	Centrifuge	Water Jet
Adjust Volume/proximit	Rollers	Surface change through pressure	RC helicopter or plane	Adhesive	Wire
Dierrhetic	High freq waves	Syringe	Robot	Extrude Towels	
Trained Animal	Rotation/Centrifuge	Telescoping/collapsible size	Shoes with springs	Melt Towels	
Personalized Frequency	Scraper	Temperature change	Shoes, belts, gloves with spikes/grabbers	Chemical/Chemical Spray	
Nanobots	Series of mesh wires	Vibration	Slide/chute	Wrinkle Free Material	
Increase Breathing	Slit plates	Water displacement	Stick	Electrically Sensitive Memory Polymer	
	Soften husk	Waterproof Coating	Stilts		
	Sorter		Thrown object		
	Teleport		Tools on a pole (blade, grabber, saw)		
	Torsion		Trained animal		
	Tumbler		Trampolin		
	Vibration		Tree shaker		
	Visual sensor		Vacuum		
	Compression		Vehicle		
	Suction/Suction Cup		Torsion		
	Press/Plate Compression		Belt Wrapped Around Tree		

Features	Participant 1						Participant 2			
	Sol 1	Sol 2	Sol 3	Sol 4	Sol 5	Sol 6	Sol 1	Sol 2	Sol 3	Sol 4
Adhesive										
Black box										
Blade										
Boil to remove shell										
Brittle shell										
Buoyancy (in liquid)										
Burn shells										
Centrifuge							1			
Chemical										
Conical rollers										
Cylindrical/spherical rollers		1								1
Eating/decomposition					1					
Filter/mesh (to filter shell a								1		
Flexible tube										
Force on ends - break shell										
Friction/abrasive										
High frequency radio wave										
High velocity impact/gravit										
Hinged Plates/Nutcracker										
Hold shell in place, nut fall										
Human				1						
Laser										
Magnet										
Mass difference/bounce (t										
Metal screen/grate/force t										
Mixer (eggbeater)										
Needles/hooks/Spikes										
No shell peanuts										
Press/Weight	1							1		
Pressurized fluids										
Punch										
Reframing the problem										
Robot hands										
Scrape/brush										
Shear										
Softening shell				1						
Spring around shell										
Squeeze from one end/com										
Thermal expansion										
Toothed Rollers/gears							1		1	
Torsion										
Train animal										1
Tumblers			1							
Vacuum										
Vibration/Shake										
Total features/solution:	1	1	1	2	1	1	1	2	1	2

APPENDIX E   - EXAMPLE SET CONCEPTS FOR ALARM PROBLEM

# FROM ONE PARTICIPANT

①

FRONT

BACK   SIDE

Can retract

Summary

A normal sized + styled wrist watch. However, on the back there is a pin-point that is able to retract into the watch so that it is flush w/ the back portion of the watch. This pin-point will be sharp but not enough to pierce the skin or cause a large amount of pain. When the wrist watch alarm time is reached, the pinpoint will "poke" the wrist multiple times before the user turns of the alarm. → oscillating

Inspiration

Being stung by a bee (That would usually wake someone up)

（2）

FRONT

Back   Side
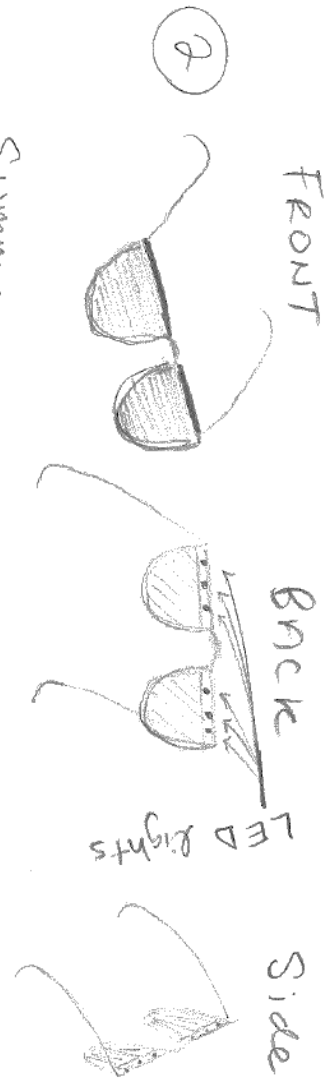
LED lights

Summary

The body of this design consists of normal everyday sunglasses. However, built into the frames of the sunglasses are LED lights, a time-piece, and a small battery. The user will be able to set the alarm and when the alarm time is reached, the lights will illuminate directly into his/her eyes causing them to awake.

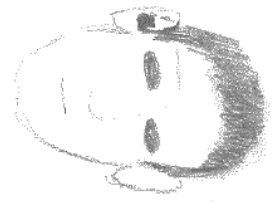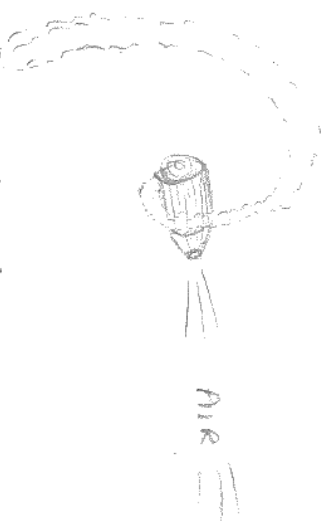## Inspiration

The sun rising. Example: Opening up blinds

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③

SIDE

FRONT

EAR PIECE

air

Summary

The design is based off of a hearing aid style. It would include a time piece, a battery, and a device that could release little "puffs" of air. The user would set the alarm and when the desired time is reached the system would release a "puff" of air into the user's ear, causing them to wake.

Inspiration

A bug flying near your ear.

125

(4)

FRONT

BACK

probes

Summary

Design in the form of a normal wrist watch.
However, on the back of the watch is located
probes. When the user defined alarm time is
reached, the watch will release a small
"shock" to the user causing them to wake
up. Preferably, the shock would consist of
enough electricity to wake the user but
not enough to make the user lose control
of their limbs or etc.

Inspiration

Lightning.

50 minutes

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APPENDIX F   - COURSE SYLLABUS

MEEN 489 – Bioinspired Engineering Design: Fall 2013
Time and Place: T and TH; 12:45-2:00; THOM 107A

Instructor Information: Dr. Daniel A. McAdams, Office ENPH 411, Office Phone: 862-7834, email: dmcadams@tamu.edu, Office Hours: Tuesday and Thursday 2:00-3:00, walk ins, and appointments.

Catalog Description: Credit 3. This course covers the current state of the art in bioninspired engineering design. Currently, there are primarily five schools of thought on how to effectively practice bionispired engineering design: directed, engineering analysis, case study, TRIZ, and, function based. After a short summary of basic engineering design methods, each of these five topics will be covered through lecture, review and discussion of current literature, and in class exercises. Following the coverage of each topic, a conceptual design exercise will be performed using the most recently discussed method. Course goals include an overall enhanced concept generation potential through the use of bioinspired design, the ability to use current state of the art methods in bioinspired design, and the ability to view nature's solutions to different problems from an engineering perspective.

Perquisite: Junior classification in Engineering.

Crediting Grades: Course grades are assigned as follows: 90%-100% = A: 80%-89%=B; 70%-79%=C; 60%-69%=D; less than 60% = F.

Grade Weights: HW = 70%; In class participation - 10%; Final Project Report - 20%.

Textbook: Handouts and articles + in class notes
Reference Book: *Biologically Inspired Design: Computational Methods and Tools,* Goel, Ashok K; McAdams, Daniel A; Stone, Robert B. (Eds.)
2014, Springer.

Course Learning Outcomes:
- Increase students' engineering innovation and creativity skill. Increase student's ability to find innovative solutions to problems.
- Improve product design and analysis skills.
- Create the ability to apply engineering methods, including analysis and design methods, to model and understand natural systems.
- Apply directed bioinspired design
- Apply engineering analysis based bioinspired design
- Apply case study based bioinspired design
- Apply TRIZ based bioinspired design
- Apply Function Based bioinspired design including the Ask Nature Taxonomy
- Improve critical thinking skills such that an analysis and evaluation of how methods emerging from the engineering research community are applicable for engineering practice can be clearly articulated.

1

Lectures and Topics:
Week 1: Introduction: BID, Assessment Methods via Active Learning
Week 2: General Design Process: Clarification, Function, Embodiment, etc.
Week 3: Directed BID and Case Studies
Week 4: Case Studies
Week 5: Engineering Analysis based methods
Week 6: Function based methods
Week 7: Function based methods
Week 8:Triz based methods
Week 9:Triz methods
Week 10: Ask Nature Taxonomy and Function
Week 11: Ask Nature Taxonomy and Function
Week 12: Solution Based / Dane
Week 13: Origami Engineering
Week 14: Final Project Presentations

Attendance: Work missed due to absences will only be excused for University-approved activities in accordance with TEXAS A&M UNIVERSITY STUDENT RULES (see http://student-rules.tamu.edu/rule7.htm).

Americans with Disabilities Act (ADA) Policy Statement: The Americans with Disabilities Act (ADA) is a federal anti-discrimination statute that provides comprehensive civil rights protection for persons with disabilities. Among other things, this legislation requires that all students with disabilities be guaranteed a learning environment that provides for reasonable accommodation of their disabilities. If you believe you have a disability requiring an accommodation, please contact Disability Services, in Cain Hall, Room B118 or call 845-1637. For additional information visit http://disability.tamu.edu

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On all course work, assignments, and examinations at Texas A&M University, the following Honor Pledge shall be preprinted and signed by the student:

"On my honor, as an Aggie, I have neither given nor received unauthorized aid on this academic work."

APPENDIX G - CLASS LECTURE MODULES

G1: *BioTRIZ Modules*

Bioinspired Ideation Methods BioTRIZ	**Bioinspired Tools and Methods** • BioTRIZ • Functional Modeling • Engineering-Biology Thesaurus
BioTRIZ • Developed by Vincent at the University at Bath • Based on Altschueller's work on TRIZ (*TIPS*) • Draws design information from hundreds of natural system and organisms rather than only engineered systems	**Similarities to TRIZ** • Uses same inventive principles as TRIZ • Organizes design information into a conflict matrix • Same basic procedure as TRIZ

Key Differences

- Contains information from *biological* solutions to design problems
- Conflict matrix is organized into a 6x6 array rather than the 39x39 matrix for TIPS

Fields of Operation	Substance	Structure	Space	Time	Energy	Information
Substance	13 15 17 20 31 40	1-3 15 24 26	1 5 13 15 31	15 19 27 29 30	3 6 9 25 31 35	3 25 26 1 3 4 15 19 24 25 35
Structure	1 10 15 19	1 15 19 24 34	10	1 2 4	1 2 4	3 15 21 24
Space	3 14 15 25 1 3 15 20 25	2-5 10 15 19	4 5 36 14 17	1 19 29	1 3 4 15 19 3 9 15 20 22	3 15 21 24
Time	38	1-4 6 15 17 19	1-4 7 38	2 3 11 20 26	25 3 5 9 22 25 32	1-3 10 19 23
Energy	1 3 13 14 17 25 31	1 3 5 6 25 35 36 40	1 3 4 15 25	3 10 23 25 35	37	1 3 4 15 16 25
Information	1 6 22	1 3 6 18 22 24 32 34 40	3 20 22 25 33	2 3 9 17 22	1 3 6 22 32	3 10 16 23 25

Adapted from: Vincent, J., et. al, *Biomimetics: Its Practice and Theory,* 2006, Journal of the Royal Society

5

Steps for Using BioTRIZ

1. Find a Design Conflict (from QFD)
2. Translate the Design Conflict into a set of conflicting Generalized Engineering Parameters
3. Find the BioTRIZ Field of Operation that corresponds to each conflicting parameter
4. Use BioTRIZ Conflict Matrix to identify appropriate Generalized Solution Principles
5. Use Generalized Solution Principles to generate ideas
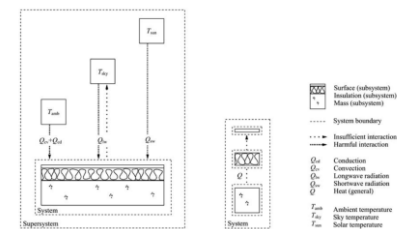
6

Step 1: Example

- Design a roof for hot climates that gets free cooling through radiant coupling with the sky.
- A good building design would cool down (passively) faster than it heats up,
- Conventional insulation prevents this

7

Step 1: Example

- The building (thermal) mass should be coupled to the sky but decoupled from the sun and local air temperature.

8

Step 2: Generalized Engineering Parameters

- Just like for TRIZ, use table 10.7 to find the 39 Generalized Engineering Parameters

GENERATING CONCEPTS

TABLE 10.7. GENERALIZED ENGINEERING PARAMETERS FOR DESCRIBING PRODUCT METRICS

1 Weight of moving object	21 Power
2 Weight of stationary object	22 Energy loss
3 Length of moving object	23 Substance loss
4 Length of stationary object	24 Information loss
5 Area of moving object	25 Waste of time
6 Area of stationary object	26 Quantity of a substance
7 Volume of moving object	27 Reliability
8 Volume of stationary object	28 Accuracy of measurement
9 Velocity	29 Manufacturing precision
10 Force	30 Harmful actions affecting the design object
11 Stress or pressure	31 Harmful actions generated by the design object
12 Shape	32 Manufacturability
13 Stability of object's composition	33 User friendliness
14 Strength	34 Repairability
15 Duration of action generalized by moving object	35 Flexibility
16 Duration of action generalized by stationary object	36 Complexity of design object
17 Temperature	37 Difficulty to control or measure
18 Brightness	38 Level of automation
19 Energy consumed by moving object	39 Productivity
20 Energy consumed by stationary object	

9

Step 2: Example

Energy Transfer with Sky

Energy Transfer with Air and Sun

Compare to table 10.7

Energy Loss

(Parameter 22)

Energy Loss

Parameter(22)

10

Step 3: BioTRIZ Parameters

- The engineering parameters from TIPS are grouped into 6 fields of operation
- Not all engineering parameters from TIPS are used in BioTRIZ

Substance	Weight of moving and stationary object		Total force
	Loss of Substance		Stress or pressure
	Quantity of Substance		Strength
Structure	Stability of objects composition	Energy	Temperature
	Manufacturing precision		Illumination intensity
	Ease of manufacture		Use of energy by moving and stationary object
	Device Complexity		Power
Space	Length of moving and stationary object		Loss of energy
	Area of moving and stationary object		Loss of information
	Volume of moving object		Reliability
	Volume of stationary object		Measurement accuracy
	Shape		generated harmful factors
Time	Speed	Information	Ease of operation and repair
	Duration of action of moving and stationary object		Adaptability or versatility
	Loss of time		Difficulty of detecting and measuring
	Productivity		

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Step 3: Example

- The fields for our conflicting parameters are Energy and Energy

Substance	Weight of moving and stationary object		Total force
	Loss of Substance		Stress or pressure
	Quantity of Substance		Strength
Structure	Stability of objects composition	Energy	Temperature
	Manufacturing precision		Illumination intensity
	Ease of manufacture		Use of energy by moving and stationary object
	Device Complexity		Power
Space	Length of moving and stationary object		Loss of energy
	Area of moving and stationary object		Loss of information
	Volume of moving object		Reliability
	Volume of stationary object		Measurement accuracy
	Shape		generated harmful factors
Time	Speed	Information	Ease of operation and repair
	Duration of action of moving and stationary object		Adaptability or versatility
	Loss of time		Difficulty of detecting and measuring
	Productivity		

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Step 4: Conflict Matrix

Fields of Operation	Substance	Structure	Space	Time	Energy	Information
Substance	13 15 17 20 31 40	1-3 15 24 26	1 5 13 15 31	15 19 27 29 30	3 6 9 25 31 35	3 25 26
Structure	1 10 15 19	1 15 19 24 34	10	1 2 4	1 2 4	1 3 4 15 19 24 25 35
Space	3 14 15 25	2-5 10 15 19	4 5 36 14 17	1 19 29	1 3 4 15 19	3 15 21 24
Time	1 3 15 20 25 38	1-4 6 15 17 19	1-4 7 38	2 3 11 20 26	3 9 15 20 22 25	1-3 10 19 23
Energy	1 3 13 14 17 25 31	1 3 5 6 25 35 36 40	1 3 4 15 25	3 10 23 25 35	3 5 9 22 25 32 37	1 3 4 15 16 25
Information	1 6 22	1 3 6 18 22 24 32 34 40	3 20 22 25 33	2 3 9 17 22	1 3 6 22 32	3 10 16 23 25

Adapted from: Vincent, J., et. al, *Biomimetics: Its Practice and Theory*, 2006, Journal of the Royal Society

Each entry in the matrix corresponds to one of Altscheuller's inventive principles (Tables 10.8 & 10.9)

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TABLE 10.8. TIPS' DESIGN PRINCIPLES (1–20) TO SOLVE ENGINEERING CONFLICTS

1	Principle of segmentation.	Divide the object into independent parts that are easy to disassemble, increase the degree of segmentation as much as possible.
2	Principle of removal.	Remove either the disturbing part or the necessary part from the object.
3	Principle of local quality.	Change the object's or environment's structure from homogeneous to non-homogeneous. Let different parts of the object carry different functions.
4	Principle of asymmetry.	Make object asymmetrical, or increase asymmetry.
5	Principle of joining.	Merge homogeneous objects or those intended for contiguous operations.
6	Principle of universality.	Let one object perform several different functions. Remove redundant objects.
7	The nesting principle.	Place one object inside another, which in turn is placed in a third, etc., or, let an object pass through a cavity into another.
8	Principle of counterweight.	Attach an object with lifting power or use the interactions with the environment, e.g., aerodynamic lift.
9	Principle of preliminary counteraction.	Perform a counter-action to the desired action before the desired action is performed.
10	Principle of preliminary action.	Perform the required action before it is needed, or set up the objects such that they can perform their action immediately when required.
11	Principle of introducing protection in advance.	Compensate for the low reliability of an object by introducing protections against accidents before the action is performed.
12	Principle of equipotentiality.	Change the conditions such that the object does not need to be moved up or down in the potential field.
13	Principle of opposite solution.	Implement the opposite action of what is specified. Make a moving part fixed and the fixed part mobile. Turn the object upside down.
14	Principle of spheroidality.	Switch from linear to curvilinear paths, from flat to spherical surfaces, etc. Make use of rollers, ball bearings, spirals. Switch from direct to rotating motion. Use centrifugal force.
15	Principle of dynamism.	Make the object or environment able to change to become optimal at any stage of work. Make the object consist of parts that can move relative to each other. If the object is fixed, make it movable.
16	Principle of partial or excessive action.	If 100% is unobtainable, try for slightly less or slightly more.
17	Principle of moving into a new dimension.	Increase the object's degree of freedom. Use a multi-layered assembly instead of a single layer. Incline the object or turn it on its side. Use the other side of an area.
18	Use of mechanical vibrations.	Make the object vibrate. Increase the frequency of vibration. Use resonance, piezovibrations, ultrasonic, or electromagnetic vibrations.
19	Principle of periodic action.	Use periodic or pulsed actions, change periodicity. Use pauses between impulses to change the effect.
20	Principle of uninterrupted useful effect.	Keep all parts of the object constantly operating at full power. Remove test or set-up runs.

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Reproduced from: Otto, K., Wood, K., *Product Design: Techniques in Reverse Engineering and New Product Development*, 2001

TABLE 10.9. TIPS' DESIGN PRINCIPLES (21–40) TO SOLVE ENGINEERING CONFLICTS

21	Principle of rushing through.	Carry out a process or individual stages of a process at high speed.
22	Principle of turning harm into good.	Use harmful factor to obtain a positive effect. Remove a harmful factor by combining it with other harmful factors. Strengthen a harmful factor to the extent where it ceases to be harmful.
23	The feedback principle.	Introduce feedback. If there already is feedback, change it.
24	The go between principle.	Use an intermediary object to transfer or transmit the action. Merge the object temporarily with another object that can be easily taken away.
25	The self service principle.	The object should service and repair itself. Use waste products from the object to produce the desired actions.
26	The copying principle.	Instead of unavailable, complicated or fragile objects, use a simplified cheap copy. Replace an object by its optical copy, make use of scale effects. If visible copies are used, switch to infra-red or ultra-violet copies.
27	Cheap short life instead of expensive longevity.	Replace an expensive object that has long life with many cheap objects having shorter life.
28	Replacement of a mechanical pattern.	Replace a mechanical pattern by an optical, acoustical or odor pattern. Use electrical, magnetic or electromagnetic fields to interact with the object. Switch from fixed to movable fields changing over time. Go from unstructured to structured fields.
29	Use of pneumatic or hydraulic solutions.	Use gaseous or liquid parts of an object instead of solid parts.
30	Using flexible membranes and fine membranes.	
31	Using porous materials.	Make the object porous or use porous elements, e.g., inserts, covers, etc. If the object is already porous, fill the pores in advance with some useful substance.
32	The principle of using color.	Change the color or translucency of an object or its surroundings. Use colored additives to observe certain objects or processes. If such additives are already used, employ luminescence traces.
33	The principle of homogeneity.	Interacting objects should be made of the same material, or material with identical properties.
34	The principle of discarding and regenerating parts.	Once a part has fulfilled its purpose and is no longer necessary, it should automatically be discarded or disappear, e.g., evaporate, or change its shape. Parts that become useful after a while should be automatically generated.
35	Changing the aggregate state of an object.	Change state, e.g., solid to liquid. Use pseudostates and intermediary states, e.g., elastic solid bodies.
36	Use of phase changes.	Use phenomena occurring in phase changes, e.g., use of volume changes, heat dissipation, etc.
37	Application of thermal expansion.	Use expansion or contraction of materials by heat. Use materials with different thermal expansion coefficients.
38	Using strong oxidation agents.	Replace air with enriched air or replace enriched air with oxygen. Treat the air or oxygen with ionizing radiation. Use ionized oxygen. Use ozone.
39	Using an inert atmosphere.	Replace the normal environment with an inert one or a vacuum.
40	Using composite materials.	Switch from homogeneous materials to composites.

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Reproduced from: Otto, K., Wood, K., *Product Design: Techniques in Reverse Engineering and New Product Development*, 2001

Step 4: Example

Fields of Operation	Substance	Structure	Space	Time	Energy	Information
Substance	13 15 17 20 31 40	1-3 15 24 26	1 5 13 15 31	15 19 27 29 30	3 6 9 25 31 35	3 25 26
Structure	1 10 15 19	1 15 19 24 34	10	1 2 4	1 2 4	1 3 4 15 19 24 25 35
Space	3 14 15 25	2-5 10 15 19	4 5 36 14 17	1 19 29	1 3 4 15 19	3 15 21 24
Time	1 3 15 20 25 38	1-4 6 15 17 19	1-4 7 38	2 3 11 20 26	3 9 15 20 22 25	1-3 10 19 23
Energy	1 3 13 14 17 25 31	1 3 5 6 25 35 36 40	1 3 4 15 25	3 10 23 25 35	3 5 9 22 25 32 37	1 3 4 15 16 25
Information	1 6 22	1 3 6 18 22 24 32 34 40	3 20 22 25 33	2 3 9 17 22	1 3 6 22 32	3 10 16 23 25

Adapted from: Vincent, J., et. al, *Biomimetics: Its Practice and Theory*, 2006, Journal of the Royal Society

The inventive principles nature uses to resolve similar conflicts are: 3 5 9 22 25 32 37

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Step 4: Example

- 3. Local Quality
- 5. Merging/Consolidation
- 9. Preliminary anti-action, prestressing
- 22. Blessing in disguise, turn harm into benefit
- 25. Self-Service
- 32. The principle of using color
- 37. Application of thermal expansion

Step 5: Example

- We need to choose one or more IP and generate some solutions

- Consider IP 3: Local Quality

Step 5: Example

- Change the insulation from uniform to non uniform.
- Create "empty" vertical pathways with a view of the sky.
- A honeycomb structure might allow for air to stagnate during radiation cooling to form an infrared transparent insulator
- Perhaps Infrared fiber optics would let long wave radiation pass

Step 5: Example
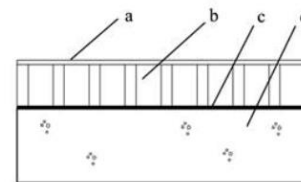
(a) **Shortware reflector / longwave transmitter / convection guard** - e.g. thin white tile

(b) **Honeycomb** – insulates from ambient heat gain, but allows longwave radiation to pass

(c) **Radiator** - e.g. concrete surface painter black

(d) **Thermal mass** - e.g. concrete

Step 5: Example

- Computational analysis (and associated assumptions) suggest that such a roof would keep a building 4.5 C colder over the course of a year in Riyadh.
- This example taken from
  - Salmaan Craig, David Harrison, Andrew Cripps, and Daniel Knott, "BioTRIZ Suggests Radiative Cooling of Buildings Can Be Done Passively by Changing the Structure of Roof Insulation to Let Longwave Infrared Pass" Journal of Bionic Engineering 5 (2008) 55–66

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Steps for Using BioTRIZ

1. Find a Design Conflict (from QFD)
2. Translate the Design Conflict into a set of conflicting Generalized Engineering Parameters
3. Find the fields of operation that corresponds to each conflicting parameter
4. Use BioTRIZ matrix to identify appropriate Generalized Solution Principles
5. Use Generalized Solution Principles to generate ideas

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Comparing BioTRIZ and TRIZ

- Engineering and biological systems often use the different principles to resolve a design conflict
- Compare the BioTRIZ matrix (bottom) and the condensed TRIZ matrix (top) – Common entries are highlighted

Reproduced from: Vincent, J., et. al, *Biomimetics: Its Practice and Theory,* 2006, Journal of the Royal Society

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Comparing BioTRIZ and TRIZ

- Using BioTRIZ to find IPs to resolve our example conflict we got: 3 5 9 22 25 32 37

- If we used the condensed TRIZ matrix to find IPs, we get: 14 19 21 25 36 37 38

- Only IPs 25 and 37 are shared. We would likely arrive at a very different solution using TRIZ.

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Bioinspired Ideation Methods

Bio-keyword searches and
Functional Modeling

Finding Biological Inspiration

- Need a way to make biology textbooks, literature, etc. accessible to engineers
- Bio-thesaurus can help find biology analogs to engineering terms

Bio-Thesaurus

- The Functional Basis has been shown to be adequate for modeling mechanical and electrical systems
- The Functional Basis can also be used to model biological systems
- The Bio-Thesaurus provides biologically significant keywords that correspond to terms in the Functional Basis

Class	Secondary	Tertiary	Biological Function Correspondents
Branch	Separate		Bleaching, meiosis, *react*, flower, replicate, mitosis, segment, *electrophoresis*, dialysis, denature, free, detach, release
		Divide	Division, prophase, metaphase, anaphase, cleave, cytokinesis
		Remove	Deoxygenate, filtrate, deamination, liberate, expulsion, evacuate
	Distribute		Circulate, diffusion, exchange, disperse, scatter, spread, spray

Class	Secondary	Tertiary	Biological Function Correspondents
Branch	Separate		Bleaching, meiosis, *react*, flower, replicate, mitosis, segment, *electrophoresis*, dialysis, denature, free, detach, release
		Divide	Division, prophase, metaphase, anaphase, cleave, cytokinesis
		Remove	Deoxygenate, filtrate, deamination, liberate, expulsion, evacuate
	Distribute		Circulate, diffusion, exchange, disperse, scatter, spread, spray
Channel	Import		*Absorb*, attract, consume, inhale, intake,
	Export		*Bind*, block, breakdown, excrete, inactivate, repel
	Transfer		Migrate
		Transport	Circulate, conduct, diffuse, pump, shift, displace, fly, swim, jump, bounce
		Transmit	Communicate, *transducr*
	Guide		Orient, position, slide, tunnel
		Translate	*Synthesize*, transcribe
		Rotate	Oscillate, spin, turn, swivel, roll
		Allow DOF	Articulate
Connect	Couple		Recombination, mate, build, phosphorylate, bond, synthesis, latch, lock, extend, link, overlap, *stretch*
		Join	*Bind*, adhere, bond, fuse
		Link	Clamp, *activate, bind,* project
	Mix		Blend, *contract*, exchange, fragment
Control Magnitude	Actuate		*Activate*, induce, trigger
	Regulate		*Electrophoresis*, gate, organogenesis, respire, preserve, sustain, preserve, remain, stabilize, maintain
		Increase	Hyperpolarize, *pinocytosis, grow*, expand, multiply
		Decrease	Compress, coil, divide, fold, shorten, *wrap*
	Change		*Pinocytosis, degrade*, alter, *bind*, catalyze, *contract*, hydrolysis, inflammation of, twist, *mutate*, radiate, charged, slip, acclimatize, alternate, fluctuate
		Decrement	Decarboxylation, *constrict*
		Shape	Elongate, *stretch*, attach, *spread*
		Condition	Osmosis, *constrict*
	Stop		Clog, extinguish, halt, interphase, seal, suspend
		Prevent	Constrain, obstruct
		Inhibit	Cover, destroy, inhibit, repress, surround
Convert	Convert		Polymerize, *synthesize*, burn, gluconeogenesis, metabolize, *grow, transduction*, fermentation, glycolysis, hydrolyze, hydrolysis, respiration, ionize, decompose, *degrade, develop, mutate, photosynthesize*
Provision	Store		Conserve, *hold, convert*, deposit, *photosynthesize*
		Contain	*Absorb*
		Collect	*Absorb*, catch, breakdown, concentrate, digest, reduce
	Supply		Feed, lactate
Signal	Sense		Locate, see, smell
		Detect	
		Measure	Observe, monitor, gauge, watch
	Indicate		Fluoresce, communicate, *react*, mark
	Process		Learn
Support			*Develop, wrap*
	Stabilize		Homeostasis, cling, *hold, bind, connect*
	Position		Envelope
			Overall increasing degree of specification →

Class	Secondary	Tertiary	Biological Flow Correspondents
Material	Human		Being, body
	Gas		Oxygen, nitrogen, chlorine
	Liquid		Acid, chemical, water, concentration, solute, cytokinin, pyruvate, fluid, nicotine, auxin, opium, glycerol, carotenoid, plasma, repressor
	Solid	Object	body, substrate, microfilament, microtubules, structure, DNA, motor, fiber, chain, matter, nucleus, organ, tissue, muscle, ligand, cilia, grp, flagella, RNA, tRNA, mRNA, tube, vein, heart, plant, ribosome, seed, apoplast, endotherm, ectotherm, stem, kidney, egg, ovaries, leaves, embryo, bacteria, gene, oncogene, cryptochromes, urea, chloroplasts, carbon, glucagons, adipose, angiosperm, meristems, mineral, stoma, shoot, capillary, receptors, hair, bone, tendon, neuron, photoreceptors, mechanoreceptors, host, chromosome, algae, petiole, promoter, phyla, lysosome, introns, exon, archaea, allele, cone, strand, centriole, spore, euryarchaeota, sporangia, zygote, sulfur, ctenophore, lipoproteins, stp, nephron, hyphae, plasmodesma, angiosperms, conifer, plasmid, xylem, pigment, sperm, hippocampus, somite, parathormone
		Composite	Molecule, enzyme, virus, phloem, ribozyme, prokaryote, macromolecule, polymerase, nucleotide, polypeptide, organelle, symplast, mesophyll, brood, codon, messenger
	Mixture	Gas-gas	Air, dioxide
		Liquid-liquid	Solution, poison, slime, blood, urine, cytoplasm, peptide, hormone, melatonin, thyroxine, calcitonin, thyrotropin, estrogen, somatostatin, cortisol, glucagons, adrenocorticotropin, testosterone
		Solid-solid	Adenosine, glial, glomerulus, blastula, monosaccharides, membrane mulch, phosphate, gibberellin, plastids
		Solid-Liquid	Lipids, glutamic acid, synapse, peptidoglycan, cell, centrosomes, phytochrome, retina, insulin, protein, hemoglobin
Signal	Status		Change, variation, lateral, allosteric, swelling, catalyzes, translation, exposed, active, separated, cycle, form, reaction, redox, deficiency, saturated, diffusion, broken, vicariant, hybridization, orientation, resting, cues, magnetic, volume, under, organized, fruiting, fatty, anaphase, metaphase, conjugation, osmolarity, senescence
		Auditory	Sound
		Olfactory	Smell
		Tactile	Cold, pain
		Taste	Gustation
		Visual	Length, shortened, long, dark, full, double
	Control		Place, inhibit, release, excretory, development, match, inducer, digest, integrate, translation, transduction, equilibrium, grown, splicing, capture, distributed, prophase, phosphorylation
		Analog	Flowering, center, synthesis, binding, photosynthesis
		Discrete	Flower, translocation
Energy	Human		
	Acoustic		Echolocation, waves
	Chemical		Calorie, metabolism, glucose, glycogen, ligand, nutrient, starch, fuel, sugar, mitochondria, synthesis, o, lipids, glucose, gibberellins
	Electrical		Electron, potential, q, feedback, charge, fields
	Electromagnetic	Optical	Light, infrared
		Solar	Light, sun, ultraviolet
	Hydraulic		Pressure, osmosis, osmoregulation
	Magnetic		Gravity, fields, waves
	Mechanical		Muscle, pressure, tension, removing, stretch, depress
		Rotational	
		Translational	
	Pneumatic		Pressure
	Thermal		Temperature, heat, infrared
			Overall increasing degree of specification →

Using the Bio-Thesaurus

1. Develop a functional model of the engineering system
2. Select a function within the function structure for bioinspired ideation
3. A. Translate function and flow in functional basis to biological keywords

   B. Find biologically significant keywords that correspond to the selected function

4. Use search engines to find biological systems that can inspire new solutions

   A. Bio Search: http://www.designengineeringlab.org/delabsite/BioSearch.html

   B. AskNature.org

   C. Google

Step 1: Nerf Dart Gun Example

- *Develop a functional model of the engineering system using the Functional Basis*
- Example of the Nerf Dart Gun
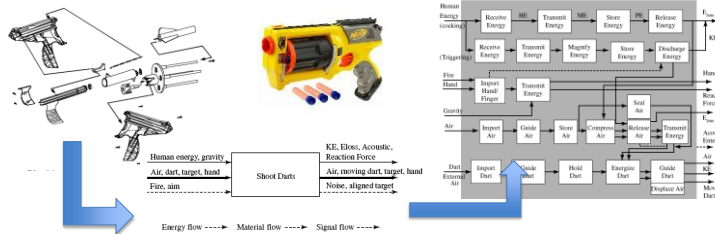
▼ Figure 5.19.
Black box of a toy dart gun. Assumes that dart enters the system.

Step 1: Functional Model
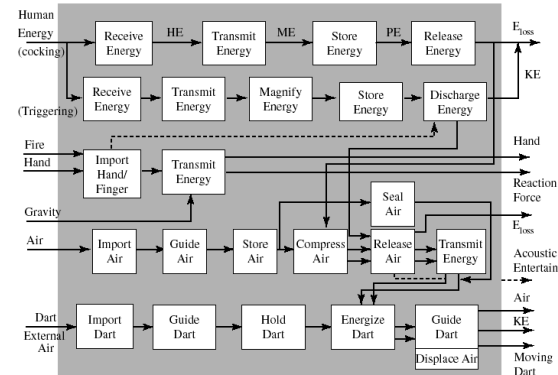
Step 2: Select a Function

Select a function within the function structure for bioinspired ideation
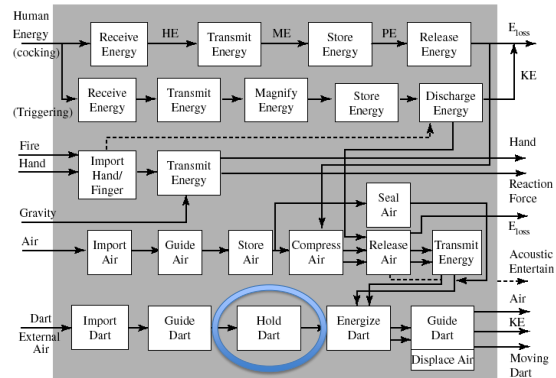
Step 3a: Translate to Biological Function: "Hold Dart" to ?????

- Because our function structure is not in the Functional Basis, we need to select appropriate terms before using the thesaurus

- "Hold" function translates to "Stabilize"

Step 3a: Translate to Biological Function: "Hold Dart" to ?????

- Because our function structure is not in the Functional Basis, we need to select appropriate terms before using the thesaurus
- "Dart" flow translates to "Object"
- Final Result is "Hold Dart" translates to "Stabilize Object"

Step 3b: *Find biologically significant keywords that correspond to the selected function*

- Finding useful search terms requires some intuition. A cursory knowledge of what the biological terms mean can help.
- Let's search for "algae cling"

Step 4: Use search engines- Bio Search

- http://www.designengineeringlab.org/delabsite/BioSearch.html
- Demo

Step 4: Use search engines- Ask Nature

- Asknature.org
  - Use search and browse

Step 4: Use search engines- Google Scholar, Library

Enter the biologically significant keywords, "algae cling" into a common search engine to find biological systems that can inspire new solutions

- Learn to love Google Scholar!

- A&M Library Article search tab. A&M will get you almost any article.

Seems promising
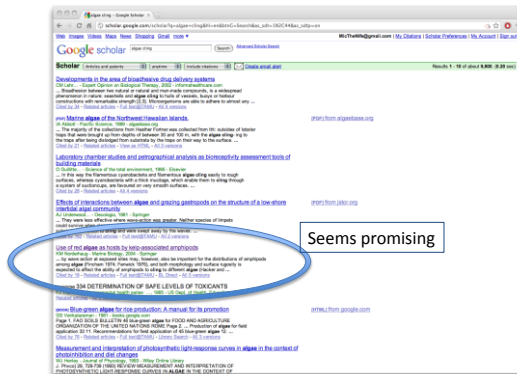
Step 4: Google Scholar Result

- A quick look at the abstract shows that this paper isn't really what we need. However, the conclusion cites a paper that discuss how amphipods (freshwater shrimp) cling to algae. These papers may be more relevant to our problem. Check the references, find the paper

Dislodgement by wave action at exposed sites may, however, also be important for the distributions of amphipods among algae (Fincham 1974; Fenwick 1976), and both morphology and surface rugosity is expected to affect the ability of amphipods to cling to different algae (Hacker and Steneck 1990). Caprellids use their pereopods to hold on to the substratum, and P. elongata may be suitable for C. septentrionalis to cling to (cf. Guerra-Garcia and García-Go´mez 2002), while P. gunneri may have been more suitable for the tube-building A. rubricata and J. falcata. The smooth surface of P. palmata may be difficult to cling to.

Reproduced from: Noderhaug, K.M., *Use of red algae as hosts by kelp-associated amphipods,* 2004, Marine Biology

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Step 4: Google Scholar Result- Look up Citation

- This passage from Hacker and Steneck is much more relevant to the problem.

- Can we conceptualize a novel dart holding mechanism based on the behavior of amphipods?

"Gammarellus is highly tenacious, and clings to algal fronds by encompassing them with their appendages (Bousfield 1973). Generally they swim into clumps of algae, retreat into the interstitial spaces, and perch vertically on a branch or filament in such a way that their antennae face out towards the open water. If the algal thallus is large, such as with foliose or sheet-like morphologies, amphipods are generally found on the folds near the holdfast, or encompassing the edges of the algae. They may not be able to functionally grasp the planar surface of the alga unless they can puncture the thallus with their appendages."

In-Class Activity

- Sketch or describe at least 2 dart holding mechanisms using this passage for inspiration

"Gammarellus is highly tenacious, and clings to algal fronds by encompassing them with their appendages (Bousfield 1973). Generally they swim into clumps of algae, retreat into the interstitial spaces, and perch vertically on a branch or filament in such a way that their antennae face out towards the open water. If the algal thallus is large, such as with foliose or sheet-like morphologies, amphipods are generally found on the folds near the holdfast, or encompassing the edges of the algae. They may not be able to functionally grasp the planar surface of the alga unless they can puncture the thallus with their appendages."

Tips for finding useful information using Bio-Thesaurus and Biology Literature

- Abstract, Introduction, Conclusion. Read these first, then decide whether to read the rest.

- Don't be overwhelmed by unfamiliar language! Lots of terms you'll see in biology literature aren't relevant to identifying core functionality.

- Keep a dictionary handy (or dictionary.com) for when a new term seems important.

- The paper you find may reference a more helpful paper. Check the references.

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APPENDIX H   - HOMEWORK INSTRUCTIONS

Directed, Case Study
- 50 minute individual activity
- Aim to generate as many ideas as possible
- Can do longer for extra credit, but draw a line across the page at the 50 minute point
- Sketch and note all designs even if they're not technically feasible
- Maximize quality and variety
- Sketch one solution per page
- **Afterwards, mark any analogies you used to solve this problem (bioinspired or not)**
  - o **Write a description or circle parts of the sketches or both**

AskNature
- 50 minute individual activity
- Aim to generate as many ideas as possible
- Can do longer for extra credit, but draw a line across the page at the 50 minute point
- Sketch and note all designs even if they're not technically feasible
- **Note search terms or browsing terms**
- Maximize quality and variety
- Sketch one solution per page
- **Afterwards, mark any analogies you used to solve this problem (bioinspired or not)**
  - o **Write a description or circle parts of the sketches or both**

BioKeyword Search
- Create a function structure first
- Then spend 50 minutes generating ideas
- Aim to generate as many ideas as possible
- Can do longer for extra credit, but draw a line across the page at the 50 minute point
- Sketch and note all designs even if they're not technically feasible
- **Note search terms and literature**
- Maximize quality and variety
- Sketch one solution per page
- **Afterwards, mark any analogies you used to solve this problem (bioinspired or not)**
  - o **Write a description or circle parts of the sketches or both**

BioTRIZ
- 50 minute individual activity
- **Note the conflicts and principles used**
- Aim to generate as many ideas as possible
- Can do longer for extra credit, but draw a line across the page at the 50 minute point
- Sketch and note all designs even if they're not technically feasible
- Maximize quality and variety
- Sketch one solution per page
- **Afterwards, mark IF you used analogies to solve this problem**
  - o **BioTRIZ creates bioinspired solutions without the designer actively looking for natural analogies**
  - o **Note the analogy used**
  - o **Write a description or circle parts of the sketches or both**

APPENDIX I   – GROUP PROJECT PROBLEM STATEMENTS

Team 1

There is a need to develop an inexpensive, reliable, easy to clean, and compact tool that will help reduce the meal preparation time. This tool must facilitate the task of dicing vegetables. It should not require electrical power to operate and major components of the device should be designed to allow for easy repair or replacement when needed.

Team 2

Through observation of a subject golfer, it became apparent that the golf balls are hard to track after being hit. For a golf swing, the golfer swings the club and keeps their head down until the swing follow through in order to ensure a solid strike. By the time the golfer raises their head to find the ball, it climbs high into the sky and is easily lost in the clouds.

There is a need for a way to track the position of a golf ball while it is in flight. The system must not disrupt the flight path of the ball and must fit within rules and regulations of the PGA Tour. The system will need to be made easily portable and fit within a golf bag. It must have the ability to be mass produced in order to lower cost and to serve as many golfers as possible.

Team 3

There is a need to design a new deployable entertainment center for tailgating that is lightweight, simple, and quick for the user to set up and repack. This new entertainment center must provide a comfortable setting by providing seating and maintaining a satisfactory temperature range for users within its boundary. However, it must protect the items within and be sufficiently compact when in travel mode. Also, the center must also provide necessary appropriate apparatuses for users to prepare, maintain, and serve food and refreshments as well as provide entertainment. The entertainment center must be affordable for the zealous tailgating fan. This new deployable entertainment system should not impede the spirit of traditional tailgating while reducing the set up and repack time for the user.

Team 4

There is a need for a device that reduces ambient and incoming noise to levels appropriate for such "quiet" activities as studying or sleeping. This device should have portable characteristics, but should also have the potential to be a permanent fixture in such living spaces as an apartment or dormitory. The target audience for such a device is primarily a collegiate student body, and as such expense is a primary factor in its design. The device must also not be too difficult to setup or use, and must be kept to a suitable size as could fit easily into a typical dorm room.

Team 5

Camping during the summer in warm climates can be miserable and a deterrent to leave the A/C. It can be nearly impossible to fall asleep in a hot and stuffy tenet and it is even worse waking up in the middle of the night covered in sweat. A problem exists in this situation: campers in warm climates that are outside are exposed to uncomfortably hot temperatures and have no easy way to escape the hot temperatures. This leaves the campers with comfort issues when it comes to sleeping and staying in a tent. Design a widget or system to continually cool a person or group of persons when camping outdoors. This solution must be easily transportable, sized to fin into a backpack, and require no external electrical power source.

Team 6

There exists a need for a sleeping pad that makes it easier for backpackers in the wilderness to fall asleep and keeps them comfortable throughout the night. Comfort for a backpacker depends on two important things; being cushioned from the hard ground as well as providing insulation from cold ground which typically acts as a heat sink in the night drawing warmth from a backpackers body. While backpacking, the weight of the equipment is extremely important and can't be overlooked. It is not unusual for backpackers to add another mile per day per pound of equipment which can be taken out of the backpack. It is also important for the pad not to be bulky. The size of a sleeping pad is important because it must fit into a backpacker's backpack which may be very full from other gear and food. Finally the pad must be easy to set up and priced appropriately. The primary focus will be on limiting the weight of the pad while improving comfort.

Team 7

There is a need for a device that can assist someone in transporting groceries from his vehicle to his home.

Design requirements:

- Can transport at least 20 grocery bags full of groceries
- Can transport all groceries in one trip
- Is a portable device that can fit in car trunks
- Is able to be operated by average person
- Is cost effective

Team 8

Dorm Residents have no time to clean dishes due to busy school schedules. Due to the lack of time, dishes pile up in the sink for days until someone is capable of cleaning them or at least putting them in the dishwasher to be cleaned. But even after being cleaned they may not find their home in a cabinet for weeks and may just sit in the dishwasher. Finding clean dishes to cook with then becomes problematic. Since each guy has a different schedule, there must be a way to have clean dishes at any time of the day.

There is a need to keep dishes clean throughout the course of a week for the entire school year with limited or no human action. The solution must be low cost in nature & provide results quickly. Not only does it need to work quickly to keep up with five hungry guys, but it also must be easily and quickly implemented for the remainder of the school year.

Team 9

Leaving a car parked in the sun during hot southern months causes the inside of the car to reach hazardous temperatures. There is a need to decrease the temperature inside the parked car during these months

Team 10

The average Texas A&M student endures hot, unpleasant weather on a daily basis. Walking across campus with a heavy backpack can cause the student to feel more hot and sweaty. This can also cause the student to be uncomfortable in their classes, as embarrassing sweat marks on their back might appear. The source of this problem is the heat being trapped between the backpack and the body of the student. The contact of the backpack against the back of the student causes the heating of the body, ultimately causing uncomfortable and sweaty students. What is needed is to design a way for backpack wearers to keep their back cool. This backpack needs to be a cost effective, lightweight tool that can easily be implemented on the backpack that will keep them cool and dry. The backpack itself will mimic a standard backpack used today in that it will have straps around the shoulder to help in the ease of carrying, be comfortable on the back, and lightweight. The solution cannot use any devices that will be heavy and a burden to carry around. The design must be able to store as much as a standard backpack. It must also be waterproof, as backpack wearers will experience rain on occasion and the backpack will need to be able to safely store the items inside.

Team 11
The link between West campus and Central campus at Texas A&M University has been called one of the most dangerous places for pedestrians. Due to its design, bikers, long boarders, as well as pedestrians are all funneled into a blind corner situation that has had disastrous outcomes in the past. Not only does this blind corner obstruct the view of individuals, but it also combines three opposing flows of traffic into one. Combine these opposing flows with the fact that this area exists at the bottom of a hill, and high speed collisions are not only possible, but actually quite likely. There is a great need on campus to protect students from bike crashes on campus. Once place in particular has the greatest need since there are bike crashes there almost daily. This place is located right near the Pickard underpass going to the Rec. A functional need statement was developed to be to design a convenient and cost effective system to prevent and/or lessen the severity and/or frequency of bicycle on bicycle, bicycle on pedestrian collisions, and single bicycle accidents.

APPENDIX J – FINAL REPORT AND PRESENTATION

INSTRUCTIONS

Final Project: Semester Team Project Concept via Various Bioinspired Concept Generation Methods
The written report and presentation are graded as one final HW.
General Format and Outline:

Title
Team Member Names
Executive Summary
1. Background and Introduction
2. Problem Clarification (ethnographic study and early semester problem clarification go here)
3. Concepts Generated Using Bioinspired Design Methods
>   **3.1 Directed**
>   **3.2 Case study**
>   **3.3 Asknature**
>   **3.4 Biotriz**
>   **3.5 Function Based Keyword Search**
>   Use the function based and bio keyword design method to generate a solution concept or concepts.
>   - Create a black box functional model of the design problem
>   - Create a detailed functional model for the problem
>   - Using either the black box function or an "important" function from your model, search the biological data base.
>   - Review the results.
>   - From this, do your best to develop a design solution for the problem.
>   - Include in your HW submission, the passage that "sparked" an idea.
>   - Sketch out your solution etc.
>   - Also, be sure to include any discussion or critique of the applicability of the method in the slides.
>   - Identify and properly reference any additional material you looked up to help you understand the system, entity, etc.
>   - Generate your solution. Include sketches, descriptions, etc.
>   - Categorize your inspirational system and solution according to the bioinspired technology tree
>   - Identify and describe the key analogies used in your solution

4. Discussion, Comparison, and Critique of Methods
5. Detailed Presentation and Refinement of the Best Concept
>   Take your best concept, refine it as much as you can. Identify what "method" it came from, including "none" is that is the case.

6. Summary and Conclusions

PRESENTATION
Create a 12 minutes presentation of this report. You will present it as a team at a time yet to be scheduled.

APPENDIX K   - METHOD USEFULNESS SELECTED RESPONSES

BioTRIZ
o *"The BioTRIZ are was pretty useful, because there were so many different options and dimenstions to do"*
o *"The BioTRIZ method was most useful, it was the most user friendly and gave better results than the rest"*
o *"I liked the Bio-TRIZ method. This method required more thought on analyzing your actual problem. This was useful for finding a solution and looking at the problem in a different manner"*
o *"BioTRIZ – was a great starting point. Allowed me to have multiple ideas to branch from instead of being fixated or stuck with my current knowledge in order to start an idea.*
o *"The method is found the most useful was BioTRIZ. This is because biotriz does not suggest any one particular solution but simply directs you into looking at possible ways of solving the problem while still leaving plenty of room for creativity."*
o *"...The other strategies such as BioTRIZ would help with how to solve the problem but not necessarily point to nature...."*

AskNature
o *"ASK Nature - Provided me with a plethora of ideas for solutions to rather specific problems and/or design criteria"*
o *"AskNature – was a very good resource. It was organized and easy to find inspirational examples"*
o *"I liked the Ask Nature method because it was a relatively large database and an efficient method."*
o *""Personally my favorite method was asknature. I liked the two main parts: a branching-logic problem statement and examples for each one. For example: you could find whichever specific strategy most applied to your problem and then subsequently find examples for each. Even if the strategy did not match exactly what you wanted, usually the examples are broad and numerous enough that something would help you out..."*

Bio-Keyword
o *"Functional modeling - breakdown of import functions then know what to focus/design. Biokeywords - takes time but lots of function words and summary words than can spark ideas pretty easy."*
o *"Functional Modeling – I found this method to be very useful. It helped me to think of the design problem in a broader perspective. Also, it allowed me to see certain aspects of the design problem that I wouldn't have been able to see otherwise."*
o *"...And the keyword search and case studies were so broad that they provided no method for solving the problem, only a large number of superfluous examples."*

APPENDIX L – PROBLEM EQUIVALENCY STUDY MATERIAL

L1: *Blind Cup Packet*

NAME:_____   **MEEN 489 Fall 2014**

Instructions

Consider the design problem on the following page. Please read these instructions and the design problem description carefully. You will be given 5 minutes to read this information, followed by 35 minutes to create design solutions to the design problem. Your goal is to create *as many solutions to the problem as possible*, while maximizing quality, novelty and variety.

Use the provided sheets of paper to record your solutions.
Each solution should be on a <u>SEPARATE</u> page.

An adequate solution should include a sketch of the solution, labels of major elements, and a 1-2 sentence description of how the solution works. Please feel free to record any thoughts or comments that you might have used as you developed each solution.

Include any thoughts and comments you desire

Use sketches and labels to present solution ideas

Label 1

Label

Notes
Notes
Notes
Notes
Comments

Describe the solution with 1-2 sentences

First sentence that describes the idea/solution
Second sentence that describes the idea/solution

Page #

Design Problem – Measuring Cup for the Blind

Problem Description:

Design a volume-measuring apparatus for use while cooking by a person who is blind. It needs to be easy to operate and able to be used for both powders and liquids without splattering during operation. The apparatus needs to measure graduated quantities from 1/4 to 2 cups.

Customer Needs:

- Prevent waste of food products.
- Easy to clean.
- Low cost.

No need to use a specific method of design. Just solve the problem as you see fit and provide as many solutions as you can.

Please sketch and note (with words) one design solution per page.

Have you seen or heard about this design problem before today's session? This will NOT affect the credit you receive.

□ YES   □ NO

If yes, did you generate solutions before the session?

□ YES   □ NO

L2: *Peanut Shelling Packet*

NAME:_____   **MEEN 489 Fall 2014**

Instructions

Consider the design problem on the following page. Please read these instructions and the design problem description carefully. You will be given 5 minutes to read this information, followed by 35 minutes to create design solutions to the design problem. Your goal is to create *as many solutions to the problem as possible*, while maximizing quality, novelty and variety.

Use the provided sheets of paper to record your solutions.
Each solution should be on a <u>SEPARATE</u> page.

An adequate solution should include a sketch of the solution, labels of major elements, and a 1-2 sentence description of how the solution works. Please feel free to record any thoughts or comments that you might have used as you developed each solution.

Include any thoughts and comments you desire

Use sketches and labels to present solution ideas

Label 1

Label

Notes
Notes
Notes
Notes
Comments

Describe the solution with 1-2 sentences

First sentence that describes the idea/solution
Second sentence that describes the idea/solution

Page #

148

Recall the **"Peanut Sheller"** problem you recently provided solutions for.

In a few words, please list as many **man made** solutions that you can think of that exists on the market or that you may have already encountered in your experience that could solve this problem.

Please list below, and add quick sketch if necessary. If more space is needed, use extra pages at the end of packet.

Recall the **"Peanut Sheller"** problem you recently provided solutions for.

In a few words, please list as many **biological analogies or biological systems** that you can think of that could solve this problem.

Please list below, and add quick sketch if necessary. If more space is needed, use extra pages at the end of packet.

Recall the **"Blind Measuring Cup"** problem you recently provided solutions for.

In a few words, please list as many **man made** solutions that you can think of that exists on the market or that you may have already encountered in your experience that could solve this problem.

Please list below, and add quick sketch if necessary. If more space is needed, use extra pages at the end of packet.

Recall the **"Blind Measuring Cup"** problem you recently provided solutions for.

In a few words, please list as many **biological analogies or biological systems** that you can think of that could solve this problem.

Please list below, and add quick sketch if necessary. If more space is needed, use extra pages at the end of packet.

L4: *Experimental Script*

Experiment Script   **Day One**   **Blind Measuring Cup**

MEEN 489 Fall 2014   **Date:**   **Time start:**   **Time end:**

Bring:

- ☐ *30 Blind Measuring Cup problem packets*
- ☐ *1 Ream of blank paper.*
- ☐ *Extra pencil or pens*
- ☐ *A stapler*
- ☐ *A timer*

*This will take approximately **45 minutes**: 5 minutes to pass out packets and provide instructions, 5 minutes to read problem, 35minutes to solve problem.*

1- *Hand out Blind Measuring Cup problem (face-down) packet to each student.*

"We are doing an individual activity. Please sketch and describe with words all designs you can think of, even if they are not technically feasible. Aim for as many ideas as possible at as high of quality and variety as possible. Please sketch **one solution per page** and only use one side of the paper. If you need more paper, let us know. Please write your name on the first page."

"Please turn off cell phones. You are not allowed to leave to take calls or talk to each other"
 "Turn over packets, you will have 5 minutes to read the problem, and note if you have heard about this problem ahead of time on page 3"

2- *After 5 minutes*
"You may begin sketching or writing on the blank sheets of paper. You have 35 minutes. Remember to only sketch one design per page"

3- *30 minutes in*
"You have 5 minutes remaining."

4- *35 minutes in*
"Please finish up what you're working on. Make sure you wrote your name on the first page"
"Bring your work to me when you're done and staple any extra pages you may have together"

5- *Collect work*

MEEN 489 Fall 2014   **Date:**   **Time start:**   **Time end:**

Bring:

- ☐ *30 Peanut Sheller problem packets*
- ☐ *1 Ream of blank paper.*
- ☐ *Extra pencil or pens*
- ☐ *A stapler*
- ☐ *A timer*

This will take approximately **45 minutes***: 5 minutes to pass out packets and provide instructions, 5 minutes to read problem, 35minutes to solve problem.*

1- *Hand out Peanut Sheller problem (face-down) packet to each student.*

"We are doing an individual activity. Please sketch and describe with words all designs you can think of, even if they are not technically feasible. Aim for as many ideas as possible at as high of quality and variety as possible. Please sketch **one solution per page** and only use one side of the paper. If you need more paper, let us know. Please write your name on the first page."

"Please turn off cell phones. You are not allowed to leave to take calls or talk to each other"

"Turn over packets, you will have 5 minutes to read the problem, and note if you have heard about this problem ahead of time on page 3"

2- *After 5 minutes*
"You may begin sketching or writing on the blank sheets of paper. You have 35 minutes. Remember to only sketch one design per page"

3- *30 minutes in*
"You have 5 minutes remaining."

4- *35 minutes in*
"Please finish up what you're working on. Make sure you wrote your name on the first page"
"Bring your work to me when you're done and staple any extra pages you may have together"

5- *Collect work*

MEEN 489 Fall 2014   **Date:**   **Time start:**   **Time end:**

Bring:

☐   *30 problem packets*

☐   *1 Ream of blank paper.*

☐   *Extra pencil or pens*

☐   *A stapler*

☐   *A timer*

*This will take approximately **35 minutes**: 28 mins during survey and additional 7min for instructions, passing out packets and pauses.*

1- *Hand out a survey packet to each student (face-down)*

"When I say to turn packet over, please write your name on the first page, and only read the second page. I will tell you when to move on to the third page and so on. Please write legibly"

"We will begin with page 2 only. Please list as many existing solutions that you can think of, that you may have encountered in your life or experience that shells peanuts. If you need more space, you may use pages 6 through 9 as extra space."

2- *Start timer:* "You may start. You have 7 minutes to list everything you can"
- *6 minutes in*

"You have 1 minute left"

- *7 minutes in*

"You can stop with page 2. You may now flip to page 3. List as many existing biological analogies in nature that you can think of that could solve the peanut shelling problem."

3- *Start timer:* "You may start. You have 7 minutes to list everything you can"
- *6 minutes in*

"You have 1 minute left"

- *7 minutes in*

"You can stop with page 3. You may now flip to page 4. Please list as many existing solutions that you can think of, that you may have encountered in your life or experience that solves the blind measuring cup problem."

4- *Start timer:* "You may start. You have 7 minutes to list everything you can"

- *6 minutes in*

"You have 1 minute left"

- *7 minutes in*

"You can stop with page 4. You may now flip to page 5. List as many existing biological analogies in nature that you can think of that could solve the blind measuring cup problem."

5- *Start timer:* "You may start. You have 7 minutes to list everything you can"

- *6 minutes in*

"You have 1 minute left"

- *7 minutes in*

"You can stop now"

"Please make sure your name is on the first page, and then turn the packet in to me"

6- Collect packets

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